Urbanization and Rainfall Variability in the Beijing Metropolitan Region

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ABSTRACT

In this study, rainfall variability in the Beijing metropolitan region and its link to urbanization during the first 10 years of the twenty-first century (2000–09) was examined. Analyses are based on both observations and regional climate model simulations. The study was focused on August, one of the summer months that receive most of the warm season precipitation in Beijing. Observations from surface stations and weather radars in Beijing and its surrounding regions along with satellite observations from the Tropical Rainfall Measuring Mission (TRMM) are used to characterize the spatial and temporal variability of precipitation. It is found that the urban area has fewer rain days and higher rainfall intensity compared to its surrounding region. This suggests a possible impact of urbanization on the spatial variability of rainfall for the region. Regional climate model simulations with the Weather Research and Forecasting (WRF) Model are thus performed with two land use–land cover datasets that represent different stages of urbanization in the Beijing metropolitan region to investigate such an impact. The modeling study demonstrates how urbanization modifies the surface energy budget and the planetary boundary layer, which in turn affects the production of precipitation.

1. Introduction

Urbanization that took place rapidly across developing countries from the late twentieth to the early twenty-first century is projected to continue over the coming decades (United Nations 2010). Urban development boosts economic growth but creates many environmental challenges. From a climate perspective, the urbanization process can be characterized by the induced urban heat island (UHI; e.g., Landsberg 1981; Oke 1982; Kalnay and Cai 2003), changes in urban canopy (Chen and Dudhia 2001a,b; Miao et al. 2009; Chen et al. 2011), and an increase in urban aerosols (Rosenfeld 2000). Recent studies (e.g., Shepherd et al. 2002; Diem et al. 2004; Guo et al. 2006; Holt et al. 2006; Jiang and Liu 2007; Kaufmann et al. 2007; Mote et al. 2007; Gong et al. 2007; Diem 2008; Hand and Shepherd 2009; Shem and Shepherd 2009; Zhang et al. 2009;
Qian et al. 2009; Li et al. 2011a,b) have shown that urbanization with the urban heat island, urban canopy, and urban aerosol effects can potentially influence regional precipitation. Previous studies have suggested that the influence is not only on the amount of precipitation and its spatial distribution but also the frequency of storm events and rainfall intensity (e.g., Stout 1962; Changnon 1962; Changnon et al. 1971; Huff and Changnon 1972; Changnon and Huff 1986; Jáuregui and Romales 1996; Bornstein and Lin 2000; Mölders and Olson 2004; Lei et al. 2008; Aikawa et al. 2009; Shepherd et al. 2010); thus, urbanization can significantly affect regional water resources and flash flood hazards. Lowry (1998), Shepherd (2005), and Collier (2006) provide excellent reviews of the literature on this subject.

The findings from previous studies are not always consistent. Some studies have shown that urbanization can lead to alternations in precipitation regimes in urban environments (e.g., Huff and Changnon 1972; Jáuregui and Romales 1996; Shepherd et al. 2002; Mölders and Olson 2004; Jiang and Liu 2007; Hand and Shepherd 2009), as it affects the boundary layer stability (e.g., Baik et al. 2007). As early as 1921, it was noted that the UHI favors the initiation of convection through creation of a mesoscale convergence zone (Horton 1921; Bornstein and Lin 2000; Jiang and Liu 2007). Mölders and Olson (2004) show that altered precipitation regimes can be attributed to the combined effects of urban aerosols, moisture availability, and UHI via modification of the cloud microphysical paths [see also Van Den Heever and Cotton (2007) and Ntelekos et al. (2009)]. However, other studies indicate that precipitation can be adversely reduced by urbanization (e.g., Guo et al. 2006; Zhang et al. 2009). Guo et al. (2006) argued that the urban core in Beijing serves as a bifurcation zone for storms (see also Bornstein and LeRoy 1990) and reduces the total precipitation in Beijing, especially in the built-up areas. Zhang et al. (2009) found decreased precipitation in the same area, as less moisture and a deeper boundary layer combined to decrease convective available potential energy (CAPE) and reduce rainfall in the region. The increased urban aerosol loading is considered as another major player in modifying regional precipitation (e.g., Rosenfeld 2000; Givati and Rosenfeld 2004; Van Den Heever and Cotton 2007; Jin and Shepherd 2008; Ntelekos et al. 2009), but it is not clear whether and how the elevated urban aerosols decrease or increase precipitation or simply alter the convective structure of precipitation [see Ntelekos et al. (2009) for additional discussion].

