DETERMINATION METHOD OF COEFFICIENTS AND ITS PROBLEMS IN THE SIMULATION OF URBAN AIR TEMPERATURE BASED ON ONE DIMENSIONAL HEAT BUDGET MODEL

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ABSTRACT

It is required that the urban air temperature is estimated on the average and macroscopically for studying the urban thermal environmental problems in summer. The diurnal variations of urban air temperature and heat budget components are investigated using one dimensional heat budget model. The evaporative efficiency and the anthropogenic heat were estimated by means of inverse operation using the observed air temperature. Good coincidence was obtained with the observed air temperature and the calculated. The diurnal variations of convective heat flux and latent heat flux presented unusual variation. The main reasons of this unusual variation are considered the influence of the advection effect caused by sea breeze, the transfer coefficient of surface layer used here, and the assumption of the thermal properties on the urban earth surface.

INTRODUCTION

The southwest part of Japan Island has a hot and humid climate in summer. Furthermore, the urbanization has brought terrible thermal environment in life. Especially, the minimum air temperature in large cities gradually has risen. The day, that the minimum air temperature is above 25C, is called "Nettaiya" (tropical night in Japanese). For example, in Osaka City, the "Nettaiya" days per year increased 17.5 days on average for 45 years from 1945 to 1989, whereas 6.4 days from 1901 to 1945. The main reasons will be able to be explained as follows: Natural earth surfaces such as green surface were being replaced the large heat storage materials such as asphalt or concrete used roads and buildings. The evaporative cooling effect is lost, and the solar radiation is stored. Furthermore, the anthropogenic heat from cooling equipment, cars and so on, have become large in a city. Consequently, the urban surface maintains warm even in the nighttime.

For studying these urban thermal environmental problems, it is required that the urban air temperature is estimated on the average and macroscopically. The simulation of urban air temperature using one dimensional heat budget model is appropriate for such a purpose[1), 2)]. In this model, it is assumed that the air temperature near the ground is equal to the surface temperature on the equation. In the estimation process, coefficients depending on the surface characteristics is required; albedo, roughness parameter, the specific heat of earth surface, the density of earth surface, the thermal conductivity of earth surface, evaporative efficiency, anthropogenic heat. It is known that the evaporative efficiency has large effect on maximum air temperature, and anthropogenic heat has large effect on minimum air temperature[2)]. In this paper, the practical values of evaporative efficiency and anthropogenic heat are determined from the comparison of observed and calculated air temperature. However, even if observed and calculated air temperature are well fit to each other, the quantitative evaluation of heat budget components is needed. In this paper, furthermore, net radiation flux, convective heat flux and conductive heat flux are calculated independently from observed air temperature, then the difference between latent heat and anthropogenic heat are determined as the residual from heat budget.

ONE DIMENSIONAL HEAT BUDGET MODEL

(A) Equation of Urban Air Temperature

One dimensional heat budget model used in this paper is as follows. Fig. 1 shows the outline of the model.

$$R + H = V + lE + A \tag{1}$$

$$R = Q_s + Q_l \tag{2}$$

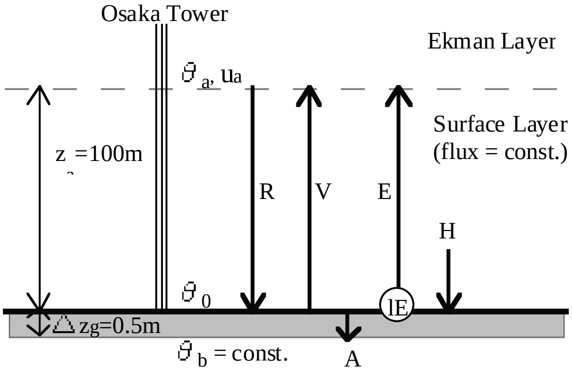

Fig. 1 Outline of the model

Here,

$$Q_s = (1-r)\ J_s \qquad (3)$$

when $\varepsilon\sigma\left(T_a^4 - T_0^4\right) = \varepsilon\cdot\alpha_r\left(\theta_a - \theta_0\right)$,

