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Changes in year-round air temperature and annual energy consumption in office building areas by urban heat-island countermeasures and energy-saving measures

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Abstract

This paper describes the effects of the installation of various countermeasures against urban heat-island (UHI) and energy-saving measures on UHI and global warming. A UHI and energy-consumption simulation model was developed by combining the one-dimensional meteorological canopy and building energy use models; further, the proposed model was expanded to evaluate the year-round air temperature and annual energy consumption. The simulation results showed that the humidification and albedo increase at building-wall surfaces reduced the total number of hours for which the air temperature was more than 30 °C during the daytime by more than 60 (h) per year. The UHI countermeasures reduced the annual energy-consumption despite causing a small increase during the winter period. However, they may result in certain unfavorable conditions for pedestrians. Energy-saving measures, on the other hand, reduce the total number of hours for which the air temperature is more than 30 °C by only a few hours per year. Thus, we demonstrate the effectiveness of the UHI countermeasures and measures against global warming by extending the calculation period from summer to an entire year.

Keywords: Canopy model; Building energy model; Urban heat-island; Building energy-consumption

1. Introduction

In Japan, the air temperature of big cities has been increasing rapidly since the 1980s. This is referred to as the "urban heat island (UHI) phenomenon". For example, the total number of hours for which the air

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temperature was more than 30 (°C) from July to September in Tokyo is estimated to have doubled from 168 (h) to 357 (h) during the last 20 years [1]. UHI is caused by superfluous urbanization such as the increase in anthropogenic heat and change in land coverage. Indeed, UHI is a pivotal environmental problem that results in unfavorable conditions for human health, such as hypothermia, increased CO_2 emissions due to increased cooling demand, etc. Various local activities against UHI have been increasingly promoted after the Outline of Countermeasures to urban heat island [2] was brought into law in March 2004.

If the UHI countermeasures are installed, energy consumption, especially air-conditioning demand, will change due to the decrease in air temperature and the change in thermal insulation. Global warming is also one of the important environmental issues. Japanese government has enacted the Outline of Countermeasures to Global Warming (New Outline) [3]; it primarily encompasses the energy-saving measures. Accordingly, even when the UHI countermeasures are installed, it is required that there be no significant increase in energy consumption.

From the viewpoint of global warming, it is natural to evaluate the energy consumption throughout the year. However, most researches conducted on UHI countermeasure thus far have only considered the energy consumption during summer. To the best of our knowledge, no research has evaluated the annual changes in energy consumption resulting from the installation of UHI countermeasures using meteorological simulations.

This study evaluates both the changes in thermal environment and energy consumption resulting from the installation of various UHI countermeasures from the viewpoints of UHI and global warming using annual meteorological and building energy models. We also investigated the installation procedures for the various UHI countermeasures.

2. Evaluation model for UHI mitigating countermeasures

To evaluate the UHI countermeasures, we modified the evaluation model for UHI mitigating countermeasures (CM–BEM) [4]. CM–BEM is composed of two sub models – canopy model (CM) [5] and building energy model (BEM). The model describes the feedback process, which is composed of the impact on a building's air-conditioning energy-demand from the weather inside an urban canopy and the effects of exhaust heat on the external environment. An overview of the CM–BEM is shown in Fig. 1.

The CM vertically resolves the phenomena occurring inside an urban canopy layer in order to describe the several-hundred-metres-scale weather changes. Same-sized parallelepiped buildings are arranged horizontally, and the existing density of buildings is considered for every altitude in the vertical direction. All weather components are calculated using the one-dimensional vertical diffusion equations for sensible and latent heats, as shown in Eqs. (1) and (2)

$$C_p\rho\frac{\partial\theta}{\partial t} = C_p\rho\frac{1}{m}\frac{\partial}{\partial z}\left(K_{\mathrm{h}}\cdot m\cdot\frac{\partial\theta}{\partial z}\right) + Q_{\mathrm{Ws}} + Q_{\mathrm{Rs}} + Q_{\mathrm{As}} + Q_{\mathrm{Vs}}, \tag{1}$$

$$l\rho\frac{\partial q_V}{\partial t} = l\rho\frac{1}{m}\frac{\partial}{\partial z}\left(K_{\mathrm{q}}\cdot m\cdot\frac{\partial q_V}{\partial z}\right) + Q_{\mathrm{Wl}} + Q_{\mathrm{Rl}} + Q_{\mathrm{Al}} + Q_{\mathrm{Vl}}. \tag{2}$$

In the above equations, the first term on the right-hand side represents the vertical turbulent diffusion of sensible or latent heat. The remaining terms on the right-hand side represent the sensible or latent heat fluxes from the buildings, i.e., Q^*_{A}: anthropogenic waste-heat; Q^*_{V}: exchange heat from building ventilation; Q^*_{W}: heat flux from sidewalls; and Q^*_{R}: heat flux from roofs (* is s when it represents sensible heat and l when it represents latent heat). Furthermore, $C_{\mathrm{p}}\rho$ (J/m^3 K): sensible heat capacity of the air; θ (K): outdoor air temperature; K_{h} (m^2/s): vertical turbulent diffusion coefficient of sensible heat; $l\rho$ (J/m^3 (kg/kg)): latent heat capacity of the air; q_V (kg/kg): outdoor air specific humidity; K_{q} (m^2/s): vertical turbulent diffusion coefficient of latent heat; and m (–): effective volume rate of the urban canopy ($m = \{1 - b^2/(w+b)^2 P_w(z)\}$), where b, w, and $P_w(z)$ are the average building width, average inter-building distance, and building existence ratio at vertical mesh level z, respectively (Fig. 1).

The radiations are considered to be three-dimensional – the surface temperatures on and the sensible heat fluxes from the sidewalls, roofs, and ground surfaces are calculated. In the case of the sidewalls, the radiation from the north, south, east, and west are taken into account individually.