Numerical Study on Regional Climate Change Due to the Rapid Urbanization of Greater Ho Chi Minh City's Metropolitan Area over the Past 20 Years

Quang-Van Doan [1], Hiroyuki Kusaka [2]

[1, 2] *University of Tsukuba, Tenodai 1-1-1, Tsukuba, Japan, E-mail: s1230216@u.tsukuba.ac.jp*

Abstract

This study examines climatic impact of urbanization on the variability of the urban heat island (UHI) effect over Greater Ho Chi Minh City metropolitan area (GHCM), since the late 1980s, using the dynamical downscaling with very high-resolution regional climate model coupled to urban canopy model (RCM/UCM). In assessing the impacts of urbanization, the land-use/cover and anthropogenic heat release datasets during the selected three periods (circa 1989, 1999, and 2009) were derived. Simulated results show that the increase in the surface air temperature is about 0.3 °C in the pre-existing urbanized area and about 0.6 °C in newly urbanized area in the last 20 years. Main factor of these changes is conversion from agriculture or grass land to urban structure which results in increase in sensible heating and decrease in latent heating. In addition, the simulated urbanization impact is 0.31°C, while the observed temperature increase in the central GHCM is 0.64°C in the last 20 years. This suggests that the urbanization may contribute about half to the increase of surface air temperature in the central GHCM.

1. Introduction

Urban heat islands (UHI), have been garnering substantial attention in recent decades. Extensive studies have been carried out not only to seek a universal mechanism of the UHI effect but also to explore the impact of urbanization on the UHI effect in cities with unique landscapes and histories of urbanization (Georgescu et al., 2009a, 2009b; Kusaka et al., 2012a, 2012b; Argüeso et al., 2014; Hamdi et al., 2014). However, there have been fewer studies focused on cities in the Southeast Asian region.

The Greater Ho Chi Minh City metropolitan (GHCM) area, Vietnam's largest metropolitan area, has been undergoing rapid urbanization accompanied by high population growth and a continuing influx of migrants since the late 1980s. The change of urban landscape was expected to put pressure on local climate as well as human living environment.

A purpose of the present study is to numerically examine impacts of the multidecadal urbanization on the UHI over the GHCM area, since the late 1980s. In the present numerical experiments, dynamical downscaling with high-resolution regional climate model (RCM) coupled to urban canopy model (UCM) is adopted for the past three periods (circa 1989, 1999, and 2009). This is the first application for a city in developing countries in Southeast Asia, although this approach is not new in urban climate study. Additionally, the present study will estimate the contribution of urbanization to the past temperature increase of the GHCM.

2. Data and Methodology

We used the Weather Research and Forecasting (WRF) model V3.1.1 to simulate the meteorological conditions in GHCM during April of 2009~2011. The model configurations are summarized in Table 1. The model's domains are a nested system with four grids. Grid cells with horizontal spatial resolutions of 27 km, 9 km, 3 km, and 1 km, and a total of 35 vertical model levels were used. The simulation period was from 0 hour 25th March to 0 hour 1st May (UTC) of 2009, 2010, and 2011, and the simulated results from 0 hour 1st to 23 hour 30th (Local time) of April for three years were used for analysis. For surface fluxes, we used the coupled scheme of the Noah land surface model (LSM) (Chen and Dudhia, 2001) and a single layer urban canopy model (Kusaka et al., 2001; Kusaka and Kimura, 2004).

In this research, the WRF/UCM was modified to incorporate the gridded urban fraction and the gridded sensible anthropogenic heat fluxes in the UCM (Adachi et al., 2014). In the original WRF, the land-use type in a grid cell is defined by the most dominant land-use category in the grid cell; therefore, urban areas in the model are limited to densely urbanized areas. Modified-WRF/UCM in this study allows taking grid cells with small urban fraction into account.

Three simulations based on LUC and AH were conducted (Table 3). The urban cases U09, U99, and U89 represented urban LUC and AH circa 2009, circa 1999, and circa 1989. Climate boundary conditions are fixed to the current time (April of 2009~2011), using NCEP/FNL data sets for all four urban cases.

