ARTICLE IN PRESS
UCLIM-00259; No of Pages 28

Urban Climate xxx (2016) xxx–xxx'

Contents lists available at ScienceDirect

Urban Climate

journal homepage: http://www.elsevier.com/locate/uclim

Numerical simulation of urban impact on precipitation in Tokyo: How does urban temperature rise affect precipitation?

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A R T I C L E   I N F O

Article history:
Received 31 May 2016
Received in revised form 21 November 2016
Accepted 22 November 2016
Available online xxxx

Keywords:
Urban impact on precipitation
Numerical simulation
Urban canopy scheme
Urban heat island
Tokyo
Precipitation variability

A B S T R A C T

This study explored how heat island intensification affects precipitation in the Tokyo metropolitan area. Numerical experiments were made for the month of August from 2006 to 2013 using the Non-Hydrostatic Model (NHM) with a horizontal grid interval of 2 km and the Square Prism Urban Canopy (SPUC) scheme. We performed the experiments with two different specifications for the Tokyo area: the current highly urbanized surface conditions (CRNT experiment) and less urbanized conditions (MDUB experiment). The simulation results suggest that the mean monthly precipitation in the central Tokyo area was approximately 10% larger in the CRNT experiment than in the MDUB experiment, associated with a mean temperature rise of as much as 1 °C. We also examined the modification of daily precipitation characteristics in the two experiments. The CRNT experiment generally yielded larger amounts of area-maximum precipitation in the urban domain; however, differences between the experiments in daily precipitation varied among cases. Composite analysis was performed to investigate the processes associated with the differences in simulated precipitation. We found that in afternoon rainfall cases without preceding precipitation, a thermally induced change in circulation, particularly enhanced ascending motion, played an important role in the precipitation increase in the CRNT experiment.

1. Introduction

Evaluating the impact of urbanization on precipitation is an important problem in urban climate research. Precipitation variability is critical for water resource management in and around urban areas, and estimates of precipitation modification in urban areas, particularly for heavy rainfall, are necessary for disaster

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http://dx.doi.org/10.1016/j.uclim.2016.11.007
2212-0955

Please cite this article as: Seino, N., et al., Numerical simulation of urban impact on precipitation in Tokyo: How does urban t..., Urban Climate (2016), http://dx.doi.org/10.1016/j.uclim.2016.11.007

preparedness. Urban climate in the Tokyo metropolitan area, an agglomeration of 38 million inhabitants (United Nations, 2014), has long been studied using various approaches (Fujibe, 2011, 2012), but the urban influence on precipitation in this area is still not fully understood. The Tokyo metropolitan area is on the southeastern coast of central Japan and usually has an abundant moisture supply. Temporal and spatial variations in precipitation depend predominantly on the activities and tracks of mid-latitude disturbances and tropical cyclones, which means that an urban effect is not easily detected in long-term observation data.

Yonetani (1982, 1989) pioneered research on the urban influence on precipitation variability at Tokyo. Kanae et al. (2004) analyzed Tokyo precipitation records from 1890 to 1999 and showed that hourly heavy precipitation in the 1990s was not unprecedented in strength or frequency. Fujibe et al. (2009) investigated hourly precipitation data from the same station for a longer period (1890–2007) and the Automated Meteorological Data Acquisition System (AMeDAS) data from surrounding stations for the most recent 30 years. They found that "no preceding precipitation" (NPP) cases showed both an increasing trend at a rate of 30%/century or more and a positive spatial anomaly in Tokyo between afternoon and early evening in the warm season. Although increases in heavy rainfall have been detected at many other stations in less urbanized parts of Japan (Fujibe et al., 2005; Japan Meteorological Agency, 2014), Inoue and Kimura (2004, 2007) used satellite imagery to show that cumulus formation was enhanced in the Tokyo area in the warm season. Moreover, Sato et al. (2006) and Takahashi et al. (2011) suggested an enhancement of precipitation over or downwind of the most urbanized parts of Tokyo. These observation-based findings suggest the possibility of an urban effect on the increase of warm-season short-term precipitation in Tokyo.

The urban effect on precipitation has been investigated for many cities (Shepherd, 2005; Kanda, 2007; Pielke et al., 2007; Shepherd, 2013; Han et al., 2014; Mitra and Shepherd, 2016), particularly in the United States, with an emphasis on convective precipitation. METROMEX was the first major field program to investigate the existence and causes of urban rainfall anomalies that had been suggested in several previous climatological studies (Changnon, 1981). Changnon et al. (1976) used METROMEX data to infer statistically significant increases in summer rainfall and thunderstorms in and just downwind of St. Louis, Missouri. Subsequent studies have suggested various kinds of urban impacts, such as the enhancement of precipitation around urban areas, based on observations (Kishtawal et al., 2010; Kug and Ahn, 2013), changes in diurnal precipitation patterns (Balling and Brazel, 1987), urban-induced rainfall (Bornstein and Lin, 2000; Dixon and Mote, 2003), precipitation increases downwind of urban areas (Shepherd et al., 2002; Mote et al., 2007; Hand and Shepherd, 2009), and spatial rainfall modifications, including storm splitting (Niyogi et al., 2011). Ashley et al. (2012) demonstrated positive urban amplification of thunderstorm frequency and intensity for major cities in the Southeast United States by using radar reflectivity and lightning data. Results of Haberlie et al. (2015) revealed that isolated convective initiation (ICI) events occurred more often over the urban area compared to its surrounding rural counterparts. Meanwhile, some studies have documented decreases in rainfall due to urbanization (Rosenfeld, 2000; Kaufmann et al., 2007). Changnon (2001) confirmed that the net urban effect was an increase in storm activity over the central part of Chicago and suggested that urban complexes of more than three million inhabitants are likely to have locally altered storm activity. The variety of precipitation responses revealed by these studies shows that urban effects on precipitation are quite complex and dependent on many factors including city size, surrounding land use, water cycles, and regional climate. Mitra and Shepherd (2016) states that complex urban land-atmospheric interactions are not easy to grasp and more research must be done to understand the impact of morphology, shape, aerosols and microscale temperature patterns on urban precipitation variability.

Numerical simulations are useful for analyzing and quantifying urban processes, and the number of numerical experiments has grown in recent years (e.g., Baik et al., 2001; Rozoff et al., 2003; Gero and Pitman, 2006; Niyogi et al., 2006, 2011; Shem and Shepherd, 2009). Trusilova et al. (2008) and Hamdi et al. (2012) showed that inclusion of urban land cover resulted in an increase of winter precipitation and a reduction of summer precipitation in Europe. Numerical investigations have also addressed urban effects on precipitation in Asian cities (Lin et al., 2008; Zhang et al., 2009; Wang et al., 2012; Yang et al., 2014; Zhang et al., 2014), and several have been carried out for cases involving rainfall in Tokyo.

Matheson and Ashie (2008) modeled the effect of land surface changes in Tokyo for two selected rainfall cases and showed that the presence of urban land use types enhanced rainfall in one case and slightly reduced it in the other case. Shimoju et al. (2010) showed that urbanization in Tokyo apparently increased rainfall in five of nine localized heavy rain events and decreased it or had no effect in the other four cases. Ikebuchi et al. (2007) found that changes in urban distribution and anthropogenic heat output greatly affected the positions and amounts of rainfall in a heavy rainfall case. Souma et al. (2013) confirmed that both anthropogenic heat

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