As one of the world’s largest megacities, Beijing has undergone a rapid urban expansion in the last two decades. Although there has been significant improvement in the basic infrastructure for transportation and storm water management, the city has experienced severe urban floods once very few years produced by heavy precipitation during the summer months. Observations have shown a decreasing trend in precipitation in Beijing in recent years (Lu 2003; Xu et al. 2006; Zhao et al. 2006; Li et al. 2008; Wei et al. 2008; Zhang et al. 2009), with an increase in total rainfall from intense storm events (Li et al. 2008). The reduction in rainfall over the Beijing area has been hypothesized to result from urbanization through altered surface energy and water fluxes (Zhang et al. 2009) and increasing urban aerosol loadings (Zhao et al. 2006). The decreasing trend in total rainfall with rising contribution from summer heavy rainfall events threatens the water sustainability of the city and also increases flood risks in the urban area of Beijing.

In this study, we use satellite observations of rainfall from the Tropical Rainfall Measuring Mission (TRMM), along with observations from surface stations and weather radars, to study the spatial and temporal variability of precipitation over the greater Beijing region (Fig. 1)—an area where urbanization has progressed rapidly over the last 20 years. We then explore how precipitation variability is associated with urbanization through sensitivity studies using regional climate model simulations. The study focuses on the month of August—one of the summer months that receive a large portion of the annual precipitation over the region (Xu et al. 2006). This decision is also made owing to limitations in surface observation availability. Data from a dense surface network and four operational weather radars in Beijing and its surrounding area are available for August 2008 to provide observational support for short-term weather forecasting during the Beijing 2008 Summer Olympics.

The paper is organized as follows. Section 2 describes all observational data used in this study and presents the observational analyses on the regional precipitation variability in the greater Beijing area. Section 3 then presents the numerical sensitivity study to examine the impacts of urban expansion on regional precipitation, containing the description of the design of the numerical experiments and the results. A summary and conclusions are presented in section 4.

2. Observational analyses
   a. Observational data

The principal data used to analyze the observed precipitation variability in this study are satellite-based rainfall products from TRMM. The satellite-derived datasets are based on the TRMM Multisatellite Precipitation Analysis (TMPA) rainfall products that are available at
a 3-h time interval with the finest grid resolution of 0.25° × 0.25° [see Huffman et al. (2007) for details]. This study used the merged daily [3B42, version 6 (V6), derived] and the monthly (3B43 V6) versions of the TMPA, which are derived from observations made by microwave and infrared sensors. The TMPA products have been evaluated against rain gauges and weather radars in various regions (e.g., Katsanos et al. 2004; Dinku et al. 2007; Ebert et al. 2007; Huffman et al. 2007; Tian et al. 2007; Villarini and Krajewski 2007; Villarini et al. 2009; Sapiano and Arkin 2009; Han et al. 2011). Satellite-derived rainfall products have also been broadly used in precipitation studies examining the spatial variability of rainfall induced by urbanization (e.g., Mote et al. 2007; Hand and Shepherd 2009). In this study, TMPA products over the 10-yr period (2000–09) play a key role in regional rainfall variability analysis, so we first evaluate the daily and the monthly TMPA products against surface observations in the study area (section 2b).

