Numerical estimate of the effect of urban land use on precipitation in Osaka Prefecture, Japan

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Abstract

This study utilized the Weather Research and Forecasting model (WRF) version 3.5.1 to estimate the effect of urban land use on precipitation in Osaka, Japan. The effect was estimated by comparing the WRF simulations with the present land use and no-urban land use (replacing "Urban" with "Paddy") for August from 2006 to 2010. The mean air temperature was increased by 2.1 °C in urban areas because of increased sensible heat flux, and mean humidity decreased by 0.8 g kg^{-1} because of decreased latent heat flux. The effect of urban land use changed the local circulation patterns, and consequently increased precipitation in the urban area and decreased in the surrounding area. The mean precipitation in the urban area was increased by 20 mm $month^{-1}$ (27% of the total amount without the synoptic-scale precipitation). The precipitation increase was generally due to the enhancement of the formation and development of convective clouds by the increased sensible heat flux from afternoon to evening. The urban areas of Osaka substantially affects spatial and temporal distribution patterns of summertime precipitation and evaporation, and consequently the water cycle in and around the areas.

1. Introduction

The land cover alteration through urbanization have changed the surface energy budget and the local climate in urban areas. The well-recognized impact of urbanization is the urban heat island (UHI) effect characterized by higher temperature in urban areas relative to their surrounding areas. The UHI effect may influence local circulation patterns and precipitation events.

A number of studies have investigated the effect of urbanization on precipitation based on analyses of observation data and numerical simulations [e.g., 1, 2]. Although there are many studies on the urbanization impact on precipitation, the mechanism on the urban-induced precipitation is less understood compared to that on the urban-induced higher temperature. This study utilized the Weather Research and Forecasting model (WRF) [3] version 3.5.1 to estimate the effect of urban land use on precipitation in Osaka, which shows the largest UHI intensity among large Asian cities [4].

2. Method

This study focused on Osaka Prefecture, which includes the third largest megacity in Japan and is characterized by a small fraction of forest areas and particularly high fraction of urban areas. Figure 1 shows the WRF modeling domains from domain 1 (D1) covering the Kinki Region of Japan to domain 2 (D2) covering Osaka Prefecture. The horizontal grid resolutions and the number of grid cells in the domains are 3 and 1 km, and 90 × 90 and 90 × 90 for D1 and D2, respectively. Topography and land use data were derived from the 30-sec resolution data of the United States Geological Survey (USGS) and the 100-m resolution National Land Numerical Information data of the Geospatial

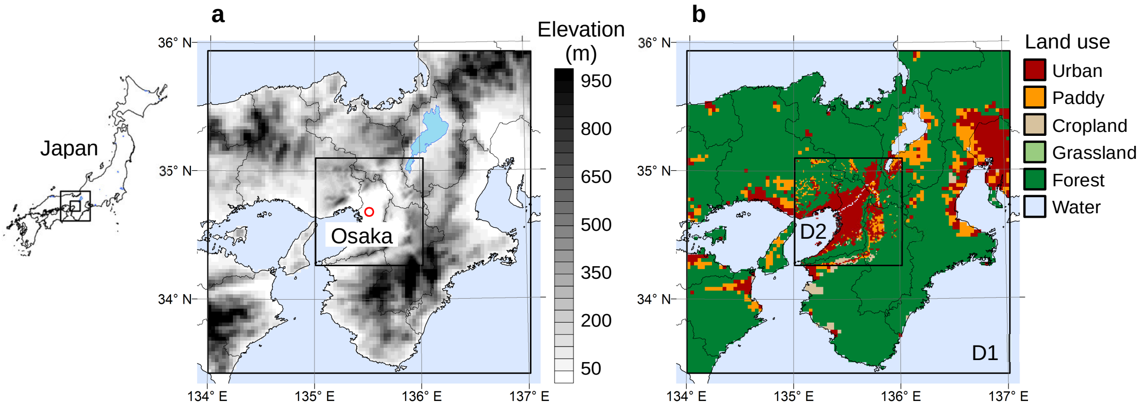

Figure 1: Modeling domains with elevation (a) and dominant land use (b)

Information Authority of Japan (GIAJ), respectively. The vertical layers consisted of 30 sigma-pressure coordinated layers from the surface to 100 hPa. The WRF simulations were conducted with on-line one-way nesting in the two domains.