$$Q_l = -(1-K\cdot cc)\left\{(1-B_r)\varepsilon\sigma T_a^4 - \varepsilon\cdot\alpha_r(\theta_a - \theta_0)\right\} \qquad (4)$$

$$V = \alpha_c\left(\theta_0 - \theta_a\right) \qquad (5)$$

$$\begin{aligned} lE &= w\cdot l\cdot\alpha_w\left(q_0 - q_a\right) \\ &= a\cdot w\cdot l\cdot\alpha_w\left(\theta_0 - \theta_a\right) + w\cdot l\cdot\alpha_w\left(a\cdot\theta_a + b - q_a\right) \end{aligned} \qquad (6)$$

$$A = \lambda_g\left(\theta_0 - \theta_{\Delta z_g}\right)\Big/\Delta z_g \qquad (7)$$

Next equation is derived from the equation (1)-(7).

$$\begin{aligned} \theta_0 = &\frac{1}{(1-K\cdot cc)\alpha_r + \alpha_c + a\cdot w\cdot l\cdot\alpha_w + \lambda_g/\Delta z_g}\times\left\{(1-r)J_s\right. \\ &-(1-K\cdot cc)\varepsilon\sigma T_a^4\left(0.49 - 0.209\sqrt{P_{wa}}\right) - w\cdot l\cdot\alpha_w\left(a\cdot\theta_a + b - q_a\right) \\ &\left.+H + \lambda_g\theta_{\Delta z_g}\quad\Delta z_g + \left((1-K\cdot cc)\alpha_r + \alpha_c + a\cdot w\cdot l\cdot\alpha_w\right)\theta_a\right\} \end{aligned} \qquad (8)$$

In this paper, the surface temperature θ_0 represented in the equation (8) is assumed as the air temperature near the earth surface (about 1.5m high). The temperature in soil is solved by the finite difference from the following heat conduction equation.

$$\frac{\partial\theta}{\partial t} = \frac{\lambda_g}{C_g\cdot\rho_g}\frac{\partial^2\theta}{\partial x^2} \qquad (9)$$

(B) Transfer Coefficient of Surface Layer

The “transfer coefficient of surface layer” is derived using Monin-Obukhof’s similarity method. The universal function was used the experimental equations proposed by Businger et.al.[3].

$$\zeta = z/L \qquad (10)$$

$$L = -\frac{u^{*3}\cdot T_o}{\kappa\cdot g\left(V/C_p\rho_a\right)} \qquad (11)$$

For stable condition,

$$F_m = \int_{\zeta_0}^{\zeta_a}\frac{1+4.7\zeta}{\zeta}d\zeta = \left[\log\zeta + 4.7\zeta\right]_{\zeta_0}^{\zeta_a} \qquad (12)$$

$$F_h = \int_{\zeta_0}^{\zeta_a}\frac{0.74+4.7\zeta}{\zeta}d\zeta = \left[0.74\log\zeta + 4.7\zeta\right]_{\zeta_0}^{\zeta_a} \qquad (13)$$

For unstable condition,

$$F_m = \int_{\zeta_0}^{\zeta_a}\frac{(1-15\zeta)^{-\frac{1}{4}}}{\zeta}d\zeta = \left[2\arctan(1-15\zeta)^{-\frac{1}{4}} + \log\left|\frac{(1-15\zeta)^{-\frac{1}{4}}-1}{(1-15\zeta)^{-\frac{1}{4}}+1}\right|\right]_{\zeta_0}^{\zeta_a} \qquad (14)$$

$$F_h = \int_{\zeta_0}^{\zeta_a}\frac{0.74(1-9\zeta)^{-\frac{1}{2}}}{\zeta}d\zeta = \left[0.74\log\left|\frac{(1-9\zeta)^{-\frac{1}{2}}-1}{(1-9\zeta)^{-\frac{1}{2}}+1}\right|\right]_{\zeta_0}^{\zeta_a} \qquad (15)$$