To validate the satellite rainfall estimates, we use observations from surface-observing systems, including a dense surface meteorological network and four operational weather radars distributed in Beijing and its surrounding regions (see domain 2 in Fig. 1). The radar rainfall fields in this study are derived from 3D composite radar reflectivity measurements. They are derived at a 6-min time interval for the entire month of August 2008, utilizing the convective Z–R relationship \[ R = aZ^b; \]

\[ a = 0.017, b = 0.71, \]

where \( R \) is the rainfall rate (mm h\(^{-1}\)) and \( Z \) is the radar reflectivity factor (mm\(^6\) m\(^{-3}\)). The radar rainfall fields are then bias corrected (see Smith and Krajewski 1991) based on surface rain gauge observations. The surface stations are broadly distributed in domain 2, with half of the stations located in domain 3 (Fig. 1). These stations provide surface meteorological variables averaged every minute. Rain gauge observations have been processed to 1-min and hourly accumulations. These observations are only available for the Olympic month of August 2008; thus, they are primarily used to correct the bias in radar rainfall fields and to validate numerical model simulations for the period.

b. Observational analyses

The TMPA data are compared with the bias-corrected radar rainfall at the monthly scale in Beijing for August 2008. The TMPA underestimates the local maximum values, but it does capture the spatial variation of the monthly rainfall field (Fig. 2). After spatially aggregating the daily radar rainfall fields to match the TMPA grid, we calculated the Kendall rank correlation coefficient (Kendall 1955) for daily rainfall estimates between satellite and radar. The rank correlation coefficients fall within the range of 0.47–0.69 in the entire domain with \( p \) values ranging from 0 to 0.0017 (figures not shown). This suggests that the TMPA products can serve as a reasonable surrogate for analyzing the daily and monthly rainfall variability in this region for at least summer months when surface observations are not available.
Figure 3 shows the variability of monthly rainfall within the study region for August 2000–09. The average monthly rainfall in August increases from 90 mm in the west to 115 mm in the northeast, with a local minimum of 90 mm to the south of the urban core, according to the TMPA data. This is at least partially produced by the topography of the region as Beijing is surrounded by mountains from the southwest to the northeast, and land–ocean boundary located to its east.

Figure 3. Spatial distribution of decadal-averaged (2000–09) monthly rainfall (mm) for August in Beijing based on the monthly TMPA product (3B43 V6), with topography (background color) and urban areas (MODIS and USGS urban areas are outlined by black and white, respectively) highlighted.
Although the horizontal gradient in the average monthly rainfall does not seem to be very strong within the domain, the spatial variability for wetter Augusts can be quite large. Figure 4 uses a boxplot to summarize the spatial variability of monthly rainfall within domain 3 for each August of the 10 years. The monthly rainfall in August varies from as low as 36 mm in 2003 to nearly 300 mm in 2005. The driest August over the region is in 2003 as the median monthly rainfall (i.e., the median rainfall over all pixels in the study region) reached only 55 mm. Having median values greater than 150 mm (nearly triple the 2003 median rainfall), 2000 and 2005 are wetter years. Although the 10-yr data record is not sufficiently long to fully assess the climatology and interannual variability of any climate variables, Fig. 4 does suggest that summer precipitation in Beijing varies significantly from year to year with larger spatial variability during the wetter years. This interannual variability is related to the circulation of the East Asian summer monsoon, which has been shown to be correlated with the sea surface temperature in the western Pacific (Wang et al. 2001). For example, the higher monthly rainfall in 2005 likely followed El Niño in the preceding winter.

Summer precipitation in Beijing is mostly associated with convection, so there is a large variability in daily rainfall within each August. Using the daily TMPA data, we examine the contribution of heavy rainfall events to the total rainfall. The domain-averaged daily rainfall is calculated for each day of the 10 Augusts, and then is ranked in descending order. The 10 days with largest rainfalls (i.e., one event per month on average) contribute 25% of the total rainfall in August during the 2000–09 period, while the largest 60 rainfall days contribute 75% of the total rainfall (Fig. 5).

