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OBSERVED AND SIMULATED EFFECTS OF URBAN CANOPY ON AIR TEMPERATURES IN SUMMER TOKYO

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1. INTRODUCTION[*]

Intensive urbanization is in progress in Asia with possibilities to induce regional-scale climate change well known as heat island phenomena, which may cause the rapid increase in building energy demand for air-conditioning and its consequent growing in CO_2 emission resulting from more fossil fuel consumption. Such increase in energy demand could result in not only additional generation of anthropogenic heat but also further intensification of heat islands themselves, that is, the “vicious cycle problem”.

The above perspective suggests the necessity of the development of a new methodology to access the impacts of heat island effects on energy demands and GHG emission in Asian cities, and to contribute to this issue, we need precise numerical models which are able to reproduce the surface meteorological fields with their interaction with building energy consumption in Urban Canopy Layer (UCL).

As pointed out in previous studies, the meteorological fields in UCL to be reproduced by the “precise models”, are strongly affected by urban structure that can be characterize by urban canopy morphology, surface materials and anthropogenic heating from buildings and automobiles. Although many studies have been conducted based on observations and numerical modeling to understand these effects of urban structure on air temperatures, it is very difficult to grasp those holistic effects in entire-city-scale over gigantic city like Tokyo due to heterogeneity of urban structure and air temperature distribution in urban area. With relation to this issue, this study investigated the influences of urban canopy structure on surface air temperatures all over Tokyo based on high density meteorological observations and numerical models with implementation of urban canopy parameterization including the interaction process between meteorological fields in UCL and building energy consumption.

2. OBSERVATIONS

The surface air temperatures observed by high density meteorological monitoring network system named METROS were used for this study. METROS stands for the Metropolitan Environmental Temperature and Rainfall Observation System, which is composed of 20 stations (METROS20) settled on buildings’ rooftops and 100 ground stations mainly located in grounds of public elementary schools (METROS100) for surface observation with high horizontal resolution up to 2.5km over Tokyo 23 Wards area. In this study, hourly surface air temperatures from METROS100 in July 2002 were used as observations under actual effects of urban structure all over the highly urbanized area of Tokyo.

Additionally, the surface air temperatures observed by the Automated Meteorological Data Acquisition System (AMeDAS) of Japan Meteorological Agency were also used during the same period as that of METROS. More than 10 AMeDAS observatories are located in and out of Tokyo area. Therefore we used those data as observations indicating larger scale distributions of air temperatures including those in rural area around Tokyo.

The locations of METROS and AMeDAS observatories whose measurements were adopted in this study are shown in Figure1.

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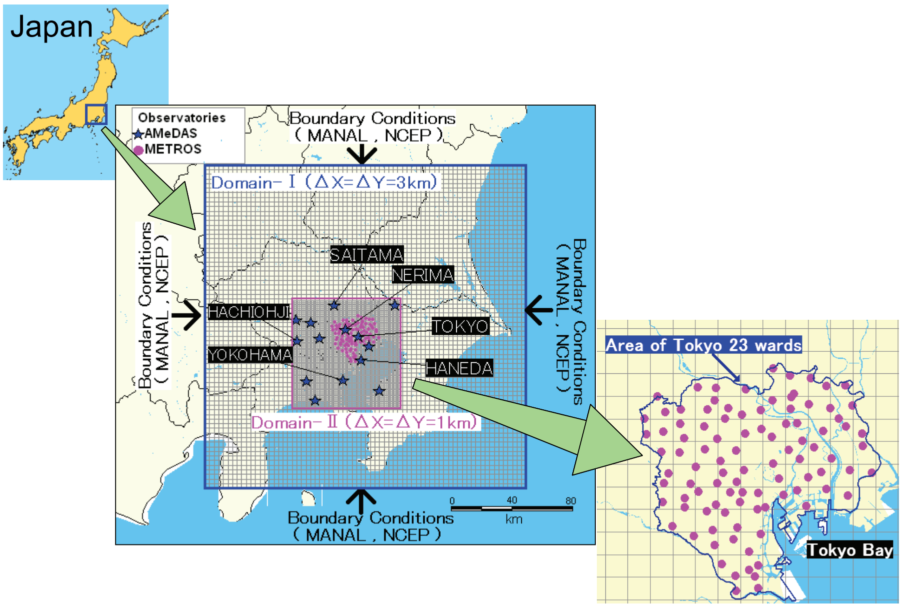

Figure 1. Computational domains and locations of observatories

3. APPLICATION OF WRF

To analyze the relationship between urban structure and UCL air temperature in Tokyo, first, the Weather Research and Forecasting model (WRF) was applied to Tokyo metropolitan area. WRF is a next-generation mesocale numerical weather prediction system that has been developed by the collaboration among NCAR, NCEP, NOAA/FSL, and AFWA, etc. In this study, the Advanced Research core version of WRF was used with its physics options shown in Table1.

