NUMERICAL SIMULATION OF URBAN HEAT ISLAND USING GRIDDED URBAN CONFIGURATION AND ANTHROPOGENIC HEAT DATA GENERATED BY A SIMPLIFIED METHOD

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Abstract

Numerical simulation of urban heat island is progressively improving with computing power and sophisticated meteorological models that can incorporate the effects of urban configuration. Urban configuration greatly affects the urban heat and boundary layer development. Therefore, in mesoscale modeling, it is useful to include the effect of urban configuration using urban canopy model. For some megacities like Tokyo, detailed urban data needed for such modeling are available. But in other urban area, population density of that area can be used to calculate urban parameters. In this research, WRF (Weather Research and Forecasting) model is used to simulate urban heat island phenomenon in Osaka, Japan. The approximate relationships between population density and urban parameters were established and the results were compared with the observation data.

Key words: urban heat island, WRF, urban canopy model, population density

1. INTRODUCTION

The improved WRF (Weather Research and Forecasting) model, which has an urban canopy model (Kusaka et al., 2001) coupled with the Noah land surface model (Chen et al., 2004), is suitable for the study of urban heat island effect. The sub-categorization of urban land-use category is needed to use the urban canopy model in WRF, and it requires the detailed classification of building data in the urban grids. But it is difficult to obtain important parameters like the building height, building coverage and urban fraction of urban grids in most of the urban regions except in some big cities. The approximate relationship between these urban parameters and the population density was established in this research to enable this model to be used in nearly all the urban regions having population data.

2. WRF MODELING

WRF model is a fully compressible, nonhydrostatic numerical weather prediction and atmospheric simulation system with a flexible, modular and portable code design (Skamarock et al., 2005). Out of the several land surface models available in WRF, Noah LSM was used in this research because it has been coupled with an urban canopy model (Chen et al., 2004). UCM (Urban Canopy Model) used in WRF is a single-layer canopy model for energy and momentum exchange between the urban surface and the atmosphere, which includes the influence of street canyons, shadowing from buildings and reflection of radiation, anthropogenic heating, and multi-layer heat transfer equation for roof, building wall and road surfaces (Kusaka et al., 2001). This urban canopy model can represent more realistic geometry of the urban region than the commonly used slab models in meteorological models. In this research, Osaka region of Japan was selected for the study of urban heat island effect. For this, 1-km domain (Domain-2 in Fig. 1) was one-way nested inside the 3-km domain (Domain-1 in Fig.1). YSU PBL scheme, RRTM radiation scheme, WSM 3-class microphysics and Noah land surface model were used for the simulation period of August 8-14, 2007. Since the grid size is very fine, no cumulus scheme was used. The initial meteorological conditions were processed from GPV-MSM (Grid Point Value – Mesoscale) Japanese data from Japan Meteorological Agency.

3. MODEL INPUT DATA

3.1. Land-use data

To use the urban canopy model of WRF, we sub-categorized the urban land-use of Osaka into high-density residential, medium-density residential, and low-density residential (Fig. 2). The 1-km land-use distribution for other non-urban land use categories was obtained from 100-m National Digital Information data of Japan.
To sub-categorize the urban land-use into three sub-categories, the cumulative distribution of urban population density was divided into three equal divisions, and subsequently the required urban parameters were calculated for each of these urban sub-categories.

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3.2. Correlation between population density and urban parameters

To find the correlation between the urban population density and urban parameters, Detailed Digital Information (10-m Grid Land Use) data obtained from Japan Map Center for the Kinki region were used. These high-resolution data contain the building stories and story-height data for different residential categories. These data were used to make gridded data of building height and building coverage area. The correlations of building height and building coverage area with respect to population density were calculated. For building coverage area and population density, a power regression equation was obtained (Fig. 3), and for building height and population density, a linear regression equation was obtained (Fig. 4). These regression equations were used to find the building coverage and building height for the urban sub-categories used in the urban canopy model.
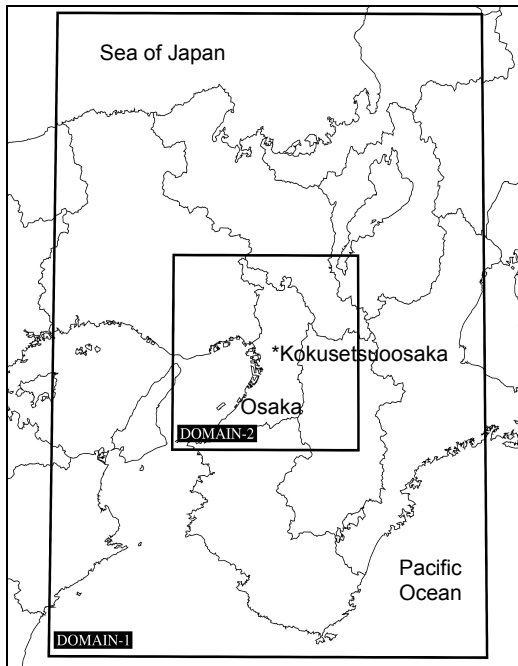

