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EFFECT OF LAND USE ON URBAN HEAT ENVIRONMENT

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SUMMARY

Effect of land use on heat island is studied numerically by an urban climate model which employs the $k - \varepsilon$ turbulence model and an eddy diffusivity model for wind, temperature and moisture fields together with a heat budget model for surface boundary layer and soil layer. Simulations were performed for a simplified terrain which consists of sea and land. Natural, urbanized and urbanized but green augmented land use conditions are discussed.

In urbanized area, it is clarified that decrease of latent heat flux and increase of sensible heat flux at urban surface raise temperature in the daytime. Urban canopy intensifies sensible heat transfer leading to higher air temperature. Sea breeze is blocked by the increased roughness in urbanized zone, resulting in the reduced cooling effect of sea breeze. The vegetation planting to increase moisture availability improves the thermal environment.

1. INTRODUCTION

Characteristics of heat reflection, evaporation, infiltration, and so on have been changed radically in heavily urbanized areas in Japan, which causes urban heat island problems. Higher temperature in summer produces deterioration of environment and higher consumption of electricity for air conditioning, and consequently raises air temperature by increased amount of exhausted heat. Heat island problems were studied in relation to air pollution at an early stage (Kimura and Takahashi(1991), Fujibe(1993)). In recent years, however, technical problems related with energy consumption, carbon dioxide and global warming have earned much concern.

The authors have worked out a series of study for quantitative prediction of the effect of land use on thermal environment as a tool of an environmental impact study in regional planning. A one–dimensional heat budget model has been developed and applied to Kanto region where the Tokyo Metropolitan area is located (Kawamata, Kawahara and Tamai(1993)). In this paper main results obtained by a two-dimensional urban climate model will be described.

2. OUTLINE OF THE NUMERICAL MODEL

The numerical model used in the present study solves wind, temperature and humidity fields through the continuity equation, two momentum equations, the thermodynamic equation, the equation for specific humidity and transport equations for the turbulence energy k and its dissipation rate ε. Turbulent stresses $\overline{u_iu_j}$, heat fluxes $\overline{u_i\theta}$, vapor fluxes $\overline{u_iq}$, and turbulent viscosity ν_t are expressed as follows.

$$-\overline{u_iu_j} = \nu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij}, \quad \overline{u_i\theta} = \frac{\nu_t}{\sigma_t}\frac{\partial \Theta}{\partial x_i}, \quad \overline{u_iq} = \frac{\nu_t}{\sigma_e}\frac{\partial Q}{\partial x_i} \qquad (1)$$

$$\nu_t = c_\mu \frac{k^2}{\varepsilon}, \qquad (2)$$

where σ_t and σ_e are the turbulent Prantdl and Schmit numbers, respectively. Main structure of the $k-\varepsilon$ model for a boundary layer is retained except for a couple of model constants which are adjusted for an atmospheric boundary layer. The values of c_μ and $c_{1\varepsilon}$ are modified from 0.09 to 0.026 and from 1.44 to 4.4, respectively (Detering and Etling(1985), Dawson et al.(1991)).

The top and bottom boundaries of the modeled atmosphere locate at 3,000m and 25m

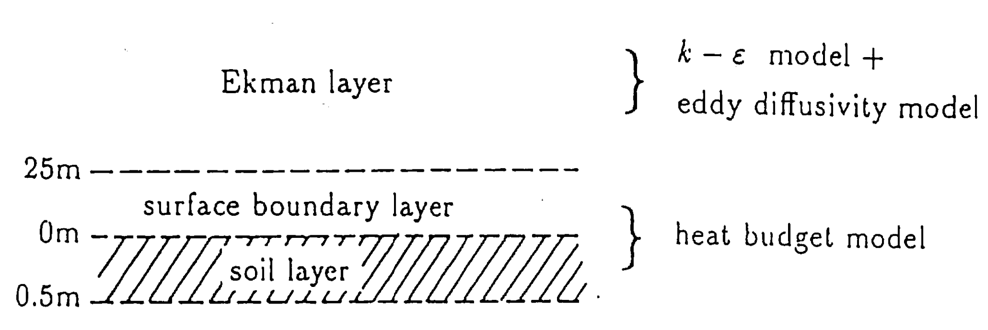


Fig. 1 Schematic presentation of an atmospheric boundary layer.