Initial and boundary conditions were derived from the final operational global analysis data by the U.S. National Centers for Environmental Prediction (NCEP FNL) and from the grid point value derived from the mesoscale model (GPV MSM) data by the Japan Meteorological Agency (JMA). Sea surface temperature was derived from the high-resolution, real-time, global sea surface temperature analysis data (RTG_SST_HR) by NCEP. The four-dimensional data assimilation technique was not applied to the WRF simulations. WRF was configured with the Yonsei University planetary boundary layer (PBL) scheme, the WRF single-moment 6-class microphysics scheme, the Noah land surface model, the rapid radiative transfer model for the long wave radiation and the Dudhia shortwave radiation scheme. The cumulus parameterization and the urban canopy model were not activated in this study.

The effect of urban land use was estimated by comparing the baseline case with the present land use data shown in Figure 1b and the case with modified land use data in which "Urban" land use was replaced by "Paddy" land use in D2. The former and the latter cases are respectively referred to as URBAN and U2PAD cases. The WRF simulations were conducted for August of five years from 2006 to 2010 with three-day spin-up periods from July 29 to 31.

The target region for the evaluation of the effect of urban land use was defined as the "Urban" dominant grid cells in the URBAN case in D2 except near the lateral boundaries (distance of six grid cells). The target period was defined as the WRF simulation periods except days with the synoptic-scale precipitation. Days on which a weather front stayed over or passed through D1 and/or the minimum distance between the center of a tropical cyclone and the lateral boundaries of D1 was less than 300 km were excluded from the target period. Based on the definition, the target period included 113 days out of 155.

3. Results and Discussion

3.1 Model performance

Figure 2 shows hourly time series of the observed and simulated meteorological variables in August 2010 at the Osaka meteorological observatory (Figure 1a). In summer,