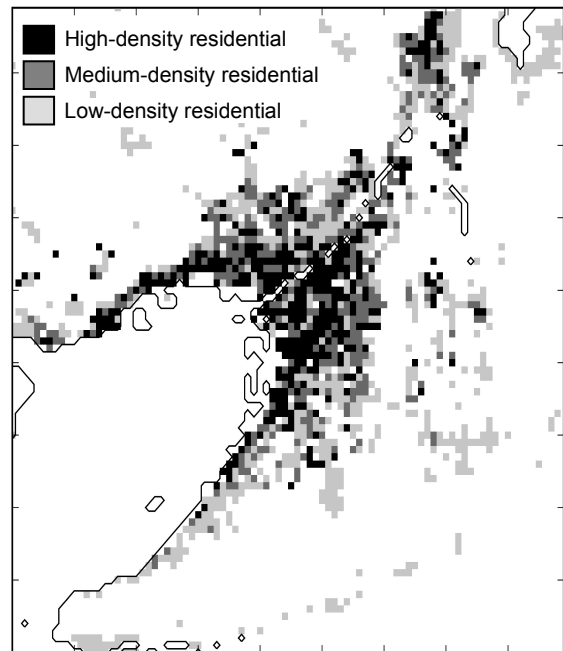Fig. 1: Domain configuration used in WRF simulation.

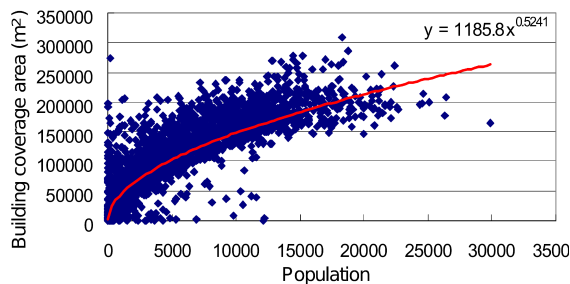Fig. 2: Sub-categories of urban land-use in Domain-2 (see Fig. 1) of the model region.

Fig. 3: Correlation between building coverage area and population density.
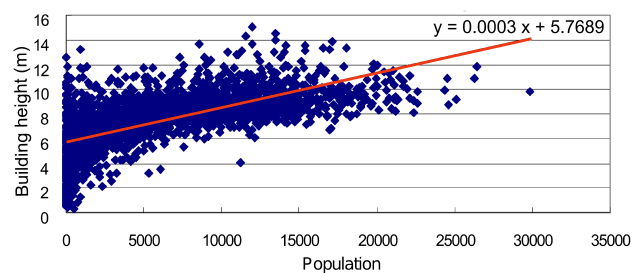

Fig. 4: Correlation between building height and population density.

Table 1: Important parameters of urban canopy model depending on land-use category

Parameter	Unit	Low-density residential		Medium-density residential		High-density residential	
		Case 1[a]	Case 2[b]	Case 1	Case 2	Case 1	Case 2
Building height	m	7.5	6.5	8.1	6.7	8.2	7.5
Building coverage ratio	-	0.46	0.28	0.49	0.32	0.50	0.33
Urban fraction	-	0.52	0.33	0.79	0.46	0.92	0.49

(a) Case 1: Using the real detailed urban classification;   (b) Case 2: Using the regression equations shown in Fig. 3 and 4.

The important parameters of the urban canopy model for the Osaka region are shown in Table 1. To compare the result of using the urban parameters calculated by regression modeling with the result of using the real detailed urban classification, parameters in case 1 (Table 1) were calculated by using the real building height and coverage data from Detailed Digital Information data (Shrestha et al., 2009). In case 1, the urban land-use was sub-categorized according to the division of urban fraction.