as shown in Fig. 1. Below the lower boundary, a surface boundary layer is assumed to exist where the momentum flux τ, the sensible heat flux H and the latent heat flux lE are constant and estimated as :

$$\tau = -\rho \frac{\kappa^2 U^2}{\Psi_m^2(\zeta)}, \quad H = -\rho C_p(\Theta - \Theta_o)\frac{\kappa U_*}{\Psi_h(\zeta)}, \quad lE = -\rho l\beta(Q - Q_o)\frac{\kappa U_*}{\Psi_q(\zeta)}, \qquad (3)$$

where $u_*^2 = -\tau/\rho$ and κ is the Karman constant. The quantity Q_o is the saturated specific humidity of the soil surface and β the moisture availability. The functions Ψ_m, Ψ_h and Ψ_q are the integrated universal functions and depend on the non-dimensionalized height ζ of the constant flux layer, ζ being defined as z/L with the Monin-Obukov length L.

In order to analyze the velocity and temperature in the surface boundary layer, the temperature at the ground surface is required to be a known parameter. The analysis for both surface boundary layer and soil layer was performed by a one-dimensional heat budget equation. Components considered at the ground surface are net solar radiation, backward radiation from atmosphere, radiation from the ground, sensible and latent heat fluxes from the surface, anthropogenic heat and conductive heat flux into the soil layer. The force restore method is employed in this study (Deardorff(1978)).

In this paper we want to discuss the effect of land use on urban heat island in terms of transfer rates of heat, vapor, and momentum for different types of land cover. Since the parameterization of the surface boundary layer is crucial to the reliable prediction, canopy layers by both vegetation and buildings require elaborate models which are described below.

In a vegetation canopy layer, the wind velocity is assumed to take the logarithmic profile with roughness height of z_0. Displacement height d is set to be 0.7 times of the height of the canopy layer. Sensible and latent heat fluxes are estimated by the bulk method with a representative velocity of the layer U_{af} that has the value of $0.83u_*$, u_* being the shear velocity in a vegetation canopy layer (Deardorff(1978)).

For an urban canopy layer a revised expression of a vegetation canopy model is applied. Sharing rate of buildings is considered. Effects of walls of buildings are taken into considered in two ways (Takahashi et al.(1990)). Firstly cut off effect of solar radiation is considered through a view factor. Secondly heat capacity of building walls is taken into account. Displacement height and roughness height in an urban canopy layer are considered to be one quarter of building height.

3. ALGORITHM AND PARAMETERS IN SIMULATION

Detailed description of basic equations and discretization are explained elsewhere (Kawamata(1994)). In this paper the principle of solution procedure and the specification of the major parameters are described briefly.

The basic equations are discretized by the finite volume method on a staggered grid mesh. Converged wind, temperature and humidity fields are obtained by the SIMPLE algorithm. The temperature at the ground surface is determined by iteration in a heat budget model where nonlinear interactions of heat and vapor exist between surface boundary layer and soil layer.

The emphasis of the simulation is placed on reproduction of sea and land breeze with no general wind to make clear the difference in temperature under different land use conditions. The boundary and initial conditions are explained as below.

Fluxes of momentum, sensible heat, latent heat as well as the turbulence energy and its dissipation rate are computed at the top of the surface boundary layer. These values then pose the lower boundary conditions of the transport equations for the upper layer. At the top of the Ekman layer, all velocity components are set zero. Constant values are given to potential temperature and specific humidity while symmetry conditions are applied for k and ε. On either side of the calculation domain, symmetry conditions are imposed on all variables except for vertical velocity which is set zero.

The numerical simulation starts from a calm and stable situation where potential temperature increases from 303K at the ground surface with the rate 0.6°C/100m. Calculated results after the first 24 hours are used for the study.

Daily energy consumption rate per unit area is prescribed utilizing statistics of energy load reported by Hiramatsu et al.(1992) and is shown in Fig. 2.

Hourly variation of anthropogenic heat production per unit area is implemented by an electricity demand record compiled by Tokyo Electric Power Company. Major elements considered are air conditioning, supply of warm water, lighting, and electric apparatus. Several examples are shown in Fig. 3.