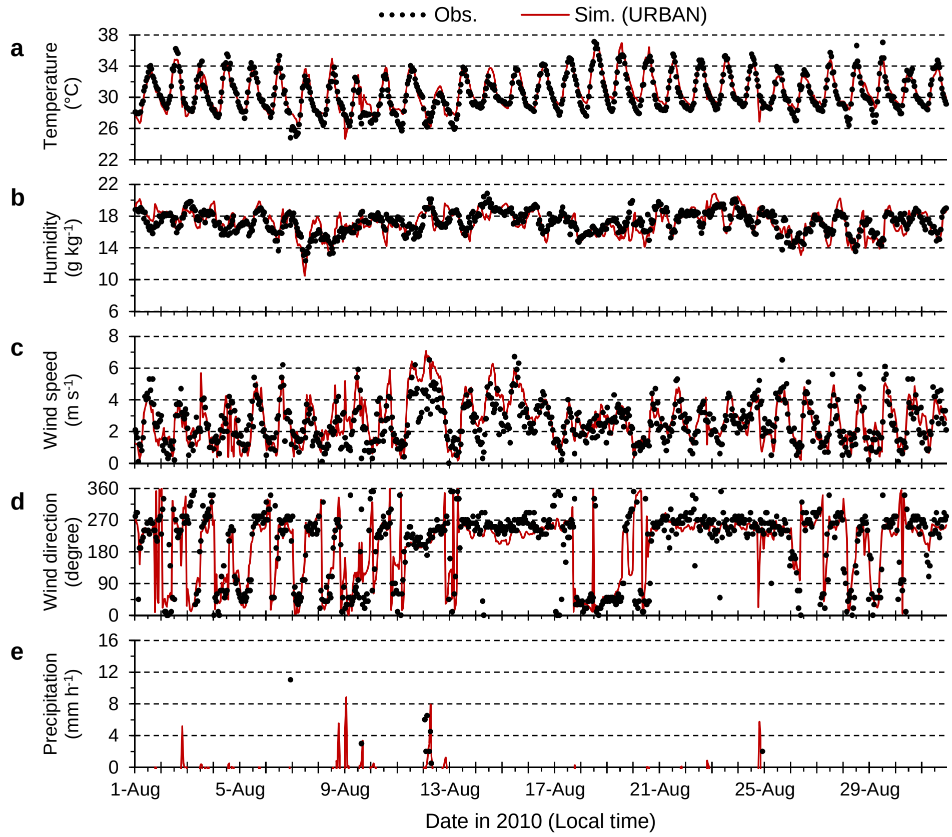

Figure 2: Hourly time series of observed and simulated (URBAN case) ground-level meteorological variables at Osaka meteorological observatory in August 2010.

meteorological conditions in the main island of Japan are typically controlled by the Pacific high-pressure system prevailing over the Northwest Pacific Ocean. Local sea and land breeze circulations are well developed under the condition. In August in Osaka, air temperature is consistently high and often exceeds 35 °C. In addition, humidity is also consistently high because substantial amount of moisture is supplied from the ocean. As shown in Figure 2c and d, while the daytime southwesterly sea breeze generally prevails in Osaka, the nocturnal northeasterly land breeze is generally weak and sometimes calm. Although WRF fairly well simulated the temporal variations of air temperature, humidity, wind speed and direction, the model had difficulty in accurately simulating precipitation in August at the Osaka meteorological observatory. The result indicates that there are large uncertainties in numerical evaluations of summertime precipitation only at specific point and/or time. Therefore, this study estimated the effect of urban land use on precipitation for the target region and period.

3.2 Effect of urban on precipitation

Figure 3 shows spatial distributions of the differences of mean ground-level air temperature, humidity and precipitation between the URBAN and U2PAD cases in the target period. The effect of urban land use obviously increased air temperature in the target region (2.1 °C on average) and slightly increased in the surrounding region. At the same time, the effect obviously decreased humidity in the target region (0.8 g kg^{-1} on average) slightly decreased in the surrounding region. The urban area caused an increase of precipitation in the target region and a decrease in the surrounding region. The monthly mean precipitation was increased by 20 mm month^{-1}, which was equivalent to 27% of the total amount without the synoptic-scale precipitation, in the target region and period.

Figure 4 shows diurnal variations of the simulated mean ground-level meteorological variables in the URBAN and U2PAD cases in the target region and period. The effect of urban land use increased air temperature because of increased sensible heat flux. The increase from midnight to dawn was remarkable (up to 3.1 °C at 0500 local time) because large part of the sensible heat was transported to the upper air by vertical mixing in daytime. In addition, a part of heat accumulated in soil layers in daytime released to the atmosphere as sensible heat after sunset. The effect of urban land use decreased humidity because of decreased evaporation from the surface, i.e. latent heat flux. The increased surface drag in the urban area generally decreased ground-level wind speed. On the other hand, the increased air temperature in the urban area enhanced sea breeze circulation. As a result, while the duration of southwesterly sea breeze was longer in the URBAN case, the mean wind speed was similar in the two case. The increased sensible heat flux caused remarkable increase of PBL height from noon to evening (up to 449 m at 1700 local time). This indicates that the atmosphere over the urban land use was relatively more unstable in the period and therefore convective clouds were more easily formed and developed. Consequently, the effect of urban land use obviously increased precipitation from

