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Ensemble simulations of the urban effect on a summer rainfall event in the Great Beijing Metropolitan Area

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ABSTRACT

The Great Beijing Metropolitan Area (GBMA), located in North China, is one of the most rapidly developing regions in the world. In this study, ensemble simulations are conducted to investigate the urban effects on a summertime heavy rainfall event in the GBMA. The Weather Research and Forecasting (WRF) model that couples with a single-layer Urban Canopy Model (UCM) is used for the ensemble simulation. Results show that the ensemble simulation with a realistic land-use representation of urban areas (i.e. control run) can well reproduce the spatial distribution and temporal variation of the rainfall event. The simulated total precipitation agrees well with observation. Compared with the sensitivity ensemble simulation, in which the urban area is replaced by cropland, the control run generates more precipitation over the southwest of Beijing, while less rainfall is found in the area to the northeast of Beijing. This result suggests that the underlying urban surface and urban canopy physics in the surface layer have remarkable impacts on precipitation. The stronger upward motion along with larger convergence and more moisture transportation caused by the urban dynamic and thermodynamic effects directly contribute to the differences in rainfall distribution between the control run and the sensitivity run. In addition, the urban effects are found to slow the cold front movement due to the intense warm air over the urban area, leading to a delayed occurrence of the peak rainfall. However, the slow-moving cold front over the urban area enhances the maximum precipitation intensity. The evolution of the rainfall pattern during the intensification period of the precipitation event is dependent on the movement of the cold front in both the control and sensitivity experiments, indicating that urban effects tend to modify the precipitation distribution and influence the temporal variation of the rainfall process.

1. Introduction

Urbanization affects regional climate by modifying planetary boundary layer structure in several ways (e.g., Hafner and Kidder, 1999; Hjemfelt, 1982; Shepherd, 2005). These modifications include changes in the wind velocity, in the mixing layer depth, in the thermal structures of the planetary boundary layer (PBL), as well as changes in local and regional atmospheric circulations (e.g., Pielke et al., 2002; Niyogi et al., 2007; Lo et al., 2007; Chang et al., 2009; Lei et al., 2008). Many previous studies have investigated the generation and effect of the famous urban heat island (UHI), which is characterized by a temperature contrast that can be up to 10 °C (Bornstein and Johnson, 1977) between urban and its surrounding rural areas. The UHI effect is one of the primary mechanisms behind the urbanization impact on local and regional climate. Meanwhile, observational and numerical researches have proven that the UHI also plays a significant role in modifying precipitation process over the urban area. Several pioneering works in urbanization impact studies (e.g., Landsberg, 1956; Changnon, 1968; Huff and Changnon, 1972) have shown that warm-season rainfall increases over the metropolitan and its downwind areas.

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The results from Metropolitan Meteorological Experiment (METROMEX), an extensive study that took place in the 1970s in the United States to investigate the modification of mesoscale and convective rainfall by major cities (e.g., Changnon et al., 1977; Huff, 1986), also revealed that urban effects can lead to increased precipitation during the summer months. To be specific, an increase of 5–25% in precipitation over background values was typically observed within and 50–75 km downwind of the city (Changnon, 1979). Burian and Shepherd (2005) found that from noon to midnight, the urban area and its downwind region received 59% and 30% more precipitation than the upwind region in Houston, respectively. In addition, the highest annual and summer lighting densities, which are closely related to deep convection and precipitation, are also found over and downwind of the city (Bouvette et al., 1982). Recent studies of daily precipitation and heavy rainstorm occurrence have suggested that the underlying urban surface would induce a convergence zone that can initiate the storm and affect the storm movement through its building barrier effect (e.g., Bornstein and Lin, 2000; Craig and Bornstein, 2002; Guo et al., 2006), and thus results in enhanced precipitation. On the other hand, precipitation downwind of an urban area may also decrease as a result of urban pollution (Rosenfeld, 2000) or as a result of evaporation changes (Zhang et al., 2009).