In the model calculation, WRF was used without urban canopy parameterization and anthropogenic heating (Table1) to generate the control meteorological fields over Tokyo in the case of neglect of the urban canopy effects.

Table 1. The outline of WRF and its physics options used in the model calculation.

Model	WRF V.2.1.2	-Compressible and Non-hydrostatic Euler equations -Terrain-following hydrostatic pressure vertical coordinate -Without anthropogenic heating <u>Adopted Physics Options</u> -Land surface : Noah LSM without UCM (Urban canopy effects were neglected) -Surface layer : Monin-Obukhov scheme -Boundary layer: Mellor-Yamada Level2.5 -Microphysics : Lin scheme -Radiation : Dudhia scheme for S↓ Rapid radiative transfer model for L↓
Duration for integration		2002/7/25 9JST – 8/1 9JST (1 week)
Duration for analysis		2002/7/26 9JST – 8/1 9JST (omitted the first 24 hours for spin up)

The integral computation was done for the period of one week in summer 2002 (Table1). As to the initial and boundary conditions used in the simulation, those shown in Table2 were adopted.

Table 2. Initial and boundary conditions used in WRF simulation

Initial Conditions & Boundary Conditions (Time-varying)	Atmosphere	JMA / MANAL (Meso-Scale objective analysis data) Resolution: 10km , 6hour
	Soil (Moisture & Temp.)	NOAA / NCEP / FNL (Global final analysis data) Resolution: 1deg. , 6hour
	Ocean	NOAA / NCEP / RTG-SST (Real-time, global, sea surface temperature analysis data) Resolution: 0.5deg. , daily
Boundary Conditions (Geographical data)	Land Use	USGS Land Use/Land Cover Resolution: 30” , 24 category
	Topographic	USGS / GTOPO30 Resolution: 30”
Ground surface parameters	Default values for Noah LSM	

With regard to the computational domain, two areas were selected as shown in Figure1. We ran the WRF with two-way nesting method for a lager domain (Domain-I) with 3km grid width and a smaller domain (Domain-II) with 1km grid spacing. The former includes the Kanto plains, mountains and seas to take account of topographic effects on mesoscale meteorological fields. And the latter includes the highly urbanized area of Tokyo.

4. DEPENDENCY ANALYSIS OF SURFACE AIR TEMP. ON URBAN CANOPY STRUCTURE

The indices of the structure of urban canopies were derived to analyze the dependency of observed and simulated surface air temperatures in Tokyo upon urban structure there. The surface air temperatures observed by METROS in 23 wards area of Tokyo during the computational period for WRF were used for the analysis. Based on the detailed building polygon data from GIS of Tokyo Metropolitan Government, the areal averaged values of the sky view factor were calculated for urban districts of the 500mx500m grids where each METROS observatory are located. Additionally, the dominant building type was clarified for the each METROS grid. The distributions of the derived indices are shown in Figure2.

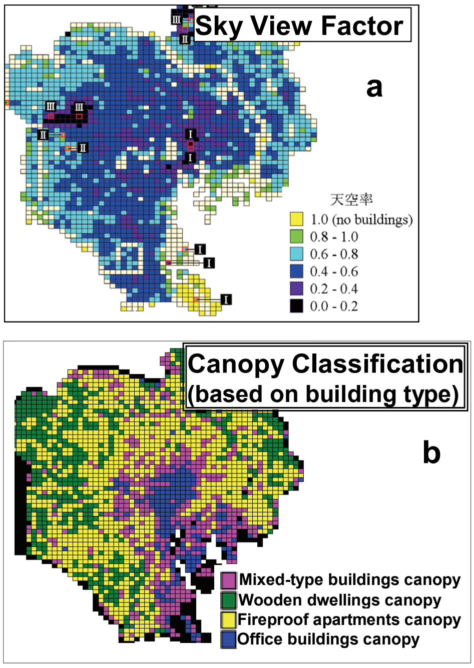

Figure 2. The derived indices of canopy structure for each 500m grids including METROS sites (a: sky view factor, b: dominant building type).