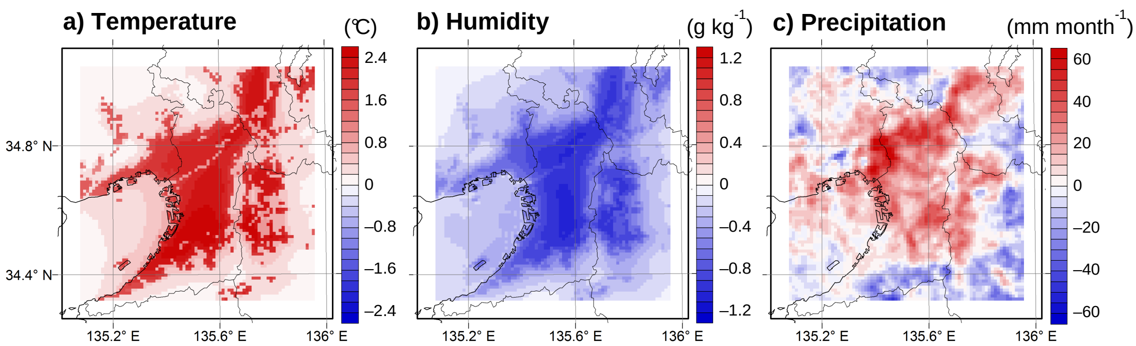

Figure 3: Spatial distributions of mean differences of temperature (a), humidity (b) and precipitation (c) between URBAN and U2PAD cases in the target period

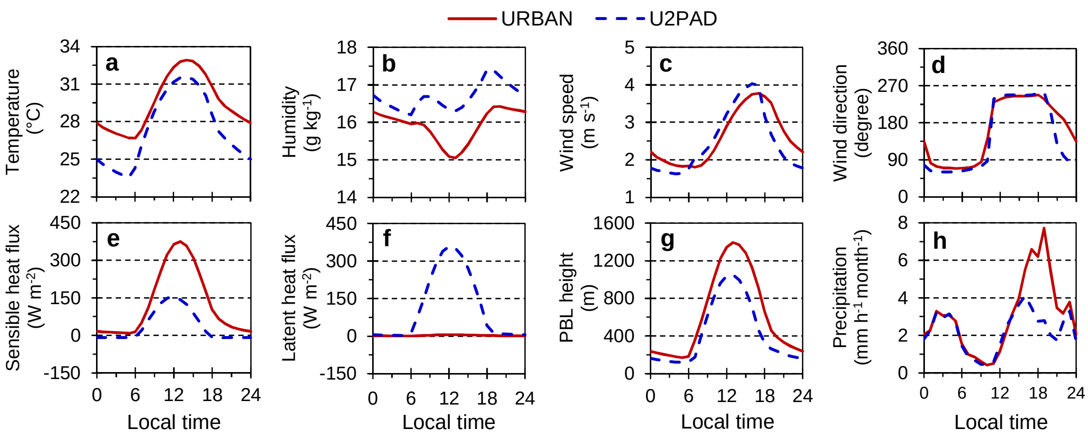

Figure 4: Diurnal variations of simulated mean ground-level meteorological variables in URBAN and U2PAD cases in the target region and period