China has been experiencing rapid economic growth and intensive urbanization since the 1980s. Due to the close ties between social development and economic growth, many individual cities have expanded to form distinctive city clusters in eastern China, such as the Great Beijing Metropolitan Area (GBMA), the Yangtze River Delta (YRD), and the Pearl River Delta (PRD) city clusters. The three urban clusters mentioned above in China have resulted in significant modifications in the underlying surface properties and atmospheric circulations, and eventually make great impact on precipitation in and around these city clusters. A recent study by Miao et al. (2010) has found that the urban land cover favors for the development of convection and gives rise to increase in total rainfall in the GBMA. Their results also show that urbanization effects can lead to the breaking of a squall line into individual convective cells over urban areas. Model results have also revealed a large increase in precipitation frequency over urban areas, mainly contributed by the increase in light rain events (<10 mm d^{-1}) (Yang et al., 2012). They found that more precipitation occurs in urban area during the afternoon when the urban PBL becomes more unstable than in rural area. The strong unstable PBL in urban areas often induces a strong vertical atmospheric mixing and upward moisture transport, which in turn is favorable for precipitation. In general, the assessment of heterogeneous urban canopy layer influence on surface energy and mass fluxes within the PBL layer is of growing importance in light of precipitation process in and around urban areas in China.

Despite the numerous studies demonstrating the important role city clusters play in enhancing rainfall in urban areas, opposite effects of urbanization in precipitation are also found. For instance, Kaufmann et al. (2007) argued that urbanization reduced local precipitation in the Pearl River Delta of China due to the changes in surface hydrology. An analysis of long-term rainfall observation has revealed that the rapid urban expansion can result in less evaporation, higher surface temperatures, larger sensible heat fluxes, and a deeper boundary layer over the urban area, eventually leading to a reduction in rainfall over the northeastern area of Beijing (Zhang et al., 2009). The results from Guo et al. (2006) also suggested that the surface latent heat flux reduced remarkably while the sensitive heat flux increased due to the urbanization effects, which help decrease the total precipitation in the urban area. The above studies clearly indicate that the effects of urbanization on precipitation depend on the climate regime and geographical locations of cities and may also be case-dependent.

Many modeling studies have been conducted to investigate the impact of urbanization on weather and climate systems. However, most of these studies are based on results of a single model simulation or sensitivity experiment. It is well known that great uncertainties exist in the modeling results, which are highly sensitive to various physics schemes, the model structures, initial conditions and model resolutions, etc. It is argued that the results from conventional sensitivity experiments are not reliable in determining the impact of urbanization on precipitation due to the uncertainties arising from the land-use change and socio-economic development (Kusaka et al., 2009; Wan and Zhong, 2013). Therefore, it still remains a challenging issue to ascertain whether the sensitivity experiment can provide reliable results to distinct the impact on weather and climate caused by land-use and land-cover change. Given these uncertainties, the advantages of ensemble simulation are apparent since the ensemble simulation can better address the uncertainties than single model simulations. Previous studies have shown that the ensemble simulation with a realistic urban boundary layer can well reproduce the near-surface meteorological variables during the precipitation period (Holt et al., 2009; Kusaka et al., 2009). Wan and Zhong (2013) used the ensemble approach to investigate the impact of large-scale urbanization on precipitation in the lower reaches of the Yangtze River Valley in China and found that urbanization plays a key role in delaying the process of precipitation and leads to an increase in precipitation in urban areas. In this study, we take advantage of the ensemble approach to simulate a heavy rainfall event in the GBMA. Results of the ensemble simulations are used to explore the influence of urbanization on the physical–dynamical process of heavy precipitation events. The paper is organized as follows. Section 2 describes the model configuration and experiment design. Section 3 compares results from the ensemble simulation with observations to validate the performance of ensemble simulation. The urban effects on precipitation are discussed and the possible mechanisms are explored in Section 4. Finally, the conclusions are presented in Section 5.

2. Case overview and model configuration

2.1. Case overview

A severe summer rainfall event that occurred in the GBMA from 0600 UTC to 1800 UTC 27 June 2008 is selected for this study. To understand the background and synoptic patterns for the heavy rainfall event, the geopotential height and temperature at 500 hPa from 0000 UTC 27 to 0000 UTC 28 June (every 12 h) are shown in Fig. 1. The low pressure system centered at Inner Mongolia with the trough axis located in Hubei province was the dominant synoptic system at 0000 UTC 27 June (Fig. 1a). Meanwhile, a cold tongue lagged behind the geopotential height trough, indicating that a cold front was