The average daily rainfall increased from about 2.6 mm in the west (mountain region) to over 4.2 mm in the east (close to the land–water boundary) with a local minimum of 2.6 mm to the south of the urban core (Fig. 6a). This conveys the same information as shown in Fig. 3 but expressed at daily level. In contrast to the
spatial pattern of mean daily rainfall, the number of rain days decreases from 15 in the west to 6 days in the east, with a local minimum number of rain days in the urban core of Beijing (Fig. 6b). The spatial variability of rainfall amount and the number of rain days lead to the spatial variability of average daily rainfall intensity that increases from 4 mm day\(^{-1}\) in the northwest to 16 mm day\(^{-1}\) in the southeast with local maximum of 14 mm day\(^{-1}\) around the urban and built-up area (Fig. 6c). The lower rainfall amount, fewer rain days, and higher rainfall intensity over the urban area compared to its surrounding regions seem to suggest urban-induced modifications to precipitation, but needs to be further tested by the numerical modeling studies described later.

We also examined the distribution of the total number of days that daily rainfall is larger than 10 mm and greater than 25 mm in August 2000-09 in the greater Beijing area. The analyses are based on the daily TMPA product (3B42 V6 derived). MODIS and USGS urban areas are shaded by lighter and darker gray, respectively.
with maximum number of days in the eastern portion of the study area. The urban and built-up area has relatively fewer days with greater than 10 mm rainfall but more days with greater than 25 mm rainfall. This further suggests that higher rainfall intensity in the urban core as shown in Fig. 6c is possibly due to urban modification of convective precipitation. In addition, there are more 10 mm days with fewer 25 mm days to the south of the urban core, which helps to explain the local minimum observed in Fig. 6a to the south of the urban area.

3. Numerical modeling experiments and analyses

The analysis of regional rainfall variability with observations indicates that the area around the urban core experienced fewer rain days with more intense rainfall in August during the 10-yr period. To test the hypothesis that urbanization can alter regional rainfall, we conducted numerical experiments with a regional climate model.

a. Model configuration

The Weather Research and Forecasting (WRF) Model is used in this study. The WRF Model is a non-hydrostatic numerical model that has been widely used in precipitation research from urban to regional scales (e.g., Chen and Dudhia 2001a,b; Ntelekos et al. 2008, 2009; Chang et al. 2009; Zhang et al. 2009). In this study, we used the advanced research version 3.1.1 of WRF (Skamarock et al. 2008).

All simulations were implemented with the same three one-way-nested domains with a horizontal grid spacing of 27, 9, and 3 km, respectively (Fig. 1). The outer domain covers central and northeastern China to fully capture synoptic forcing. The inner domain (domain 3) centers on the greater Beijing area. There are 61 × 58, 79 × 70, and 73 × 64 horizontal grids in East–West by North–South directions from domain 1 to domain 3. The vertical grid contains 51 sigma levels from the surface to 50 mb, of which the lowest twenty levels are below 1 km in order to have finer resolution in the boundary layer. The time steps of model simulations are 90 s for domain 1, 30 s for domain 2, and 10 s for domain 3. The initial and boundary conditions are provided by the Global Final Analysis (FNL) data (Shea et al. 1994) from the National Centers for Environmental Prediction (NCEP). Spatial resolution of the FNL fields is 1° × 1° and temporal resolution is 6 h.

All the simulations also share the same model dynamical and physical options that are summarized in Table 1. We used the Rapid Radiative Transfer Model (RRTM) longwave radiation scheme together with the Goddard shortwave radiation scheme that both interact with clouds. They have fixed carbon dioxide levels and prescribed ozone profiles. The Lin et al. microphysical scheme (Lin et al. 1983; Rutledge and Hobbs 1984) that contains five classes of hydrometeors (cloud water, rain, cloud ice, snow, and graupel) was selected. The Yonsei University (YSU) planetary boundary layer (PBL) scheme was used in conjunction with the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) similarity surface layer scheme that provides exchange coefficients to the land surface model. These schemes were kept the same for all the domains except that the cumulus parameterization was turned on for domain 1. Experiments with cumulus parameterization on for domain 2 resulted worse simulations of regional rainfall, thus was not used.

