Pure appl. geophys. 160 (2003) 317–324
0033–4553/03/020317–08

Pure and Applied Geophysics

Temperature Variation in the Urban Canopy with Anthropogenic Energy Use

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Key words: Urban canopy, urban warming, cooling energy, anthropogenic heat.

Introduction

One of the detrimental effects caused by the urban warming is the increase of energy consumption due to the air conditioning of buildings in summer. In the cities of United States, the urban warming is surmised to increase the peak electric energy demand by 3 to 6% with 1.0 °C temperature rise (BRETZ *et al.*, 1998). This increased rate of demand is estimated up to 3%/°C in recent years in Tokyo, and about 1.6 GW of new demand is required as the daily maximum temperature increases by 1.0 °C in the greater Tokyo area (SAKAI and NAKAMURA, 1999). Most of this huge demand of summer electricity is caused by the air-conditioning systems, and is considered to be one of the common characteristics in big cities of Asian countries. From the viewpoint of the reduction of CO_2 emission to mitigate the global warming, this huge demand should be reduced through the control of the urban warming. There were model results that analysed the relation between anthropogenic heat and temperature increase in Tokyo (URANO *et al.* (1999), ICHINOSE *et al.* (1999) etc.). However, they used mesoscale model only with static data of anthropogenic heat. Their results are too coarse, because the temperature in the city block highly depends on its structure (MURAKAMI *et al.*, 2000) and the anthropogenic heat release dynamically depends on the ambient temperature. In the present study, a multi-scale numerical simulation system is developed to evaluate dynamically the increase of energy demands caused by the urban warming, and a case study is carried out for an urban canopy over a densely urbanized area in Tokyo.

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Models

To carry out the investigation, a combination of multi-scale model system was developed as shown in Figure 1. This system consists of three numerical models: MM, CM, and BEM. MM is a three-dimensional mesoscale meteorological model developed at the National Institute for Resources and Environment (KONDO, 1995). MM was used mainly to generate the initial and upper boundary conditions for CM. For the urban canopy layer (UCL), we also developed a new one-dimensional urban canopy model (CM).

The basic equations of CM are one-dimensional diffusion equations,

$$\frac{\partial u}{\partial t} = \frac{1}{m}\frac{\partial}{\partial z}\left(K_m \cdot m \cdot \frac{\partial u}{\partial z}\right) - cau\left(\sqrt{u^2 + \mathrm{v}^2}\right) + F_u \tag{1}$$

$$\frac{\partial v}{\partial t} = \frac{1}{m}\frac{\partial}{\partial z}\left(K_m \cdot m \cdot \frac{\partial v}{\partial z}\right) - cav\left(\sqrt{u^2 + \mathrm{v}^2}\right) + F_\mathrm{v} \tag{2}$$

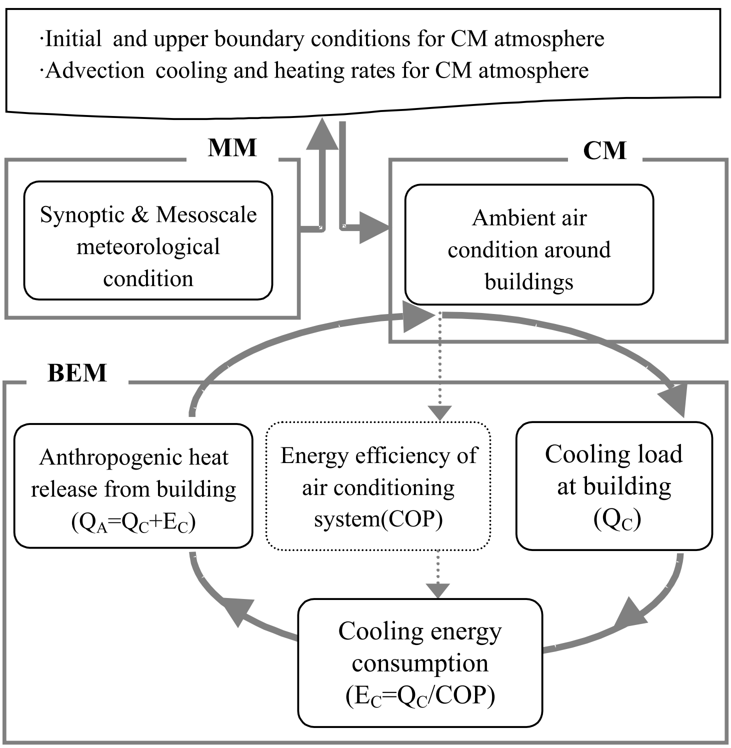

Figure 1
Methodology of modeling.