For neutral condition,

$$F_m = \int_{\zeta_0}^{\zeta_a}\frac{1}{\zeta}d\zeta = \left[\log\zeta\right]_{\zeta_0}^{\zeta_a} = \log\frac{\zeta_a}{\zeta_0} = \log\frac{z_a}{z_0} \qquad (16)$$

$$F_h = \int_{\zeta_0}^{\zeta_a}\frac{0.74}{\zeta}d\zeta = 0.74\log\frac{z_a}{z_0} \qquad (17)$$

The transfer coefficient for surface layer is represented as follows.

$$\alpha_c = \frac{C_p\rho_a\kappa u^*}{F_h} = \frac{C_p\rho_a\kappa^2 u_a}{F_m F_h} \qquad (18)$$

$$\alpha_w = \frac{\alpha_c}{C_p} \qquad (19)$$

DETERMINATION OF EVAPORATIVE EFFICIENCY AND ANTHROPOGENIC HEAT

(A) Method

According to the simulation results of diurnal air temperature in a fine summer day[2], it is known that the evaporative efficiency w has a large effect to reduce the maximum (daytime) air temperature. Therefore, in this paper, w was decided from a good coincident point between calculated values and observed values at the maximum air temperature in the diurnal variation. On the other hand, the anthropogenic heat H has a large effect to rise air temperature in the minimum (nighttime) air temperature. Therefore, new H value is decided from a good coincident point between calculated values and observed values at the minimum air temperature. The practical values of evaporative efficiency and anthropogenic heat component were determined by means of the comparison between calculated values and observed values.

The determination procedure of evaporative efficiency w and anthropogenic heat H is as follows.

a) The meteorological data required here are air temperature and air humidity ratio at about 1.5m and about 100m height above earth surface, underground temperature, global solar radiation, wind velocity and cloudiness.

b) Assumption of albedo, roughness parameter, thermal properties of ground (specific heat, density and thermal conductivity).

c) Assumption of anthropogenic heat H in the nighttime properly. Then, the determination of w from a good coincident point between calculated values and observed values at the maximum air temperature in the period mean diurnal variation

d) Determination of H from a good coincident point between calculated values and observed values at the minimum air temperature in period mean diurnal variation.

(B) Calculation Conditions

The hourly data observed at Osaka Meteorological Office on August 1 to 8, 1990 are used as the meteorological conditions. Fig. 2 shows potential temperature at the ground level and 100m high (Osaka Tower). Fig. 3 shows solar radiation and water vapor pressure at the ground level. The upper air vapor pressure is assumed the same value with the ground level. Fig. 4 shows the upper wind speed at 100m high and cloudiness. It was hot and fine days successively during this period.

The following coefficients are assumed considering the situation around the Osaka Meteorological Office. Albedo is assumed 17.2%, roughness parameter is 1.5m, and specific heat is 0.88kJ/(kgK), density is 2153kg/m^3, thermal conductivity is 1.29kW/(mK). The underground temperature is assumed 28C (0.5m deep).

(C) Results

Fig. 5 shows the evaporative efficiency in x-axis and the mean, maximum and minimum period mean values of calculated and observed air temperature in y-axis. As shown in Fig. 5, the evaporative ratio w has a large effect to reduce the maximum (daytime) air temperature. In this case, w=0.025 is a good coincident point with observed values at the maximum temperature.

Fig. 6 is taken anthropogenic heat in x-axis and the y-axis is the same in Fig. 5. As shown in Fig. 6, the anthropogenic heat H has a large effect to rise the minimum air temperature. Especially, it has a large effect on the small value region of H. As shown in Fig. 6, according to the comparison with the minimum air temperature, H=65W/m^2 is a good coincident point.

As shown in Fig. 7, on the whole, good coincidence was obtained with the observed values and the calculated values. If the accuracy of heat budget components do not care, the estimation accuracy of air temperature by this method is very high.