The diurnal and nocturnal mean values of observed surface air temperatures were calculated for each METROS observatory during the period of the analysis (i.e. from 0900JST 7/26/2002 to 0900JST 8/1/2002 as shown in Table1), and their relations with the grid-by-grid sky view factors were investigated as

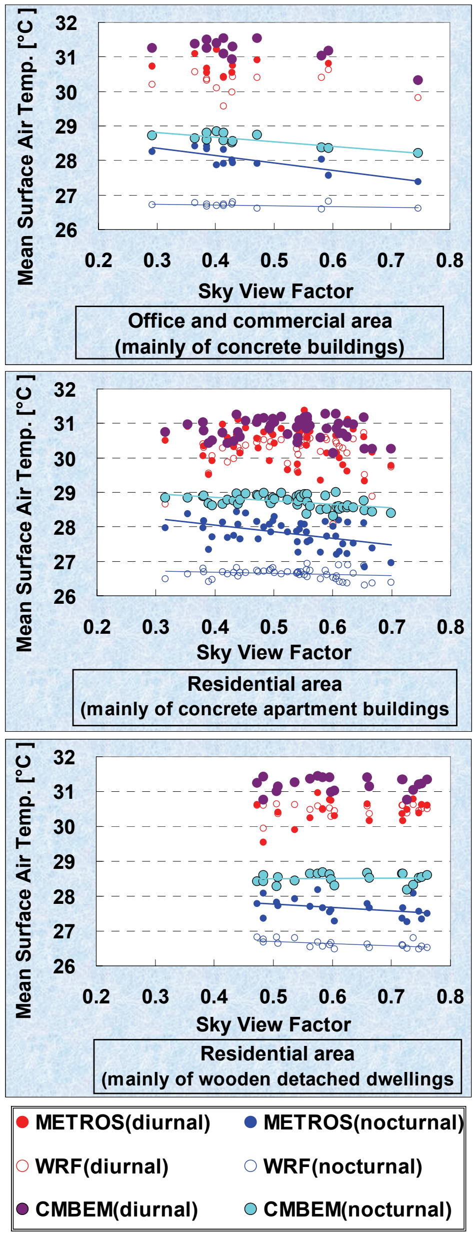

Figure 3. Observed and simulated mean values of diurnal and nocturnal surface air temperatures at METROS sites, and their dependencies on sky view factors.

shown in Figure3. As a result, in all types of districts classified by the dominant building types, diurnal mean temperature indicated no obvious dependency on the sky view factor as an index of the local canopy structure possibly due to larger scale meteorological effects caused by prevailing winds or activated mixing in the boundary layer under unstable conditions. Contrastively, nocturnal mean temperatures showed systematic dependency indicating their increases under urban canopies with smaller sky view factors. Also, that nocturnal dependency was found to be more remarkable under urban canopies composed of concrete constructions with larger heat capacities in office and commercial areas as well as in residential area of concrete apartment buildings. Such nocturnal results were supposed to imply thermal effects of urban canopy.

Additionally, the surface air temperatures computed by WRF are analyzed and indicated in the same manner as METROS observations are done in Figure3. In comparisons with METROS observations, WRF seemed to be roughly able to reproduce diurnal mean temperatures. On the other hand, WRF was found to underestimate nocturnal mean temperatures systematically and not to reproduce their observed dependency on the sky view factors due to the lack of urban canopy parameterization.

5. IMPLEMENTATION OF URBAN CANOPY EFFECTS BY APPLICATION OF CMBEM

In the next step, to take account of dynamic and thermodynamic effects of urban canopy explicitly, our original urban Canopy Model coupled with Building Energy Model (CMBEM) was incorporated into the computations.

CM is a multilayer one-dimensional urban canopy model (Kondo et al., 2005). In CM, the geometrical structure of an urban block in 0.5 to several km square is simply parameterized with the mean width of the buildings, mean distance between the buildings and distribution of the height of the buildings as shown in Figure4. Considering the vertical grid system including buildings as a porous medium, CM adopts one-dimensional diffusion equations for momentum, potential temperature, and specific humidity. The complicated radiation processes in the urban street canyon are also considered by simplified methods.