$$\frac{\partial\theta}{\partial t} = \frac{1}{m}\frac{\partial}{\partial z}\left(K_h \cdot m \cdot \frac{\partial\theta}{\partial z}\right) + \frac{Q_A}{c_p\rho} + F_\theta \quad , \tag{3}$$

where u and v are the wind velocity component of x direction (positive towards the east) and y direction (positive towards the north). We consider an urban block of 0.5 to 1 km square in which the building bottom has the same area of the square (Fig. 2). The length of the building side is assumed as b and the distance between the buildings is assumed as w. We assume that four side walls of buildings are exactly directed north, south, east and west. The height of the building is not uniform, but the distribution of the height can be considered. We define the floor density ($P_w(z)$) of the considering area at level z ($0 \le P_w(z) \le 1$). Then,

$$m = 1 - \frac{b^2}{(w+b)^2} \cdot P_w(z) \tag{4}$$

$$a = \frac{b \cdot P_w(z)}{(b+w)^2 - b^2 \cdot P_w(z)} \quad , \tag{5}$$

and c is a constant ($=0.1$). K_m and K_h are vertical turbulent diffusion coefficients based on GAMBO (1978), in which the scale length was modified with a similar idea in the plant canopy (WATANABE and KONDO, 1990). F_u, F_v and F_θ are effects of mesoscale advection which were obtained from MM calculation. The effect of complicated radiation processes among the buildings was considered to some extent (KONDO and LIU, 1998), such as shading effect and reflection of short wave, and re-emission of long wave from building and ground surfaces.

For the consideration of the dynamical variations of the anthropogenic heat released from air-conditioning systems in the buildings, BEM was developed. BEM is a simple sub-model for building energy analysis coupled with CM, and the

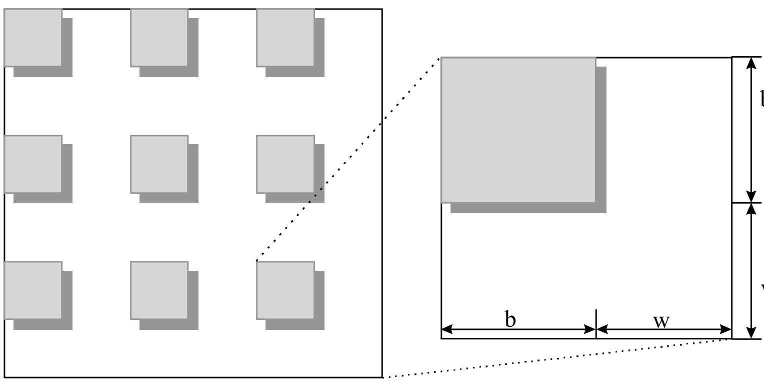

Figure 2
Assumed configuration of buildings in CM.

anthropogenic heat from buildings was calculated from the air temperature and humidity in the time integration loop of CM. BEM is a box-type heat budget model where a building in the urban block is treated as a box, and the thermal load in the buildings is calculated for the sensible and the latent heat components, separately.

To calculate the sensible heat component, we consider the heat exchange through the walls between indoor and outdoor, transmission of solar insolation through the windows, sensible heat exchange through ventilation, and the internal heat generation from machines and occupants. The outdoor condition is calculated from CM at each time step. For the latent heat component, we consider the water vapor intrusion through ventilation and evaporation from occupants. We also consider the overall heat capacity of the air in the building including interior equipment such as furniture and the overall volume of the air in the building. We simply assume that sensible and latent heat, which should be extracted by the air-conditioning systems, is a product of the thermal load and γ ($\gamma < 1.0$). Here, γ is the ratio of floor area under air-conditioning to the total floor area in a building, and depends upon the operational schedule of the air-conditioning systems.