The Noah land surface model (Noah LSM; see Ek et al. 2003) was selected as the land surface component for WRF because of its broad application in examining land surface processes and their impact on weather and climate (e.g., Chen and Dudhia 2001a,b; Holt et al. 2006; Chang et al. 2009; Zhang et al. 2009). For urban land use, a bulk parameterization was incorporated in the Noah land surface model (Liu et al. 2004). It includes changes in roughness length due to turbulence and drag by buildings, changes in surface albedo, volumetric heat capacity, soil thermal conductivity, and reduction in green vegetation fraction. The Noah LSM interacts directly with the radiation scheme and the PBL option. The changes in the land use–land cover modify the surface albedo and emissivity that affect the atmospheric radiation budget through alterations of the scattered shortwave radiation and the emitted longwave radiation at the land surface. In addition, the changes in the land use–land cover also modify

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**Table 1. Physical–dynamical process options selected for WRF simulations in this study.**

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<thead>
<tr>
<th>Physical–dynamical process</th>
<th>Option selected</th>
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<tr>
<td><strong>Physics</strong></td>
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<tr>
<td>Cloud microphysics</td>
<td>Lin et al. scheme</td>
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<tr>
<td>Longwave radiation</td>
<td>RRTM scheme</td>
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<td>Shortwave radiation</td>
<td>Goddard scheme</td>
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<tr>
<td>Surface layer</td>
<td>Monin–Obukhov scheme</td>
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<tr>
<td>Land surface</td>
<td>Unified Noah LSM</td>
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<tr>
<td>Planetary boundary layer</td>
<td>YSU scheme</td>
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<tr>
<td>cumulus parameterization</td>
<td>New Grell scheme (domain 1 only)</td>
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<td>Scalar advection</td>
<td>Monotonic</td>
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<tr>
<td>Eddy coefficient</td>
<td>Horizontal Smagorinsky 1st order closure</td>
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<td><strong>Dynamics</strong></td>
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<td>Time integration</td>
<td>Runge–Kutta 3rd order</td>
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<td>Vertical advection</td>
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<td>Moisture advection</td>
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the surface roughness length. The sensible and latent heat fluxes depend on the surface exchange coefficient for heat and moisture, respectively, and these exchange coefficients are both a function of the surface roughness length [see Chen and Zhang (2009) for details]. Consequently, the altered roughness length affects the partitioning between the surface fluxes of sensible and latent heat, which serve to provide heat and moisture for the PBL. Recent studies (LeMone et al. 2008; Chen and Zhang 2009) have shown that the roughness length is a key variable in determining the LSM performance for simulating the sensible and latent heat fluxes.

b. Experiment design

The numerical experiment was designed to examine how urban expansion can affect the regional precipitation variability. Two sets of simulations were performed and the only difference between the two sets of simulations is in the land surface characteristics that reflect the land use–land cover in two time periods with different degrees of urbanization. The U.S. Geological Survey (USGS) global land use–land cover dataset represents the land use during the period of 1992–93, while the Moderate Resolution Imaging Spectroradiometer (MODIS) land use–land cover dataset characterizes land use and cover in 2004 (Chen et al. 2011). For each land use–land cover scenario, simulations were run for 10 Augusts from 2000 to 2009. All simulations start at 0000 UTC 29 July and end at 0000 UTC 1 September of each year. The first 72 h are discarded as the spinup period to minimize the effects of the initial conditions.

From the early 1990s to the beginning of the twenty-first century, rapid urbanization swept the greater Beijing area. As shown in Fig. 1 (bottom), the urban and built-up areas (in black contour line) in the MODIS dataset are much larger than in the USGS dataset (in gray contour line). The large contrast between the two allows for and supports the sensitivity analyses examining the impacts on precipitation induced by urbanization through modifying the land surface properties. The simulations using the 1993 USGS dataset are denoted WRF-USGS, and those using the 2004 MODIS dataset are denoted WRF-MODIS. Noah LSM is capable of using land use–land cover classifications in both USGS and MODIS datasets. For each land use category, two datasets use the same parameters to describe the physical characteristics of the surface property, such as surface albedo, emissivity, and roughness length of the urban and built-up area.