ESTIMATION RESULTS OF HEAT BUDGET COMPONENTS

(A) Method

The heat budget components were calculated inversely using the given air temperature near the ground level. The calculation method is the quite same one above mentioned. The evaporative efficiency w was estimated by means of inverse operation using the observed meteorological data. Therefore, Monin-Obukhof's similarity theory is assumed, and it is also assumed the air temperature at the ground level equals to the surface temperature in the equation. The concrete procedure is as follows.

a) Assume the Monin-Obukhof's length scale L, then calculate ζ(=z/L) and the integrated values of universal function F_m, F_h from equation (12)-(17), determine L, F_m, F_h using iteration method.

b) Then, calculate the transfer coefficient of surface layer α_c from equation (18), and determine convective heat flux flux V from equation (5).

c) Net radiation R and conductive heat flux A are able to determine independently from equation (2), (3), (7), because the air temperature near ground level is given. The difference, (lE-H), between latent heat flux lE and anthropogenic heat H is calculated as the residual, then, evaporative efficiency w is determined under the condition H=0.

$$lE - H = R - V - A \qquad (20)$$

$$w = (R + H - V - A) / l\alpha_w\left(a\theta_0 + b - q_a\right)$$

(H=0 is assumed) (21)

(B) Results

The calculation results during the fine days are shown in Fig. 8-11, also during cloudy days are shown in Fig. 12-15. Fig. 11 and 15 shows the calculation results of heat budget components by the above mentioned method corresponding to Fig. 5-7.

a) In Fig. 9 and 10, α_c and convective heat flux V vary depending on the potential temperature difference (θ_o-θ_a). V becomes extraordinarily large values with the potential temperature difference in the afternoon.

b) (lE-H) and evaporative efficiency w (H=0 is assumed) become also extraordinarily large values in the morning as shown in Fig. 9 and 10. When w is negative, there is substantially no meaning, because of the assumption H=0.

c) In Fig. 10 and 14, (lE-H) in the nighttime is negative. It is considered that these values correspond to the anthropogenic heat H, because H is almost 0 in the nighttime.

It seems the diurnal variation of heat budget components in Fig. 11 and 15 are apparently more certain variation than Fig. 10 and 14. The reasons of the unusual variation in Fig. 10 and 14 are considered by means of the following problems concerning the estimation method.

a) The effect of advection is appeared because of the sea breeze, especially to the upper air in the afternoon. Consequently, the potential temperature differences become large in the afternoon. The one dimensional assumption is problem, especially in the

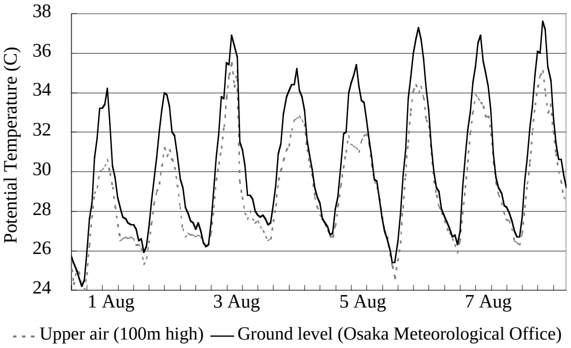

Fig. 2 Observed value of potential temperature (1-8 Aug. 1990)

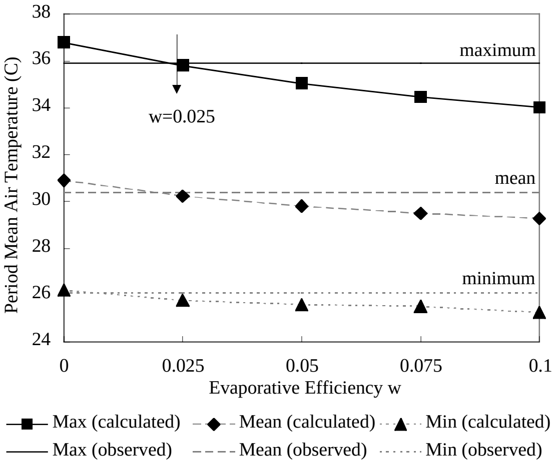

Fig. 5 Estimation of evaporative efficiency w (1-8 Aug. 1990)