Subsequently, energy demand required by the air-conditioning systems in a building is calculated using COP, which stands for the coefficient of performance of the heat pump system which represents the overall energy efficiency of air-conditioning. In BEM, the dependency of COP upon the ambient air temperature around the outdoor heat exchanger can be considered for several typical heat pump systems. Finally, the exhaust heat from air-conditioning systems of buildings, Q_A, is dynamically computed, which is equivalent to the sum of the demanded energy by the systems and the extracted thermal load itself.

Computational Results

Simulations were conducted for the Ootemachi area, the central business district in Tokyo (Fig. 3). The CM requires the parameters related with structures of the urban blocks; the averaged length of a building's base (b), the averaged distance between buildings (w) and the distribution of the floor density of buildings ($P_w(z)$). These parameters were calculated from the GIS data over an area of 500 m square including the building from which the observation of ambient temperature in Figure 4 was carried out on the roof. As for the structures of the buildings, the parameters of typical office buildings were adopted for the widths and materials of walls, the coverage of windows, thermal and radiative characteristics of the surface (Table 1). For BEM, we also set indoor conditions such as target temperature and humidity of air-conditioning, hourly building occupancy profiles and so on. As heat source machines in the air-conditioning systems, we employed two popular types of heat pumps. One is the air source heat pump which releases the exhaust heat from outdoor heat exchangers as sensible heat, and the other is the absorption type hot

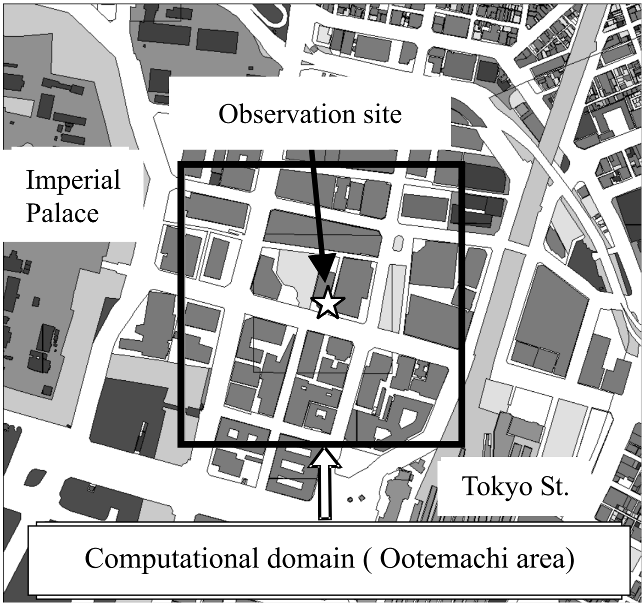

Figure 3
Computational domain.

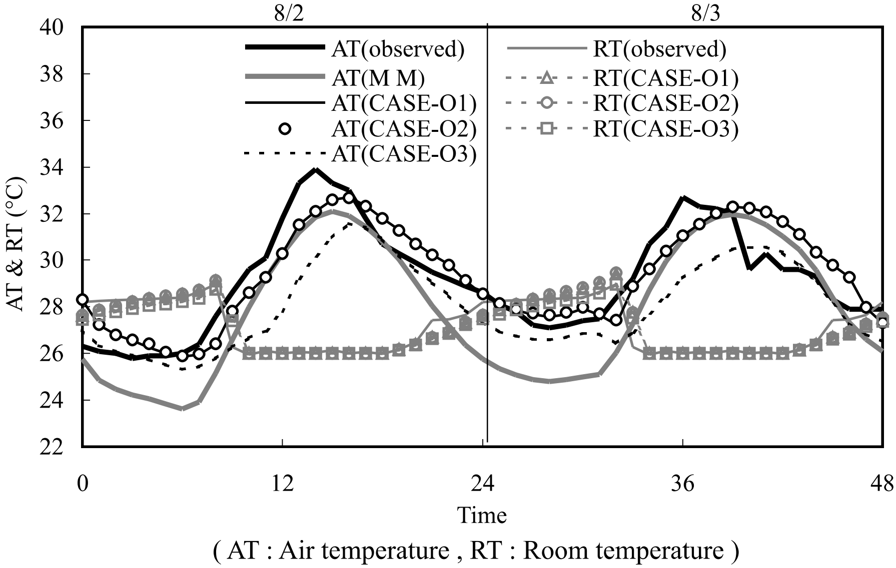

Figure 4
Computed and observed room temperatures, and those of ambient air temperature at 100 m above the ground. Observation of AT was carried out at a roof of a building in which RT was observed.