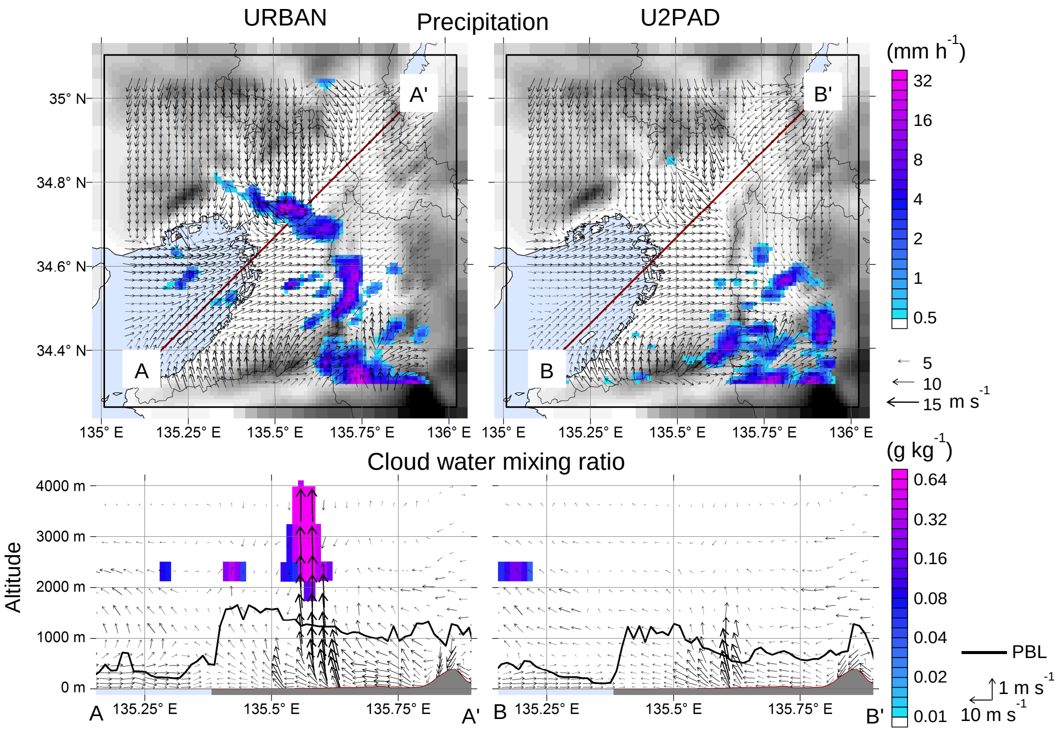

Figure 5: Horizontal distributions of precipitation and vertical cross-sections of cloud water mixing ratio with wind fields simulated in the URBAN and U2PAD cases at 1700 local time on August 9, 2008

afternoon to evening. The results indicate that in the target region, in which substantial amount of moisture is supplied from the ocean, the sensible heat flux plays a much more important role in summertime local-scale precipitation than the evaporation from the ground surface.

Figure 5 shows horizontal distributions of precipitation and vertical cross-sections of cloud water mixing ratio with wind fields simulated in the URBAN and U2PAD cases at 1700 local time on August 9, 2008 as an example representing the difference between the two cases. In both cases, upward convection occurred by the convergence of horizontal wind in the north central region of Osaka prefecture. However, the atmosphere over the target region was more unstable in the URBAN case than in the U2PAD case, and therefore the convection in the former case was much deeper. As a result, clouds formed and developed by the enhanced convection increased precipitation in the target region. There were other similar cases in which the urbanization caused local-scale precipitation associated with convective clouds in the target region from afternoon to evening.

4. Conclusion

This study estimated the effect of urban land use on summertime precipitation in Osaka, Japan by comparing the WRF simulations in the URBAN and U2PAD cases for August of five years from 2006 to 2010. The target region for the evaluation was the “Urban” dominant grid cells in the URBAN case. The target period was the WRF simulation periods except days with the synoptic-scale precipitation. The effect of urban land use increased mean air temperature in the target region and period by 2.1 °C because of the increased sensible heat flux. At the same time, the effect decreased mean humidity in the target region and period by 0.8 g kg^{-1} because of the decreased latent heat flux. The effect of urban land use on mean wind speed was not clear compared to air temperature and humidity. This was because the effect of increased surface drag was compensated by the enhanced sea breeze circulation. The urban area caused an increase of precipitation in the target region and a decrease in the surrounding region. The mean precipitation in the target region and period was increased by 20 mm $month^{-1}$, which was equivalent to 27% of the total amount without the synoptic-scale precipitation. The precipitation increase was generally due to the enhancement of the formation and development of convective clouds from afternoon to evening by the increased sensible heat flux. The results indicate that in the target region with substantial amount of moisture supply from the ocean, the sensible heat flux plays a much more important role in summertime local-scale precipitation than the evaporation from the ground surface. This study showed that the urban areas of Osaka substantially affected spatial and temporal distribution patterns of summertime precipitation and evaporation, and consequently the water cycle in and around the areas.

Acknowledgements

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