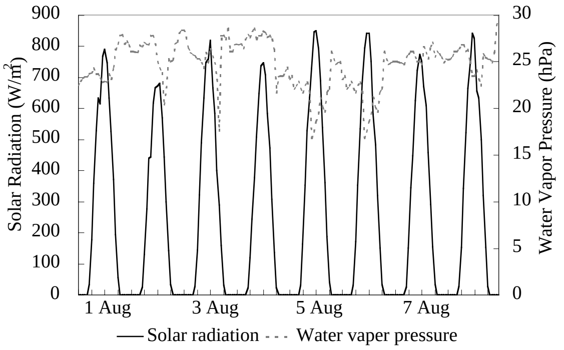

Fig. 3 Meteorological condition of solar radiation and water vapor pressure (1-8 Aug. 1990)

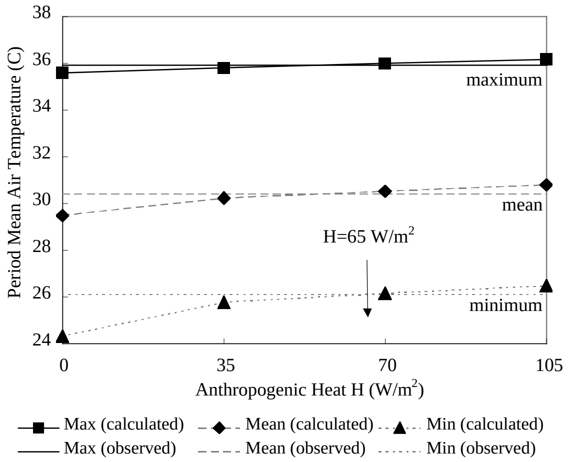

Fig. 6 Estimation of anthropogenic heat H (1-8 Aug. 1990)

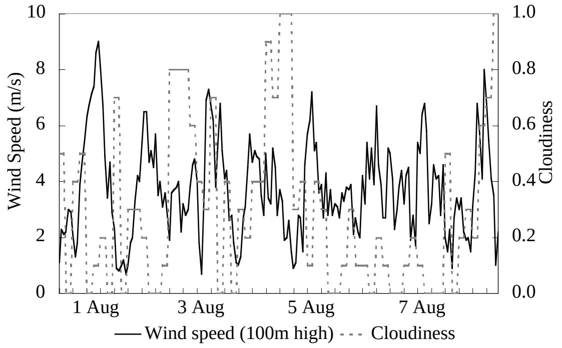

Fig. 4 Meteorological condition of wind speed and cloudiness (1-8 Aug. 1990)

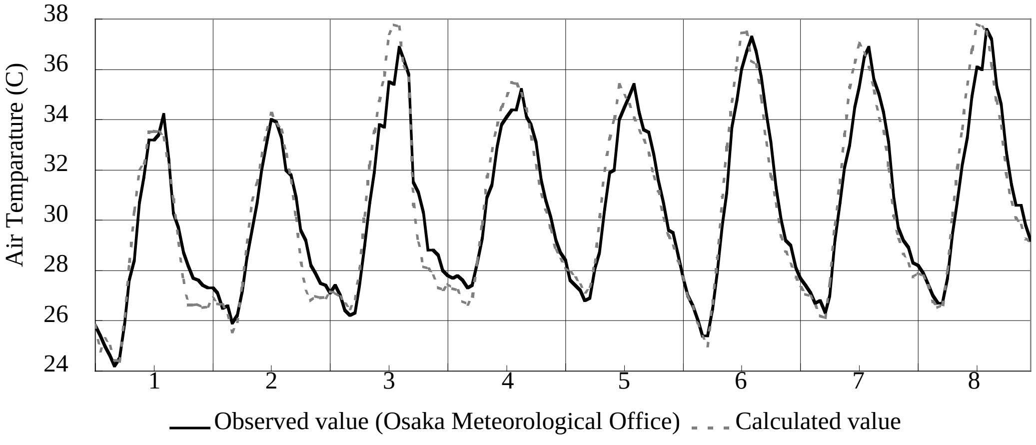

Fig. 7 Comparison between calculated value and observed value (1-8 Aug. 1990)