For the consideration of the dynamical variations of the anthropogenic heat released from buildings, BEM was developed (Kikegawa et al., 2006). BEM is a simple sub model for building energy analysis. BEM can express the response of the air-conditioning energy consumption and its consequent waste heat emission to the canopy meteorological condition predicted by CM (Figure5).

Additionally, CMBEM considers the feedback process of buildings' anthropogenic heat to canopy atmospheric heat balance. Therefore, CMBEM can simulate the interaction process between meteorological fields in UCL and building energy consumption (Ohashi et al., 2007).

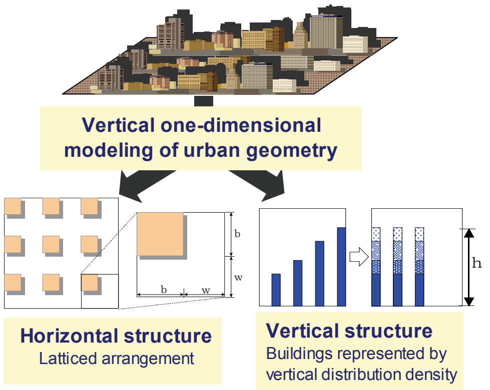

Figure 4. The one dimensional multi-layer urban canopy model (CM; Kondo et al., 2005)

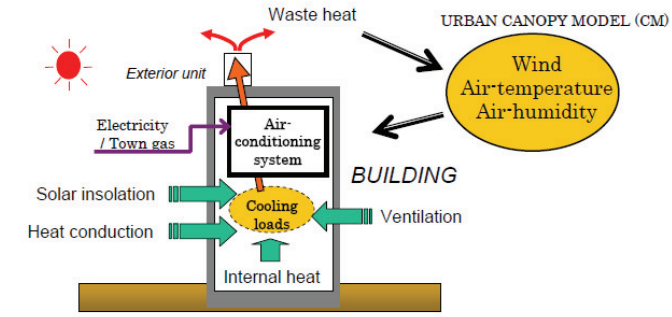

Figure 5. The heat budget between the building inside and outside as calculated with the building energy model (BEM; Kikegawa et al., 2006)

The CMBEM calculation was done with one-way offline coupling method with WRF. Its computational flow is shown in Figure6.

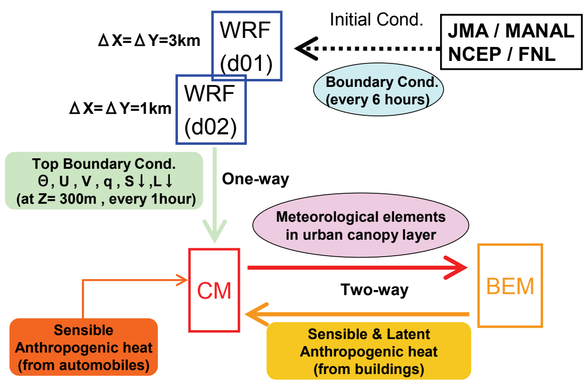

Figure 6. The flow of WRF-CMBEM calculation

Based on the computational flow in Figure6, the CMBEM was applied to the each METROS grid. Then, its calculation results were superimposed over Figure3. As a result, it was indicated that CMBEM overestimated the observed diurnal and nocturnal mean surface air temperatures from METROS by ~ 1°C with a little too emphasized effects of urban canopy and anthropogenic heating. However, it was found also that CMBEM qualitatively reproduced the dependency of the nocturnal mean temperatures on canopy structure (i.e. sky view factors) in concrete canopies.