4. RESULTS

The simulated near-surface air temperature results show a definite increase in the nighttime urban air temperature due to the use of urban canopy model (Fig. 5). The default program of WRF uses urban canopy model for the urban fraction of the grid and Noah LSM for the non-urban fraction of the grid. The non-urban fraction of the grid is treated as Crop/Grassland mosaic land-use category. Using this default behavior, a substantial decrease in daytime air temperature resulted in our case (Case UCM (2) in Fig. 5). This can be attributed to a significant amount of non-urban fraction obtained for Osaka. To tackle this problem, the default conversion of non-urban fraction of the grid was changed to the default urban land-use category. The use of default urban land-use category for the non-urban fraction of the grid reduced the daytime decrease in air temperature when using urban canopy model (Case UCM (3) in Fig. 5).
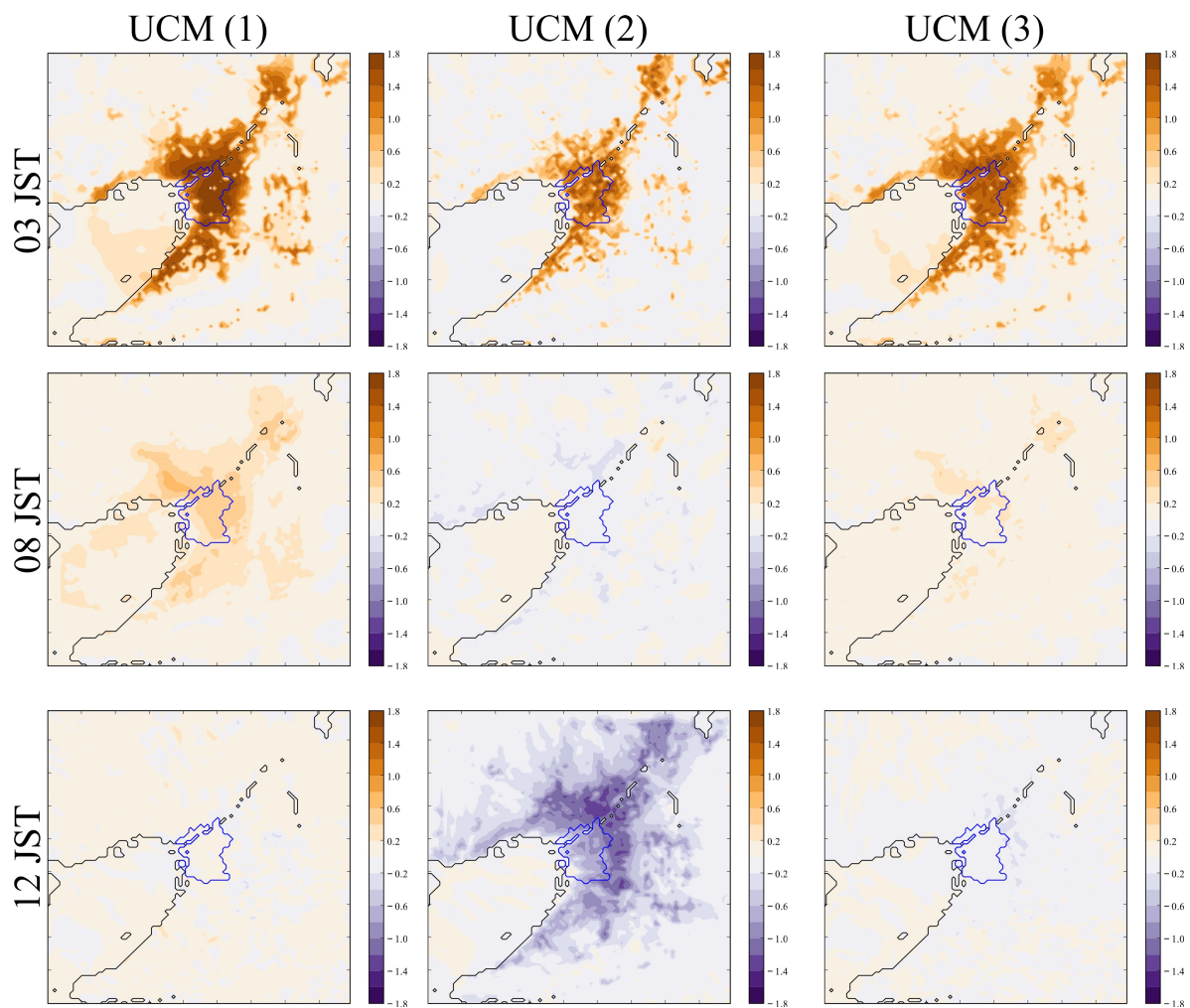

Fig. 5: Difference plot of near-surface air temperature between UCM and Default case. Central area bounded by blue line is Osaka City. UCM (1) uses real urban classification, UCM (2) uses urban parameters from regression equations, and UCM (3) is same as UCM (2) but uses default urban land-use type for non-urban fraction.