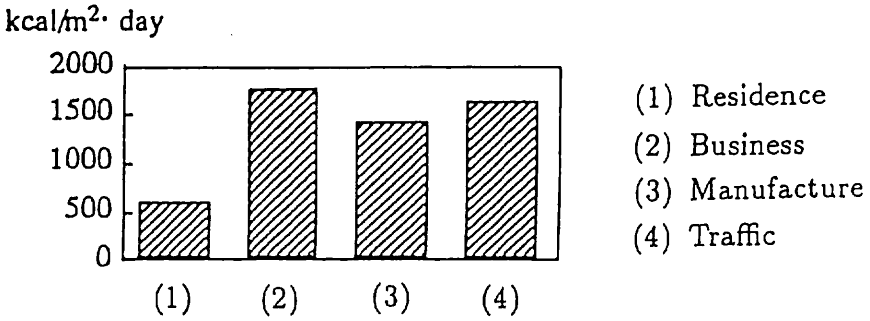
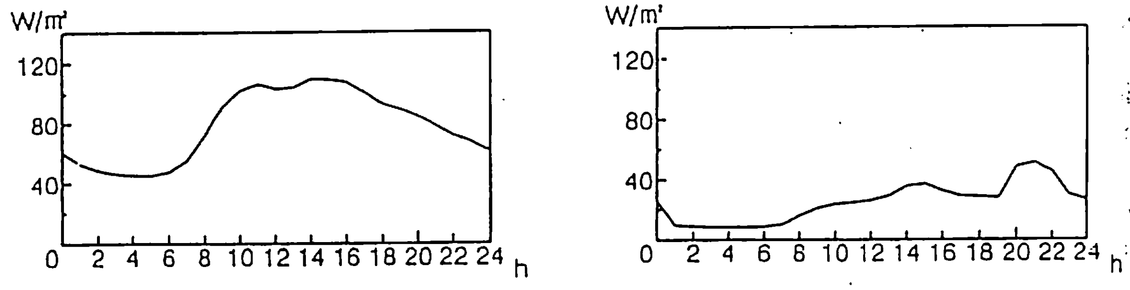
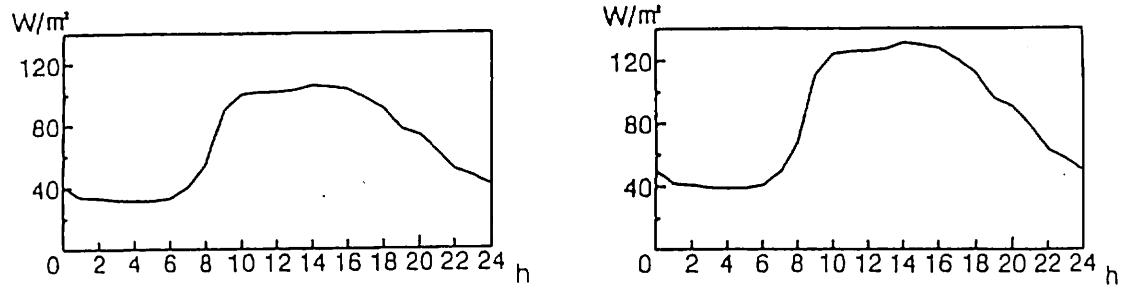


Fig. 2 Daily energy consumption rate.



(a) Street

(b) Independent House



(c) Industrial Area

(d) Office

Fig. 3 Time variation of anthropogenic heat.

4 CASE STUDIES IN A TWO-DIMENSIONAL SCHEME

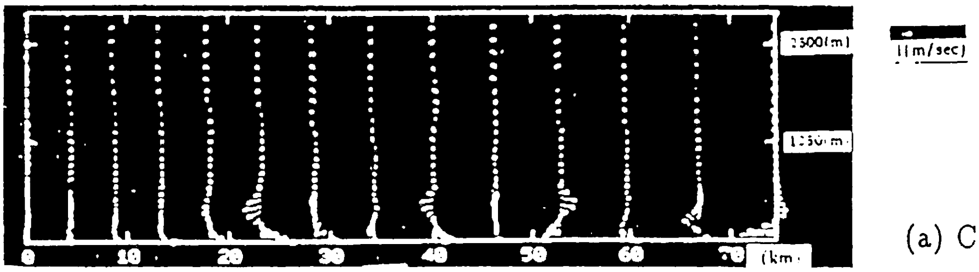
Formation of urban heat island is governed mainly by the following two factors. One is thermal factors, such as thermal effect of land covers and anthropogenic heat production. The other is a mechanical effect of intensified turbulence due to the increase of roughness. In order to clarify the effect of these factors quantitatively, four case studies are reported in this paper. Table 1 explains the combination of land use. Grass cover stands for agricultural field other than paddy field plus parks and vegetated area. For residential area parameters for independent houses are applied. Regulation means 10 % reduction of anthropogenic heat and 10 % increase of vegetated area. Basic parameters for natural conditions are selected for a typical fine day in August.

