Numerical simulation of urban influence on summertime precipitation in Tokyo - How does urban temperature rise affect precipitation?

Naoko Seino [1], Toshinori Aoyagi [1], Hiroshige Tsuguti [1]
[1] *Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Japan*
nseino@mri-jma.go.jp

dated : 1 July 2015 (Revised 7 August 2015)

1. Introduction

Precipitation modification due to the progress of urbanization is one of the key topics in the urban climate research. As for the Tokyo metropolitan area, Fujibe et al. (2009) showed that “no preceding precipitation” (NPP) cases have an increasing trend of precipitation as a rate of 30 %/century or more from afternoon to early evening of the warm season. However, the detected change in precipitation can be influenced by factors other than urbanization, such as global warming and associated regional climate change. For the better understanding of urban impact on precipitation, numerical modeling with high-performance urban scheme is a useful approach. In the present research, we conduct numerical simulations for August in recent eight years and investigate how increasing heat island intensity in Tokyo affects precipitation in the metropolitan area and its vicinities.

2. Model and experimental design

The Non-hydrostatic Model of Japan Meteorological Agency (JMA-NHM, Saito et al. 2007) is utilized in the present simulation. Horizontal grid interval is 2km and the model domain covers central Japan including the Tokyo metropolitan area (Fig. 1). We employed the Square Prism Urban Canopy (SPUC) scheme (Aoyagi and Seino 2011) to take into account the urban effect in land surface processes. The SPUC scheme is a single-layer urban canopy scheme designed for evaluating heat, moisture, and radiation exchanges between the surfaces of ground, building wall, roof and the atmosphere. Spatial distribution of time-varying anthropogenic heat in the metropolitan area (Senoo et al. 2004) is also considered in SPUC. Area fractions of buildings and other land use categories in each model grid are determined from the 100m-mesh Digital National Land Information Dataset.