c. Results from numerical experiment

The focus of the numerical modeling experiment is on the changes in spatial variability of precipitation, especially for heavy rainfall events due to urbanization. It is necessary to evaluate the model performance first to make sure that WRF Model is capable of reasonably reproducing observed rainfall patterns. Using the bias-corrected radar estimates of rainfall fields (referred to as observations) during August 2008, we first evaluate both WRF-USGS and WRF-MODIS simulations for this month. Obviously, the USGS dataset represents the land cover–land use in the early 1990s, and the MODIS dataset represents early 2004. During the first 10 years of the twenty-first century, the Beijing metropolitan area was further urbanized. Using these two land use–land cover datasets to describe the surface characteristics of the region in a simulation for August 2008 will inevitably yield some errors, but the coarse-scale features and the timing of large-scale rainfall are still expected to be well simulated.

Comparison shows that both WRF-USGS and WRF-MODIS simulations produced more rainfall than observed over domain 3 during August 2008, but the model is able to properly capture the evolution of weather systems passing through the region and to reproduce the major rainfall events reasonably well in both simulations. For both simulations and the observations, we normalized the accumulated area-averaged (over domain 3) daily precipitation by its corresponding area-averaged total rainfall during August 2008, and the time series are shown in Fig. 8. During August 2008 there was a series of rainfall events, with the 10 August event (from 9 to 12 August) accounting for more than 50% of
FIG. 9. (a)–(c) Rainfall (mm) and (d)–(f) normalized rainfall (%) of the 10 August event based on (top) radar-derived rainfall field, (middle) WRF simulation with the USGS land use–land cover dataset, and (bottom) WRF simulation with the MODIS land use–land cover map.
It is evident that both simulations were able to capture the sequence of major rainfall events representing the bulk of monthly rainfall, despite the fact that the model overestimated total domain-averaged monthly rainfall in August 2008 under both land use–land cover scenarios. Because the 10 August event produced most of the rainfall during the month, we also examined the spatial distribution of rainfall for this event in WRF simulations. Both simulations overestimated precipitation during this event as compared with radar observations (Fig. 9). To better reveal spatial rainfall patterns, we normalized the storm total rainfall at each grid by its corresponding domain-averaged storm total rainfall of this event for radar observations and model simulations. Radar observations show that most of the rainfall concentrated in elongated rainbands, extending from the southwest to the northeast in domain 3 with areas of heavy rainfall produced by convective elements in the northeast of the domain (Fig. 9). Both simulations were able to reproduce these features reasonably well.

Using WRF-USGS and WRF-MODIS simulations for the 10 Augusts from 2000 to 2009, we can demonstrate the sensitivity of regional rainfall to urbanization (Fig. 10). These two sets of simulations reflect contrasting extent of urban land cover in the Beijing region between 1993 and 2004. Mean monthly rainfall from the WRF-MODIS simulations shows an extensive area north of the urban core of Beijing with substantial reductions in rainfall compared with mean monthly rainfall from the WRF-USGS simulations, and the reduction reaches 45% in some parts. Around the urban and built-up area, WRF-MODIS simulations show more rainfall than WRF-USGS simulations.

We stratified all days during the entire simulation into different categories according to the daily rainfall intensity, and then we examined the difference between WRF-USGS and WRF-MODIS in average rain amount, number of rain days, and average rainfall intensity in each category. Figure 11 shows those differences for moderate rainfall category (10 < daily rainfall < 25 mm) and heavy rainfall category (daily rainfall > 25 mm). It becomes apparent that differences in total rainfall over the greater Beijing area between the two experiments, as shown in Fig. 10, are primarily due to the differences in the heavy rainfall category (Fig. 11a, right). With little difference in the number of rain days between two experiments in both categories (Figs. 11b, right and left), differences in rainfall intensity in the heavy rainfall category are observed from the simulations. This suggests that urbanization may influence the spatial rainfall distribution of heavy rainfall events more significantly than moderate or lighter rainfall events. Over the urban core and slightly east-northeast of urban core, a notable increase in rainfall intensity in the heavy rainfall category is observed from the experiments.