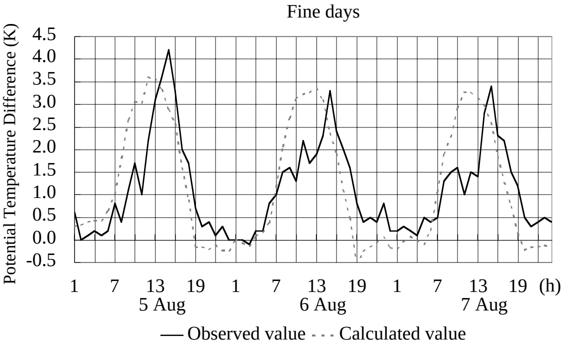

Fig. 8 Potential temperature difference between upper air and ground level (5-7 Aug. 1990)

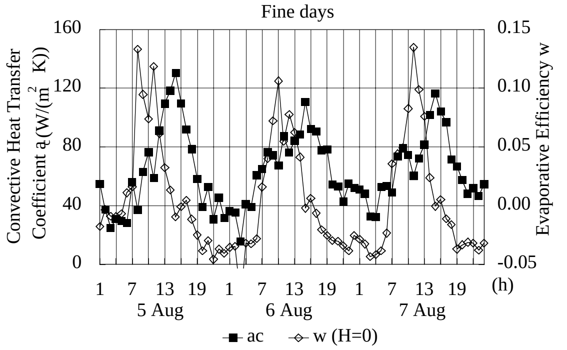

Fig. 9 Calculation results of α_c and w (5-7 Aug. 1990)

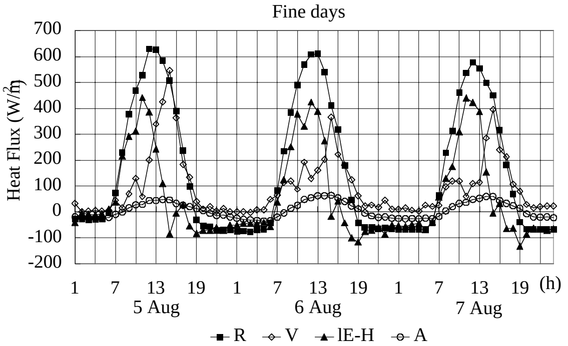

Fig. 10 Calculation results of heat budget components (5-7 Aug. 1990)

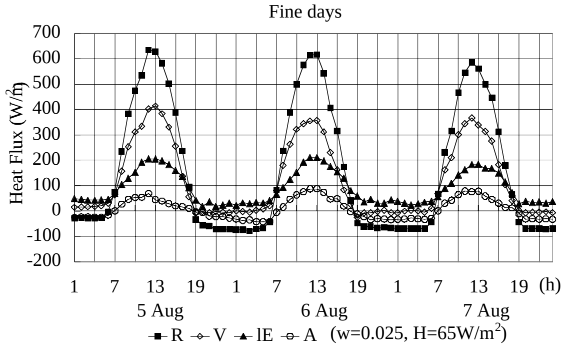

Fig. 11 Calculation results of heat budget components (5-7 Aug. 1990)
(In the case of w=0.025, H=65W/m^2 (constant))

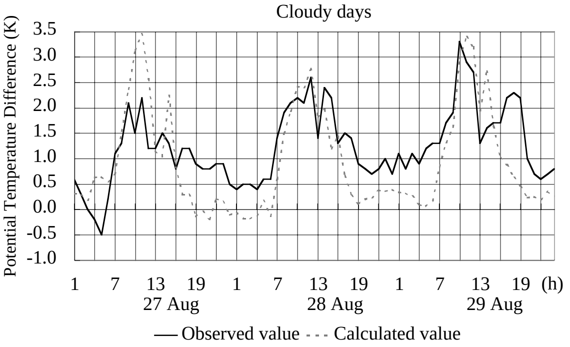

Fig. 12 Potential temperature difference between upper air and ground level (27-29 Aug. 1991)

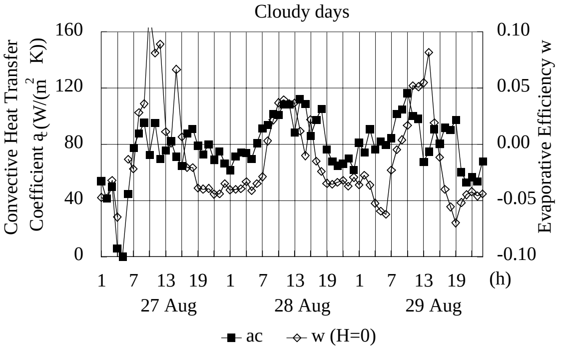

Fig. 13 Calculation results of α_c and w (27-29 Aug. 1991)