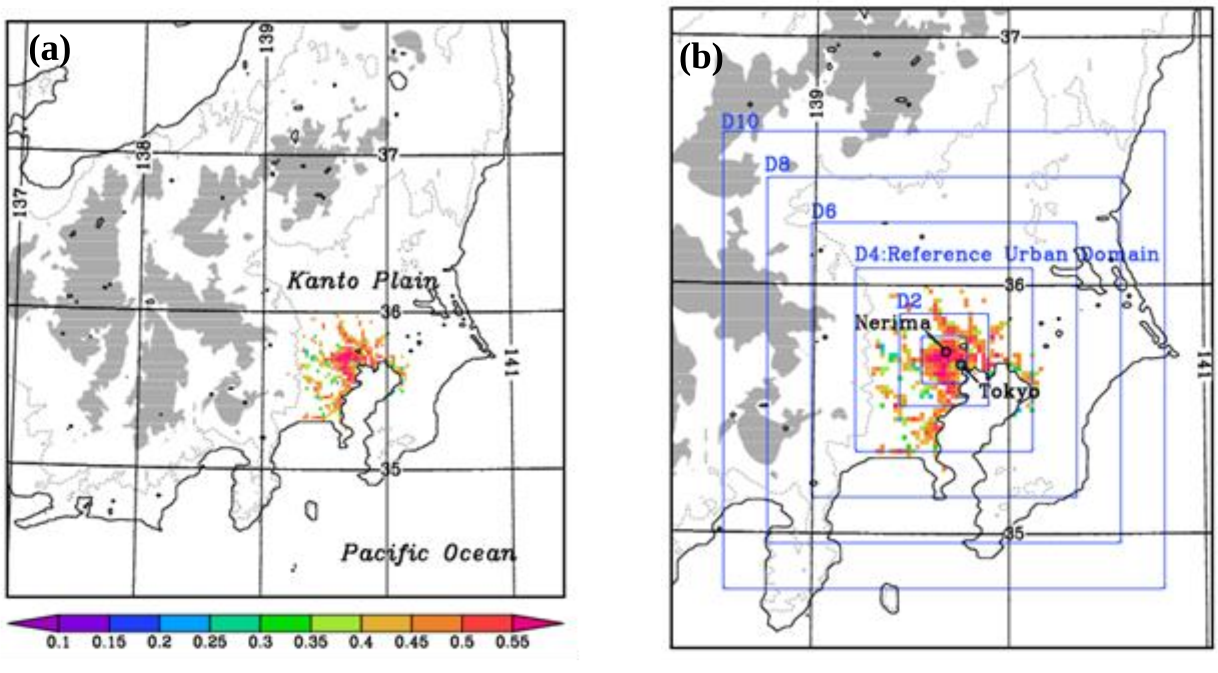

Fig. 1 (a) Model domain of JMA-NHM and (b) magnified view at around the Kanto Plain area. Colors denote building area fraction of SPUC-applied grids. Broken lines indicate topographic contours of 200 m and grey shade shows mountainous regions with altitude higher than 1000 m above sea level. Rectangles indicate domains used later for the evaluation of area-averaged precipitation.

Comparative experiments have been done with and without utilizing SPUC in the metropolitan area. In the experiment named SPUC experiment, the SPUC scheme is applied in highly urbanized grids mainly in the central Tokyo area where area fraction of artificial land use is 80% or more (Fig.1b). On the other hand, in the SLAB experiment, slab land surface treatment is applied in the entire domain with urban surface parameters representing moderate urban conditions. Simulation period was August from 2006 to 2013. Time integrations for 27 hours starting at 2100 JST (Japan Standard Time, 0000 UTC = 0900 JST) are repeated in both experiments. Initial and boundary conditions are given from operational mesoscale analyses of JMA. Simulation results in the two experiments from forecast time FT=3 to FT=27 (from 0000 to 2400 JST) are compared.

3. Results

3.1 Surface air temperature

We first examined surface air temperature field based on the hourly model output. Simulated monthly mean temperatures reasonably well agreed with observations at Automated Meteorological Data Acquisition System (AMeDAS) stations. On the average of eight-year August, simulated monthly mean temperature in the SPUC experiment was higher up to 0.8 K in the area where the land surface scheme is changed (Fig.2). Although the monthly mean temperature difference varied year to year, differences were found within the SPUC-applied area in each year and at most one degree in the central part of Tokyo. Validation against observation data shows that the SPUC experiment successfully simulate current temperature field. In the SLAB experiment, on the other hand, slightly lower temperatures in the urbanized area and thus reduced heat island intensity were represented.

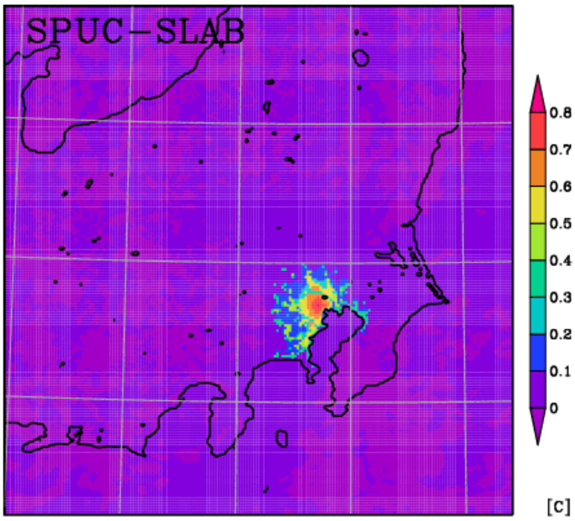

Fig. 2 Difference in simulated surface air temperature between the two experiments (SPUC - SLAB) averaged over August 2006 - 2013.