In the case of GHCM's region, correct LUC data set that captured the rapid evolution of the urban landscape is necessary to simulate the urban climate. Landsat remote sensing satellite images (at selected time: 1989, 1999, and 2009) with a spatial resolution of 30 m were used to classify the LUC distribution. For simplicity, we have focused on only three types of land use: built-up land, water bodies, and other lands. The satellite images were classified using the maximum likelihood supervised classification method with ArcGIS software. The estimated

LUC maps then were overlaid on a global land-use/cover's database of U.S. Geological Survey (USGS).

Anthropogenic heat released by human activities is one contributor to the UHI. Sources include heat generated by the combustion process of vehicles, heat created by industrial processes, the conduction of heat through building walls or emitted directly into atmosphere by air-conditioning systems, and metabolic heat produced by humans. In this study, 2-dimensional April-average AH maps for 3 urban cases were derived using statistic data of gasoline, electricity, and liquid gas consumption and the population density for districts and counties of GHCM (General Statistics Office of Vietnam).

Observed meteorological data (used to evaluate the performance of WRF) were collected from seven weather stations which are run by the Hydro-Meteorological Data Center of Vietnam.

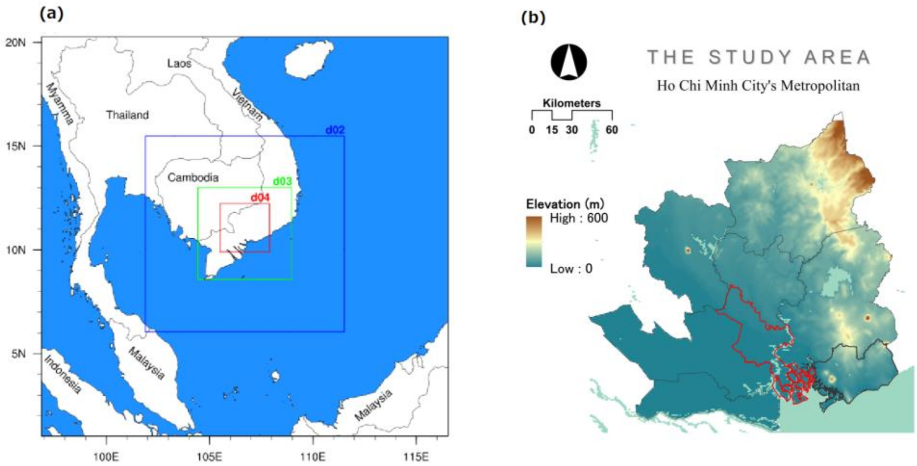

Fig. 1 (a) shows configured simulation domains. The outer boundary covers the parent domain (d01. (b) shows the study area, the Greater Ho Chi Minh City metropolitan area. Fuzzy grey lines indicate provinces' administrative borders. Ho Chi Minh City is red line.

Table 1. Model configuration

	Domain 01	Domain 02	Domain 03	Domain 04
Run time	03-25:00:00 - 05-01:00:00 (UTC) of 2009~2011			
Time period for analysis	04-01:00:00 - 04-30:23:00 (Local time) of 2009~2011			
Grid distance	27 km	9 km	3 km	1 km
Grid number	80 x 80	118 x 118	166 x 166	262 x 262
Number of vertical layers	35 layers			
Microphysics	WSM6			
Surface layer model	Noah-LSM + Single-layer UCM			
Turbulence	Mellor-Yamada TKE scheme			
Short-wave radiation	RRTMG Scheme			
Long-wave radiation	RRTMG Scheme			
Cumulus	New Grell scheme	None	None	None

Table 2. Urban cases

Urban Case	*Description*		
	Land- Use/Cover	Anthropogenic Heat Flux	Boundary Condition
U09	2009 LUC	2009 AH	April of 2009~2011 NCEP FNL data
U99	1999 LUC	1999 AH	
U89	1989 LUC	1989 AH	

3. Results

3.1 The changes of urban landscape

Fig. 2 (upper) illustrates the change in the urban area in 1989–2009. Urban area increased from 329.2 km2 circa 1989 to 507.7 km2 and 953.5 km2 circa 1999 and 2009. During 20 years, a total of 624.2 km2 of land was converted to built-up urban areas. Concurrently, almost 6 million people moved into the region, bringing the total population to nearly 17 million (General Statistics Office of Vietnam, 2009). Most of the built-up expansion occurred in the east and north-east quadrants of the study area. During the earliest period (1989–1999), urban expansion was almost exclusively contiguous to communities classified as the urban core, while in the later period (1999–2009), new urban land tended to be patchier and disconnected from urban core communities. Several factors might explain these trends. Since the early 1990s, when the process of opening the economy was accelerated, industrial zones have been implemented throughout the GHCM region that are designed to draw foreign investment; these zones are concentrated in the northern part of GHCM (Dong Nai and Binh Duong provinces). These areas have the highest rates and amounts of both land and population changes.