As studies on urban effects of rainfall were typically placed with a framework of upwind, urban, and downwind directions (e.g., Shepherd et al. 2010), we also examined the climatological low-level flow pattern over the study region in August for all days and days with heavy rainfall (daily rainfall > 25 mm) in the Beijing metropolitan region. This is based on the 30-yr (1980–2009) NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010). As shown in Fig. 12, the dominant low-level (850 mb) flow over the study region is mostly southwesterly but becomes southerly during heavy rainfall events. Thus, the increase in rainfall intensity in the heavy rainfall category linked to urban expansion takes place in the downwind direction of urbanized area.

The mechanism for changes in rainfall distribution due to urbanization is complex. We examined the response in surface energy partition, in near-surface atmosphere characteristics, and in microphysical processes to urbanization using the two sets of simulations, trying to associate these responses to changes in rainfall distribution. The WRF-USGS and WRF-MODIS simulations reflect changes in the surface energy balance associated with urbanization impacts on surface albedo, emissivity, and roughness lengths. Replacing vegetated land by urban surfaces causes increases in surface sensible heat flux and decreases in surface latent heat flux, both by over 100 W m$^{-2}$ on average in the expanded urban and built-up area. We also see a reduction in the
FIG. 11. (a) Changes in decadal-averaged (2000–09) monthly rainfall (100%) in August between the MODIS and the USGS land use–land cover scenarios in Beijing, with thresholds of daily rainfall being set at 10–25 (left) and >25 mm (right). The difference is normalized to the 10-yr mean monthly rainfall in August simulated with the USGS land use–land cover dataset. (b) Changes in the 10-yr (2000–09) averaged rain days (number of days) in August between WRF simulations with the MODIS and the USGS land use–land cover scenarios, with thresholds of daily rainfall being set at 10–25 (left) and >25 mm (right). (c) Changes in the simulated 10-yr (2000–09) averaged daily rainfall intensity (mm day$^{-1}$) in August between the WRF simulations with the MODIS and the USGS land use–land cover scenarios, with thresholds of daily rainfall being set at 10–25 (left) and >25 mm (right).
ground heat flux in the same region (Fig. 13c). It is worth mentioning that there is no noticeable change in these fluxes in the urban core between two sets of simulations because this area is categorized as urban land in both land cover–land use datasets.

As a consequence of the changes in surface energy partitioning over the expanded urban areas, the average surface temperature is about 2° higher over these areas in the WRF-MODIS simulations than in the WRF-USGS simulations (Fig. 14). Accordingly, the relative humidity dropped up to 16% over these areas. Associated with higher surface temperature, larger surface sensible heat flux, the planetary boundary layer deepens for 200–300 m on average over the urban core (Fig. 14c). As latent heat flux is an important element of the local water cycle for the lower atmosphere, the reduced latent heat flux limits the moisture availability in the

**Fig. 12.** Climatological (1980–2009) analysis of geopotential heights (m) and winds (m s\(^{-1}\)) on (top) all days and (bottom) heavy rain days (daily rainfall > 25 mm) in August at 850 mb over domain 2.

**Fig. 13.** Differences in the simulated 10-yr (2000–09) averaged land surface energy components: (a) sensible heat flux (W m\(^{-2}\)), (b) latent heat flux (W m\(^{-2}\)), and (c) ground heat flux (W m\(^{-2}\)) in August between WRF simulations with the MODIS and the USGS land use–land cover scenarios in domain 3.
atmosphere, contributing to the reduction of maximum convective available potential energy (mCAPE) up to 80 $\text{J kg}^{-1}$ over the urban core (Fig. 14d). The reduced mCAPE can change the spatial distribution of convection initiation in the urban environment and alter the evolution of preexisting convection that passes over the greater Beijing area.