Wind fields in cases 1 and 2 at 15 o'clock obtained by the simulation are shown in Fig.4. Landward intrusion of sea breeze in case 2 is shorter than that in case 1 owing to the increase of roughness near the coast. At a frontal part of the sea breeze upward convective motion is observed. The upward thermals occur at different positions in each case.

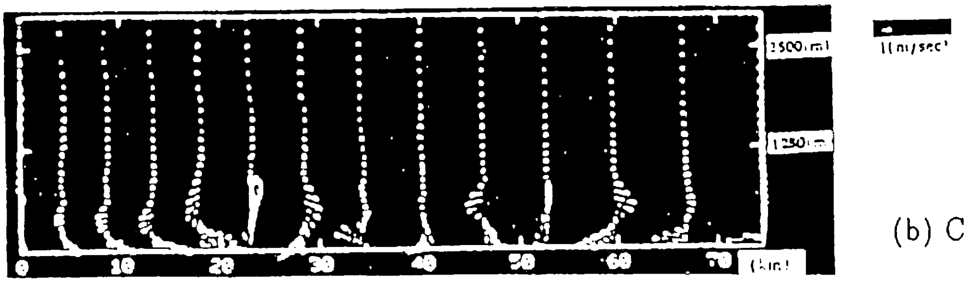
Surface temperature and air temperature at the top of the constant flux layer in case 2 are higher than those in case 1 by 2 degrees. In case 2 (urbanized case) upward convection becomes stronger than that in case 1 and the number of upward thermals also increases.

Table 1 Land use in case studies.

distance(km)	0–18	18–22	22–62	62–80
Case 1	Sea	Sea	Grass Cover	Grass Cover
Case 2	Sea	Sea	Residential Area	Grass Cover
Case 3	Sea	Business Area	Residential Area	Grass Cover
Case 4	Sea	Business Area with Regulation	Residential Area	Grass Cover



(a) Case 1

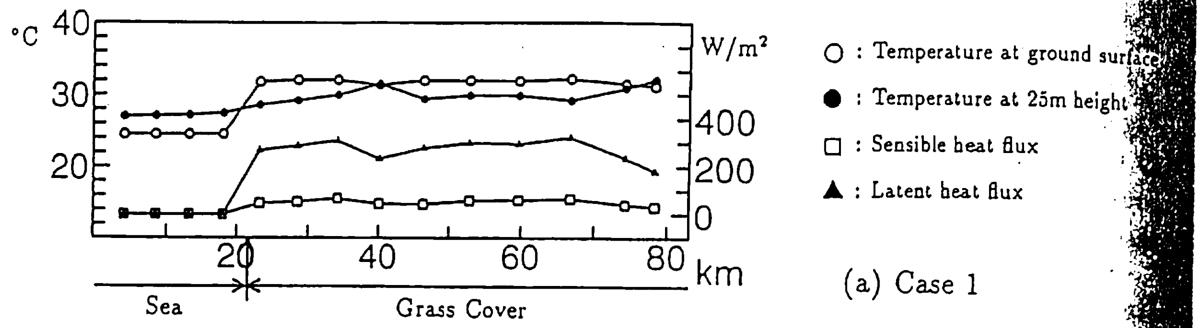


(b) Case 2

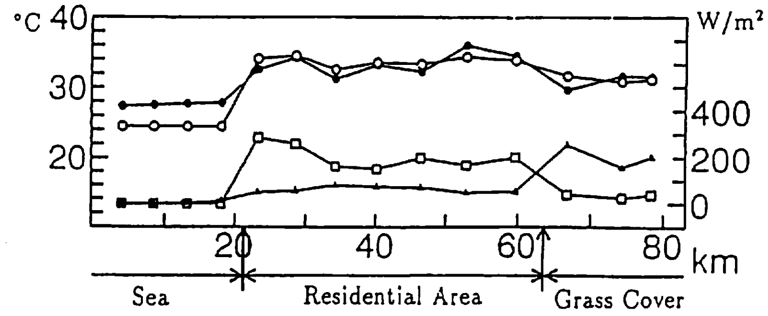
Fig. 4 Wind field at 15 o'clock obtained by the simulation.