Otherwise, Fig. 2 (lower) illustrates the change in the AH distribution in 1989–2009. Circa 2009, the average AH flux ranged from 2 W/m^2 in suburban communities to 31 W/m^2 in the central districts of Ho Chi Minh City. This was increased 2.8 times from circa 1989 due to the increased average energy consumption per person and the concentration of the population in the urban area.

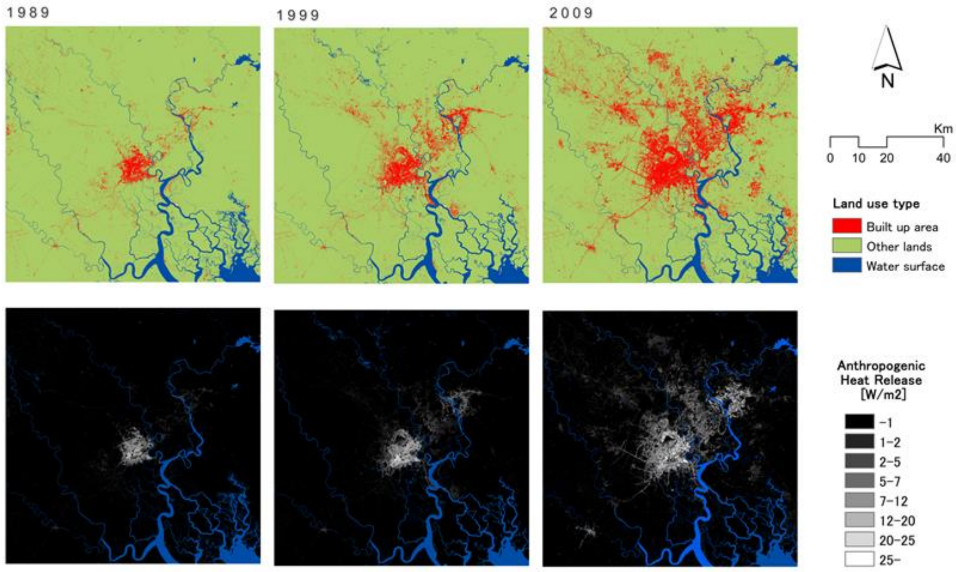

Fig. 2 The changes of LUC and AH over GHCM during last 20-years. LUC datasets were derived from Landsat images and AH datasets were estimated from statistics data.

3.2 Model validation

Performance of the model was examined by comparing probability distribution function (PDF) of WRF-U09 output with observed data for surface air temperature (T_{2m}). All hourly values (24 x 30 x 3 = 2160 hours) over the entire analysis time (April of 2009~2011) for 4 weather stations (Tan Son Hoa (TSH), Xuan Loc (XL), Dong Phu (DP), and My Tho (MT)) were used to calculate PDF. The location of such stations can be referred in Fig. 4a. Fig. 3 shown that simulated results has good correlation with the observed data, as most correlation coefficients were greater than 0.82. The bias of T2m was small, ranging from -0.53 to 0.17°C. This demonstrates that WRF/UCM is able to reproduce local climate of GHCM.