3.2 Monthly precipitation

Monthly precipitation amounts were generally well simulated in both the SPUC and SLAB experiments. Difference in monthly precipitation between the two experiments (SPUC-SLAB) is demonstrated in Fig. 3. Changes in rainfall distribution arise widely extending outside the SPUC-applied area. Positive precipitation anomalies appear more frequently in the SPUC-applied area and negative anomalies are found to the north of the area. However, the difference distribution is rather scattered even after averaging over August in eight years. Thus, for more quantitative examination, we evaluated area-averaged precipitation in rectangular domains D1 – D10 with (k*20 + 2) km length (k=1-10) each side, centered at the most urbanized area (see Fig.1b).

Figure 4 shows increasing rate (SPUC-SLAB) of area-averaged monthly precipitation to the SLAB precipitation amount in the eight-year August mean. Positive anomalies, which indicate larger amounts of monthly precipitation in the SPUC experiment, were found in domains within D6. In the domain D1, the most highly urbanized area, eight-year mean monthly precipitation was 10% larger in the SPUC experiment than in the SLAB experiment. The difference ratio decreases as the domain size increases. The differences were statistically significant by one-sided t-test at a significance level of 90% for domain D1, and 95% for domains D1 – D6.

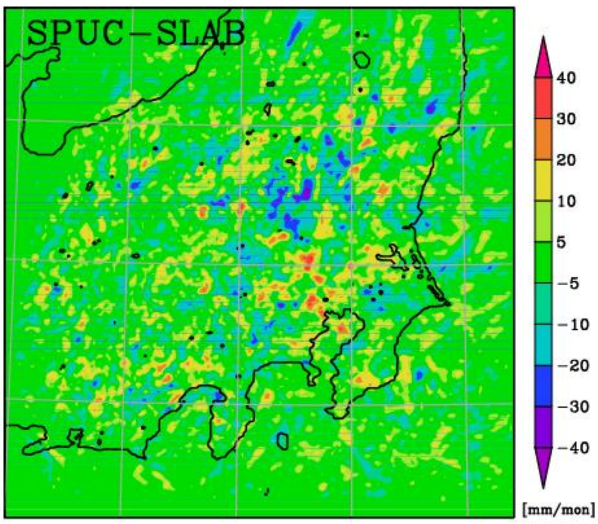

Fig. 3 Difference in monthly precipitation between the SPUC and SLAB experiments averaged over August 2006 - 2013.

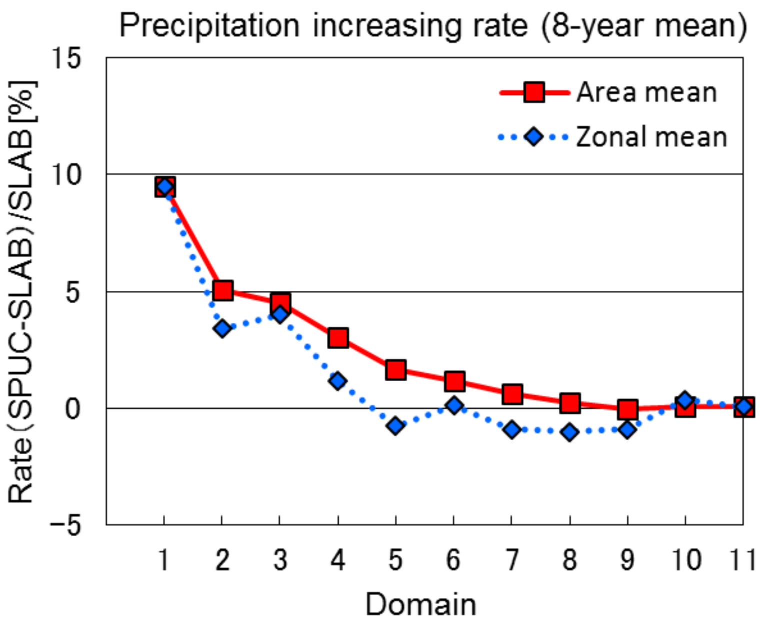

Fig. 4 Precipitation increasing rate of area-averaged monthly precipitation (percent rate) in domains D1-D10. Zonal mean values defined in differential areas between domains are also drawn.