In Fig. 5 heat fluxes near the ground surface are also compared. Over the residential area sensible heat flux becomes larger and consequently temperature becomes higher. Sensible heat flux reduces near the location 40km because downward convection prevails at this location. Temperature near the sea is shown to be cooler compared with that at inland grid point.

In case 3 the development of a reclaimed land into a business and commercial center is considered. Upward convection is further intensified compared with case 2. Waterfront development increases the roughness around the coast and produces stronger turbulence in wake region which contributes higher temperature. Fig. 6 shows temperature and heat

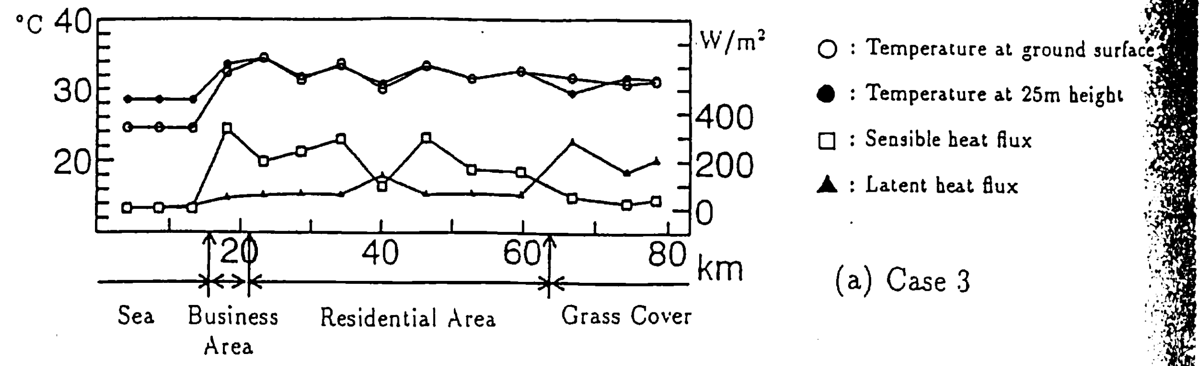


(a) Case 1

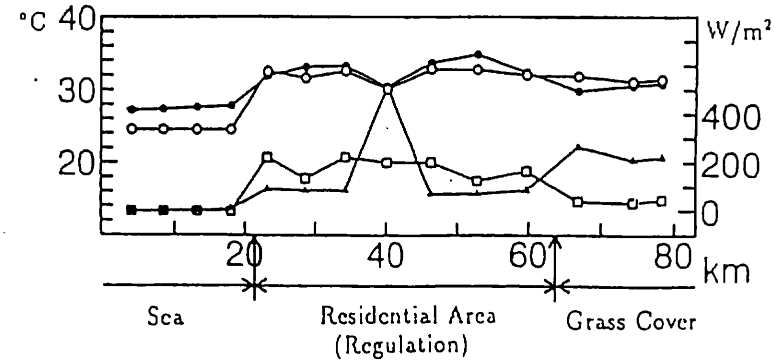


(b) Case 2

Fig. 5 Distribution of temperature and heat flux.



(a) Case 3



(b) Case 4

Fig. 6 Distribution of temperature and heat flux.

flux distributions along the longitudinal direction in cases 3 and 4. Temperature of the developed area in waterfront becomes very high and gradually decreases landward. In case 3 the intrusion length of sea breeze is interfered by urban canopy along the coast.

In case 4 sensible heat is suppressed and resulted in reduction of temperature by about 2 degrees compared with that in case 2. Lower temperature in the middle of the tested area is associated with downward drift. This decrease in temperature is mainly caused by the increase of latent heat flux accompanied by vegetation planting, because anthropogenic heat release plays a minor role in the daytime.

5. CONCLUDING REMARKS

In urbanized area it is clarified that decrease of latent heat flux and increase of sensible heat flux through the ground surface produce heat island. Urban canopy intensifies higher temperature providing strong transport of sensible heat in the surface boundary layer. Sea breeze transports cool air into urbanized area. This effect can not be expected unless the roughness near the coast is kept small.

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