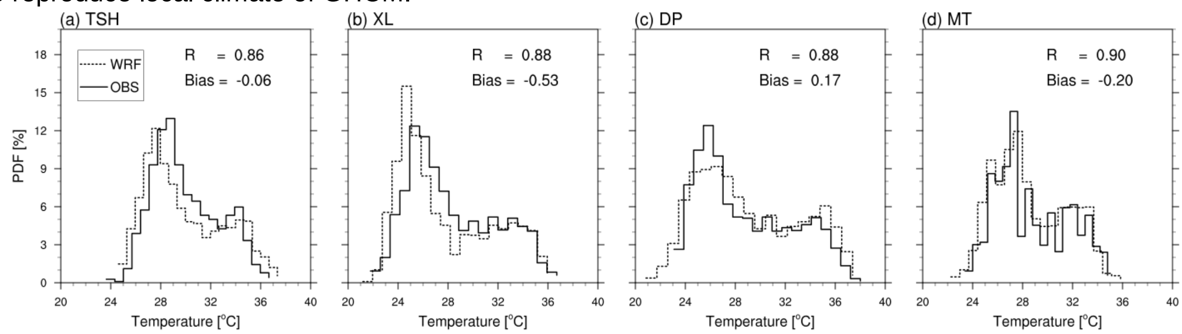

Fig. 3 Probability distribution for the observed and the WRF-U09 simulated surface air temperature at weather stations Tan Son Hoa (TSH), Xuan Loc (XL), Dong Phu (DP), and My Tho (MT).

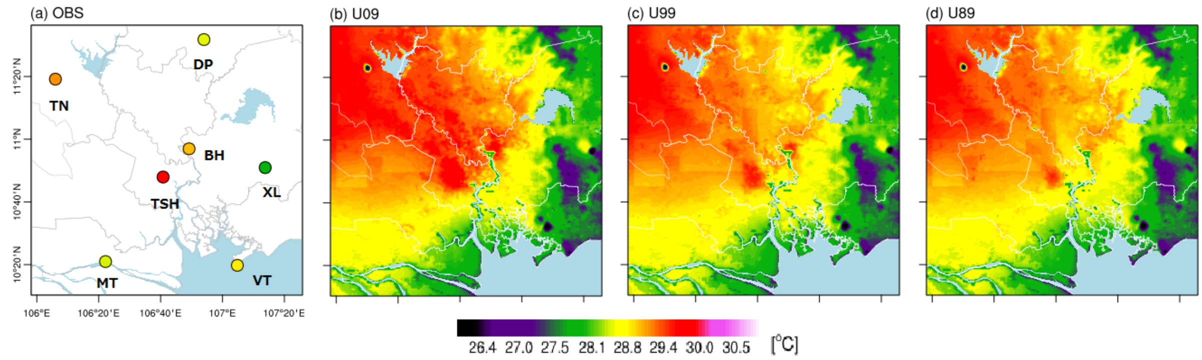

Fig. 4 Spatial distribution of the April monthly mean of T_{2m}. (a) illustrates the observed data for 7 weather stations in GHCM; (b), (c), (d), and (e) show the simulated results of cases U09, U99, and U89, respectively.

Otherwise, Fig. 4a, 4b demonstrates the horizontal distribution of the monthly mean of T_{2m} for both observed and simulated data for urban case U09. Data from seven weather stations were used in this task. T2m tends to higher in the center (corresponding with Ho Chi Minh City) and the eastern and north-eastern parts.

3.2 UHI transformation

This subsection discusses the change of UHI spatial distribution by comparison of simulated monthly mean of T_{2m} (Fig. 4b, 4c, 4d). Anomalies between the simulations were calculated and are represented in Fig. 5. Here, the anomaly of T2m between U09 and U89, e.g., the impact of urbanization over 20 years, was defined as the "U09 run" minus the "U89 run" (U09-U89).

Simulated results showed noticeable UHI variability through the 20-year period. Circa 1989 (U89 case), the UHI was recognized in relatively small areas, limited to the downtown part of Ho Chi Minh City (Fig. 4d). It became large during the first 10-year period and spread faster eastward and north-eastward in the 2000s. These changes were closely associated with the urbanization process. Anomalies between the simulations draw more intuitively these changes (Fig. 5). The increase in T_{2m} was about 0.3 °C in the pre-existing urbanized area and about 0.6 °C in newly urbanized area in the last 20 years. Most changes occurred in the last period rather than in the first one.