3.3 Daily precipitation

Next, modification of precipitation between the SPUC and SLAB experiments are examined on a day-to-day basis. We defined area maximum daily precipitation (MDP) as the maximum value of the simulated daily precipitation amounts among the grids in a domain. As shown in scatter diagrams for MDP between the experiments (Fig. 5), the SPUC experiment gives larger MDP on average in D1 and D4, as well as the monthly precipitation amount. However, MDP differences (SPUC-SLAB) vary between cases and both positive and negative anomalies appear. In the domain D1 (D4), larger MDPs in the SPUC experiment (positive anomalies) are found in roughly 70% of cases, but MDPs in the SLAB experiment are larger in the remaining 30(32)% of cases. In wider domains, the number of cases with negative anomaly increases. Hence positive and negative deviations appear almost equally in the domain D10.

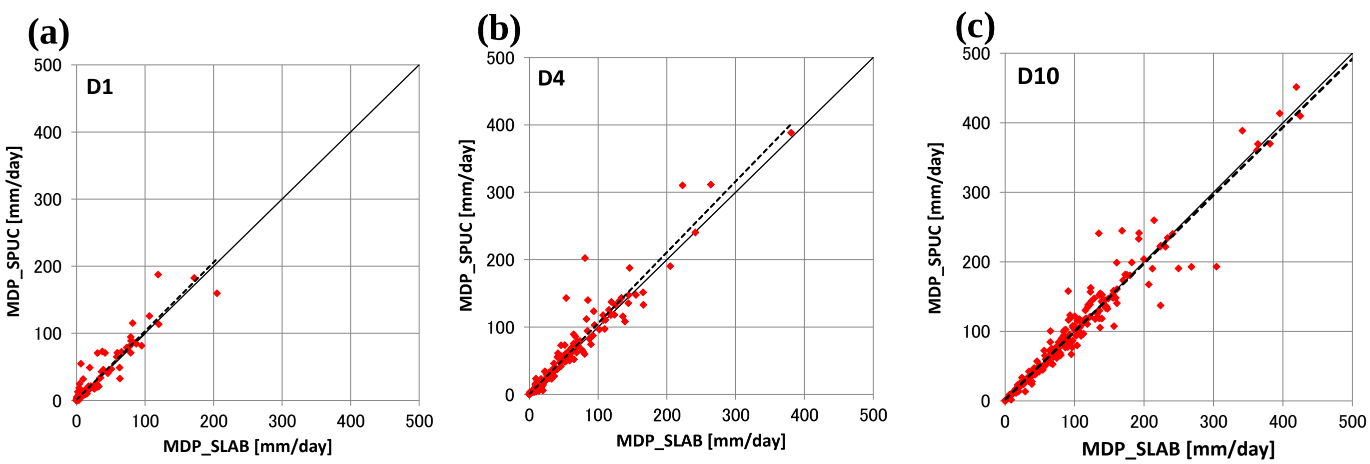

Fig. 5 Scatter diagrams for MDP between SPUC and SLAB simulation results in (a) D1, (b) D4, and (c) D10.

4. Discussion

To further discuss processes related to the precipitation response mentioned above, we investigated changes in near-surface meteorological field between the two experiments. As shown in previous studies, local flow and temperature fields at around Tokyo are largely influenced by the sea breeze circulation. Present model results well simulated the development of the sea-breeze and associated diurnal variation in the wind and temperature. In fine and cloudy cases, southerly sea-breeze has developed and covered coastal areas in the afternoon by 1500JST. High temperature is found slightly inland areas to the northwest of Tokyo. We chose 86 afternoon NPP cases in the D4 domain, defined as afternoon precipitations not preceded by 1 mm precipitation for the last six hours. Comparison of the near-surface field one hour before the onset of the rainfall indicates that higher temperature anomalies and associated horizontal convergence zone were formed in the central urban area in the SPUC experiment (Fig.6). These thermally-induced modifications are one of the possible causes of the precipitation increase at around Tokyo.