Using the urban parameters of case 1 in Table 1, and after converting the non-urban fraction of urban grid to the default urban category (Case UCM (1) in Fig. 5), the increase in nighttime air temperature was found to be similar to the Case UCM (3). This implies that the use of regression equation to correlate urban parameters with population density provides a suitable alternative to the use of a detailed land-use classification.

Compared with the observation data, the use of urban canopy model considerably improves the nighttime near-surface air temperature. To remove the effect of spatial and temporal heterogeneity in the simulation result, the area-averaged (Fig 6) and time-averaged (Fig. 7) results of air temperature were compared with the average of available observation stations in Osaka City. Both of these results confirm that the nocturnal increase in air temperature due to urban canopy improves the overall simulation of nocturnal heat island in Osaka.
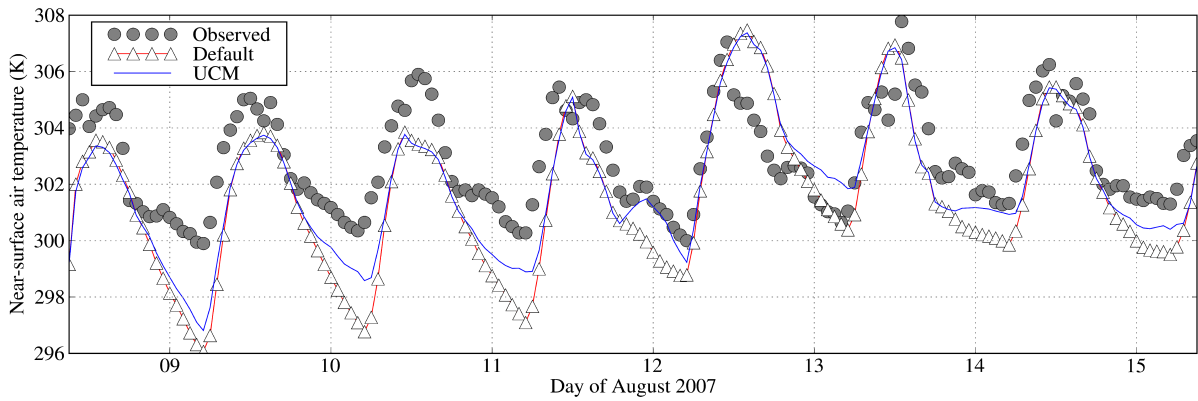
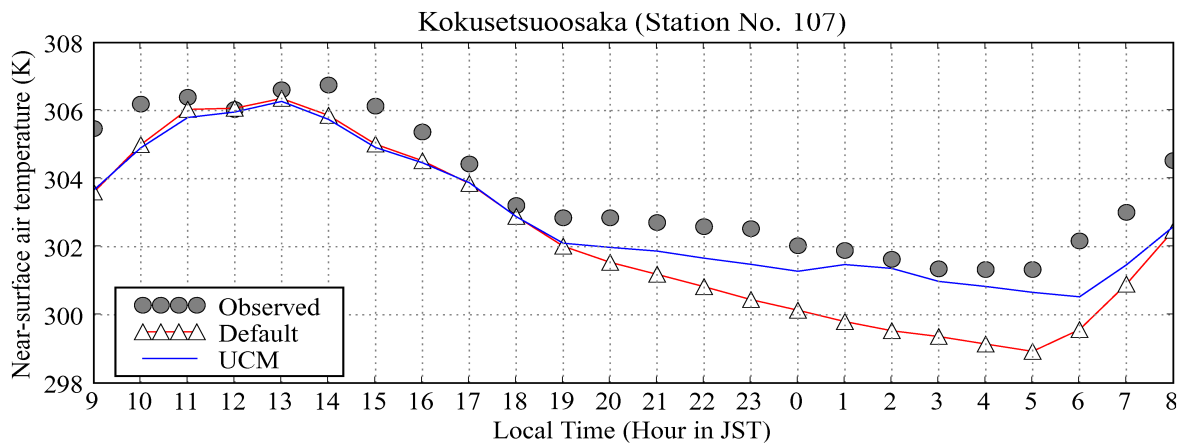Fig. 6: Area-averaged near-surface air temperature of Osaka City.

Fig. 7: One-week-averaged near-surface air temperature at Kokusetsuoosaka station in Osaka City.

5. CONCLUSIONS

The simulation of nocturnal heat island effect in Osaka City was improved by using the urban canopy model in the WRF model. To obtain the urban parameters used in the urban canopy model, a simplified method of using the correlation between the urban parameters and population density was established. The relevant population data is relatively easy to obtain and the simple method of regression modeling is efficient for WRF modeling. The use of this simplified method produced expected improvement in the near-surface air temperature results.

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