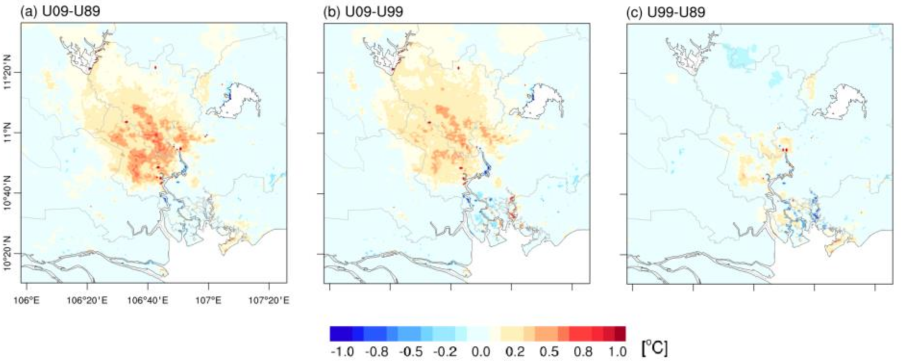

Fig. 5 (a) illustrates anomaly U09-U89, i.e., the impact of urbanization during the 20-year period; (b) and (c) show anomalies U09-U99 and U99-U89, i.e., the impact of urbanization during the last and first 10-year periods.

3.3 Discussion

This subsection focuses on increase of T_{2m} at particular locations of the TSH, BH, and MT. TSH is located in the central part of Ho Chi Minh City, which was pre-existing urbanized area, while BH is located fast-urbanizing part north-east of GHCM; MT is located in the rural southern region (Fig. 4a).

Simulated results show that in spite of the complicated nonlinear properties of numerical climate modelling, the relationship between increasing rates of air temperature show strong linear properties: U09-U99 plus U99-U89 is almost equivalent to U09-U89, i.e., the total increased rate for the two time periods is equal to the sum of the increasing rate at each stage (Fig. 6).

Historical changes in observed data are also purposely used for comparison with simulated results to approximate the contribution of urban development to local climate change. The historical data of only TSH was used in comparison (Fig. 6a). The simulated urbanization impact is 0.31°C, while the observed temperature increase in the central GHCM is 0.64°C in the last 20 years. This suggests that the urbanization may contribute about half to the increase of surface air temperature in the central GHCM

Simulated results analysis shows that changes in the local climate induced by urbanization are closely related to changes in the physical properties of the surface that alter the energy budget at the surface. Main factor of these changes is conversion from agriculture or grass land to urban structure which results in increase in sensible heating and decrease in latent heating.

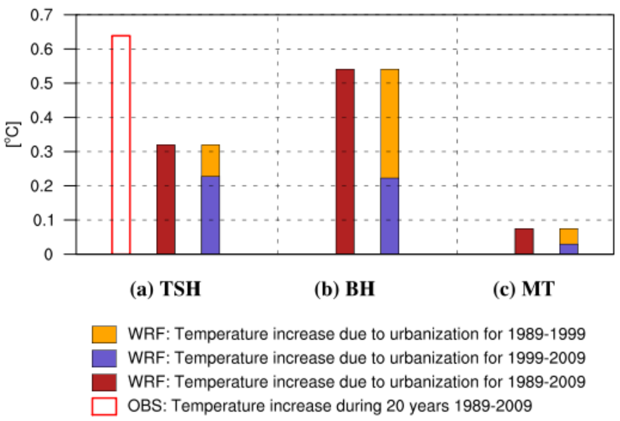

Fig. 6 Impact of urbanization on T_{2m}

4. Conclusions

The main conclusions of this study are as follows.

Agreement between simulated results (for current urban) and observed data demonstrates that the WRF/UCM is able to reproduce the urban climate of GHCM.

Simulated results show that the increase in the surface air temperature is about 0.3 °C in the pre-existing urbanized area and about 0.6 °C in newly urbanized area in the last 20 years. Main factor of these changes is conversion from agriculture or grass land to urban structure which results in increase in sensible heating and decrease in latent heating.

Analysis of simulated results suggests strong linear properties in increasing of average temperatures, i.e., increased total temperature rate is equivalent to the sum of the increased rate in the first and latter 10-year periods. In addition, in the central GHCM, the simulated urbanization impact is 0.31°C, while the observed temperature increase in the central GHCM is 0.64°C in the last 20 years. This suggests that the urbanization may contribute about half to the increase of surface air temperature in the central GHCM.

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