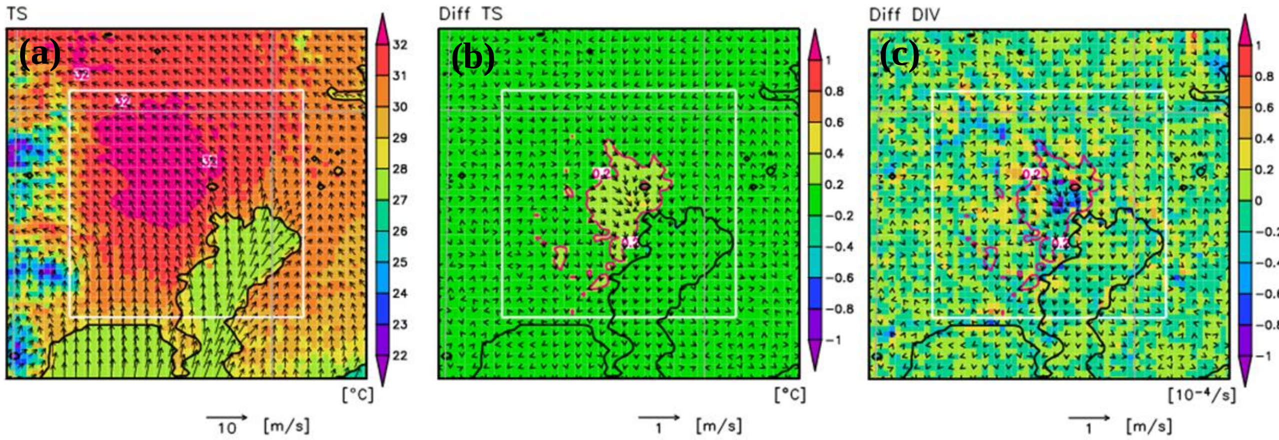

Fig. 6 Simulation results of afternoon NPP cases before the onset of rainfall for (a) surface wind and temperature of the SPUC experiment, (b) differences in the wind and temperature, and (c) differences in the wind and surface horizontal divergence between the SPUC and SLAB experiments. Boxes indicate the domain D4.

5. Concluding remarks

Numerical simulations have been carried out to investigate impacts of the enhanced urban heat island on regional precipitation amount and spatial distribution in Tokyo and surrounding areas. The present simulation results suggest that less than one degree mean temperature rise in Tokyo can lead to the statistically-meaningful increase in summertime precipitation amount in and around the area. Differences in daily precipitation amount and spatial distribution between the comparative experiments largely varied case by case. Although the simulated daily precipitation amount does not always gain in the highly urbanized condition of the SPUC experiment, frequencies of increased precipitation in the SPUC experiment were doubled compared with precipitation decrease frequencies. For the better understanding of precipitation modification due to the urbanization, relative importance of other possible causes of precipitation modification should be further discussed in future research.

Acknowledgment

This work is partly supported by the SOUSEI programmes of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan.

References

Aoyagi, T. and N. Seino, 2011. A square prism urban canopy scheme for the NHM and its evaluation on summer conditions in the Tokyo metropolitan area, Japan. *J. Appl. Meteorol .Climatol.*, **50**, 1476-1496.

Fujibe, F., H. Togawa, and M. Sakata, 2009. Long-term change and spatial anomaly of warm season afternoon precipitation in Tokyo. *SOLA*, **5**, 17-20.

Saito, K., J. Ishida, K. Aranami, T. Hara, T. Segawa, M. Narita, and Y. Honda, 2007. Nonhydrostatic atmospheric models and operational development at JMA. *J. Meteor. Soc. Japan*, **85B**, 271-304.

Senoo, H., M. Kanda, T. Kinouchi, and A.Hagishima, 2004. Estimation of anthropogenic heat and vapour emission, and the impact on local meteorology. *Ann. J. Hydr. Eng.*, **48**, 160-174 (in Japanese with English abstract).