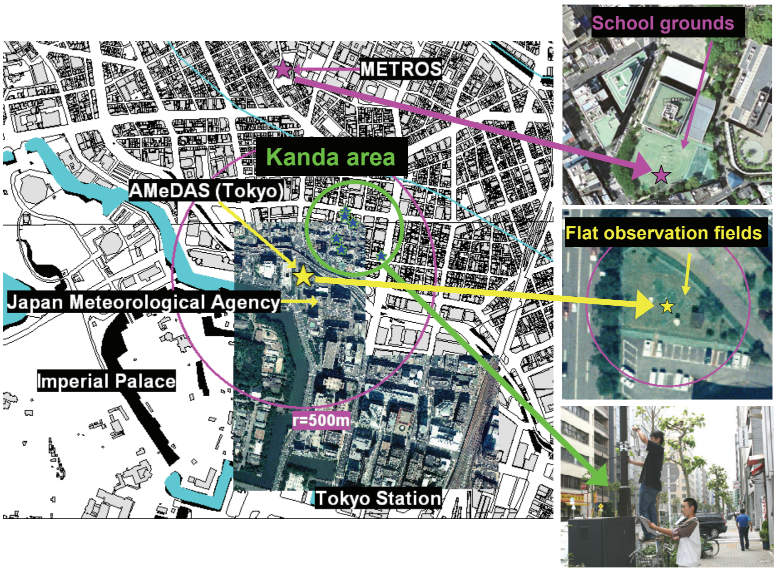

Figure 7. Locations of observatories in downtown Tokyo around Japan Meteorological Agency

6. RECONSIDERATION OF URBAN CANOPY EFFECTS RECOGNIZED IN OBSERVATIONS AND COMPUTATIONS

As described in the previous chapter 2, we used METROS observations regarding them as observations under actual effects of urban structure. However, as shown in Figure7, METROS100 observation sites are located in the flat school grounds but not at the bottom of urban street canyons. The AMeDAS observation sites are also located in the flat observation fields covered with short grass. Therefore, a possibility is implied that METROS and AMeDAS surface air temperatures may represent ones under less effects of urban canopy compared with real conditions in downtown Tokyo.

From the above point of view, other surface air temperatures observed at the bottom of street canyons in Kanda area near AMeDAS Tokyo site were additionally used for the analysis. The observation in Kanda area was conducted by us at multi-points as shown in Figure7 during 24hours in the simulation period of this study. The hourly mean values of the surface air temperatures from this multi-points-observation are compared with other observations and computations in AMeDAS Tokyo grid as shown in Figure8. As a result, the observed temperatures at the bottom of UCL in Kanda area were found to be higher than those of AMeDAS possibly due to actual urban canopy effects. And it was confirmed that CMBEM reasonably better reproduced the surface air temperatures in Kanda area under effects of urban canopy than WRF does.

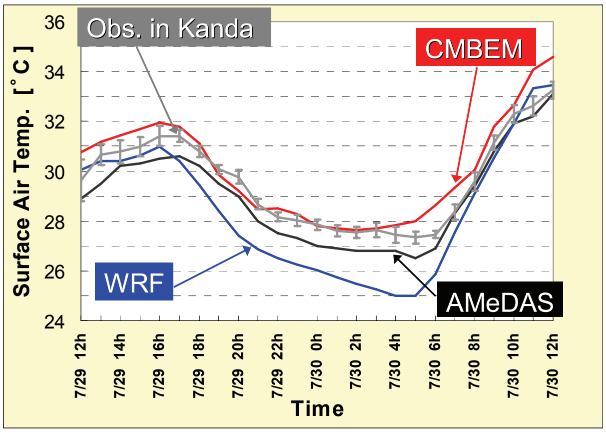

Figure 8. Comparisons of surface air temp. between simulated ones and observations in AMeDAS Tokyo grid including Kanda area.

7. CONCLUSIONS AND FUTURE WORK

This study investigated the influences of urban canopy structure on surface air temperatures all over Tokyo based on high density meteorological observations and numerical models. Finally, the conclusions are drawn as follows.

- The surface air temperatures observed in highly urbanized 23 wards area of Tokyo by METROS were analyzed using indices of urban canopy structure. Then, diurnal mean temperatures were found to indicate no obvious dependency on the local canopy structure possibly due to larger scale meteorological effects.
- On the other hand, nocturnal mean temperatures showed systematic dependency indicating their increases under canopies with smaller sky view factors due to effects of urban canopy, especially in concrete urban blocks like office and commercial area.
- WRF without urban canopy parameterization did not reproduce those nocturnal observed effects of urban structure on air temperatures.
- However, in the case of implementation of CMBEM by one-way offline coupling with WRF, CMBEM showed a potential performance to better reproduce the surface air temperatures under the actual effects of urban canopy.

In our near-future work, we plan to implement more complete two-way coupling of CMBEM with WRF. We also intend to conduct the validation of WRF-CMBEM based on our original new observations and its implementation to quantify the impacts of heat island mitigation strategies for Tokyo and Delhi.

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