Table 1

Parameters of the materials used in the calculation

	Surface albedo	Volumetric heat capacity (J m^{-3} K^{-1})	Thermal conductivity (J m^{-1} s^{-1} K^{-1})	Note
Ground (0–16 cm)	0.2 (0.15)	1.93×10^6	1.39	Concrete (with 10% of vegetation)
Ground (16–48 cm)	–	1.74×10^6	1.00	Loam
Roof materials (insulator)	–	0.06×10^6	0.04	Poli-ethylene foam
Roof materials (other part)	0.2	1.93×10^6	1.39	Concrete
Wall materials (insulator)	–	0.06×10^6	0.04	Poli-ethylene foam
Wall materials (other part)	0.2 (0.4)	1.93×10^6	1.39	Concrete (with 30% of window)

and chilled water generator which mainly releases the latent exhaust heat from cooling towers. The former is driven by electricity, and the latter by town gas. We assumed the ratio of them in a building to be 1:1, based on their market share for the Japanese office buildings in recent years. To obtain the initial and upper boundary conditions of the CM, simulations were performed using MM under the condition of typically two consecutive summer days, the 2nd and 3rd of August, 1998. The cooling and heating rates due to the mesoscale advection were also calculated in MM for CM. With the above conditions, the calculations were executed for two days with the coupled model of CM and BEM.

Figure 4 shows the comparison between computed and measured room temperature, and outdoor air temperature at a height of 100 m on the roof of the building. Anthropogenic heat sources of air-conditioning systems were put on the roofs of the buildings in case-O1(control run), whereas all the sources were set at 3 m above the ground in case-O2. The roof height of each building in the considered region was obtained from the GIS data. In case-O3, anthropogenic heat was assumed not to be released into the atmosphere but elsewhere such as sewage or ground water.

The calculated room temperatures show good agreements with the observations in all cases. As for outdoor air temperature at 100 m, results by CM and BEM (case-O1$\sim$O2) show better agreements with the observations compared to that obtained by using only MM, where the effects of the urban canopy are not considered. Particularly, CM and BEM reproduce the nocturnal course of temperature more realistically than MM does. Among the results by CM and BEM, case-O1 and O2 manifest better correspondence to the observations. This is reasonable, because many buildings in Ootemachi have heat exchangers of air-conditioning systems on their roofs as heat sources. When the release of anthropogenic heat is fully cut off in case-O3, the daily averaged temperature decreases by 1 °C compared to those in case-O1 and O2 at 100 m. At this height of upper UCL, there is scant difference in daily courses of the air temperature between case-O1 and O2 in spite of their differences in the levels of heat sources. However, their levels remarkably affect the air temperatures at the lower UCL. At 3 m above the ground, anthropogenic heat from this height increases the daily averaged temperature by 0.6 °C in case-O2 compared to that in case-O1. The temperature differences between case-O1 and O3 are also slightly increased by up to 1.3 °C in comparison with those at 100 m. This influence of anthropogenic heat on the air temperature in the lower UCL is caused by worse ventilation there.

Conclusions

A multi-scale simulation model system (mesoscale to building scale) was developed to estimate the increase of the cooling energy demands produced by urban warming in the summer. The system was applied to the Ootemachi area, a central business district in Tokyo. The computed cooling demand of electricity is also verified from the viewpoint of their sensitivity to daily maximum temperatures. If we take results of case-O1, O2 and O3, we can estimate the temperature sensitivity of the peak electricity demand to be 6.6%/°C. This sensitivity shows good agreement with actual regional averaged sensitivity over the Tokyo metropolitan area, which is reported as 6.51%/°C by the TEPCO (TEPCO, 1998). Preliminary verification of the models with observational data of outdoor and indoor conditions and of the cooling thermal load at a building in Ootemachi showed good results. In the near future of our study, we intend to apply the models to an evaluation of the countermeasures against the urban warming, from the viewpoint of urban energy savings, to stop the increase of anthropogenic CO_2 emission.

Acknowledgment

This study was supported by the Proposal-Based New Industry Creative Type Technology R&D Promotion Program from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

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(Received March 1, 2000, accepted November 2, 2000)