Unlike the direct response in surface energy fluxes and near-surface atmospheric properties to urbanization, analyses of the microphysical processes show a strong nonlinear response to land surface changes induced by urbanization. Analyses were performed at a vertical cross section that crosses the urban core (39.9°N). From the WRF-USGS to WRF-MODIS simulations, we see that the average water vapor mixing ratio was reduced below the PBL and increased slightly above the PBL (Fig. 15a). It was reduced by 0.8 $\text{g kg}^{-1}$ over the newly developed urban area. The decrease in water vapor mixing ratio below the PBL is a result of the reduced latent heat flux as discussed above. The cloud water mixing ratio was generally increased by 0.005 $\text{g kg}^{-1}$ above 3 km and decreased by about 0.003 $\text{g kg}^{-1}$ below 3 km, indicating an elevated layer of cloud water mixing ratio in the urbanization scenario. There is a notable increase in cloud water mixing ratio below the PBL, especially near the surface, to the east of the newly urbanized region (Fig. 15b). Rain water mixing ratio was increased directly above the urban area by 0.005 $\text{g kg}^{-1}$ with reductions surrounded (Fig. 15c) that is expected to be linked to the increase in precipitation over the urban area. Ice mixing ratio was reduced by 0.0005 $\text{g kg}^{-1}$ around 9 km with increases shown above and below that decreased layer (Fig. 15d). A significant increase of over 0.0004 $\text{g kg}^{-1}$ in the ice mixing ratio was shown to the east of the segment (Fig. 15d). These results highlight the impacts of urbanization on microphysical processes affecting rainfall evolution over the Beijing metropolitan region.
4. Summary and conclusions

The study examines summer rainfall variability and its link to urbanization during the first 10 years of the twenty-first century (2000–09) in the Beijing metropolitan region. Analyses are based on both observations and regional climate model simulations with WRF for the 10-yr period. Regional climate model simulations employ two representations of the urban land cover of Beijing, one corresponding to conditions around 1993 and the other corresponding to urban land use around 2004. Key findings are summarized as follows:

1) The average monthly rainfall for August 2000–09 is 100 mm in the greater Beijing area based on the TMPA fields (3B43 V6). There is large interannual variability and spatial variability in August rainfall in Beijing during the 2000–09 period. Monthly rainfall varies from as low as 36 mm in 2003 to nearly 300 mm in 2005. Median rainfall (i.e., the median rainfall over all pixels in the study region) exceeded 150 mm in 2000 and 2005, which nearly triples the minimum median value of 55 mm in 2003. Mean monthly rainfall increases from 90 mm in the west to 115 mm in the northeast, with a local minimum of 90 mm to the south of the urban core.

2) Spatial variability in the number of rain days and in rainfall rate is an important element of the regional rainfall climatology. Most notably, observations show that the Beijing urban area has fewer rain days and a higher rainfall intensity compared to its surrounding region.

3) The numerical experiment with the WRF Model suggests that urbanization can lead to a reduction of precipitation in the greater Beijing area, but with large spatial variability. The experiment also shows an increase in rainfall amount and intensity over and possibly downwind of the urban and built-up area. The changes in rainfall variability are mostly associated with changes with heavy rainfall events.
4) Because of urban expansion from the 1993 scene to the 2004 scene, changes in surface energy budget are seen in the model experiment over the urban area. We highlight the associated impacts on planetary boundary layer and cloud microphysical processes. The replacement of vegetated land by urban surface leads to an increase in sensible heat flux and decreases in latent heat flux and ground heat flux. Increases in sensible heat flux lead to increases in the surface air temperature, decreases in relative humidity, and an elevated PBL. Lower latent heat flux decreases the moisture availability and results in reduced convective available potential energy, which is associated with the reduction in rainfall in the greater Beijing area. Urbanization also leads to a reduction in the water vapor mixing ratio below the PBL, an elevated layer of cloud water mixing ratio, a decreased ice mixing ratio, and an increased rainwater mixing ratio directly above the urban core. Unlike the direct responses in surface energy fluxes and near-surface atmospheric properties to urbanization, analyses of the microphysical processes show a strong nonlinearity in storm environment to land surface changes induced by urbanization.

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