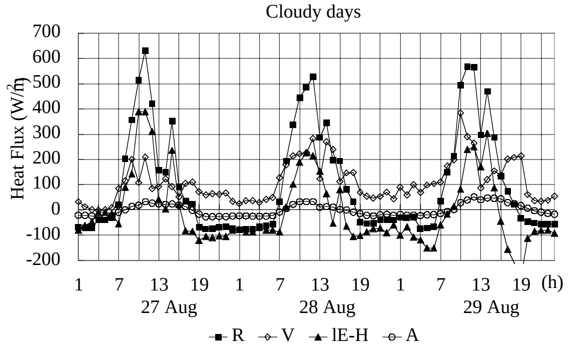

Fig. 14 Calculation results of heat budget components (27-29 Aug. 1991)

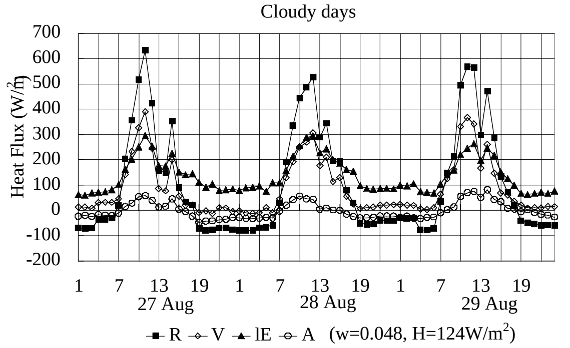

Fig. 15 Calculation results of heat budget components (27-29 Aug. 1991)
(In the case of w=0.048, H=124W/m^2 (constant))

afternoon.

b) The thermal transfer coefficient of surface layer is assumed Monin Obukhof's similarity law and used the experimental equation proposed by Businger et. al.. It seems to overestimate at the region of large temperature difference and underestimate at the small difference.

c) The calculated conduction heat flux A seems to be smaller in the morning than the anticipated value. The assumption of thermal properties at the earth surface will be problem.

d) In this calculation process, the nighttime long wave radiation seems to be overestimated. It is also a problem that the data of cloudiness is observed only every 3 hour at the meteorological station.

Further investigation is needed. The following procedure will have a worth to investigate; assuming LE=0, determine H in the nighttime, then determine w at the maximum temperature.

CONCLUSIONS

The estimation method of urban temperature and the diurnal variation of heat budget components were investigated using one dimensional heat budget model. The air temperature of ground level was considered to equal to the surface temperature in the heat budget equation.

a) The evaporative efficiency w was estimated by means of inverse operation using the maximum air temperature data. Then, the anthropogenic heat was decided also by means of inverse operation using the minimum air temperature data.

b) According to the calculation results of air temperature, on the whole, a good coincident was obtained with the observed values and the calculated values.

c) In the calculation results of heat budget components, the diurnal variation of the convective heat flux and the latent heat flux show unusual diurnal variation reflecting the potential temperature difference between upper air and ground level. The latent heat flux was overestimated in the morning. It seems the reason is 1) the conduction heat flux is underestimate, 2) the transfer coefficient of surface layer is also underestimate. The convective heat flux was also overestimated in the afternoon. It seems the reason is 1) the advection effect caused by sea breeze, and 2) the transfer coefficient of surface layer is overestimate.

ACKNOWLEDGEMENTS

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NOMENCLATURE

a, b: constants, $q_s=a\theta+b$ (q_s: saturated specific humidity),
A: conductive heat flux (W/m^2),
Br: equation of Brunt (=0.51+0.209x$(P_{wa})^{0.5}$),
cc: cloudiness (-),
C_g: specific heat of soil (kJ/(kgK)),
C_p: specific heat of air (kJ/(kgK)),
F_m, F_h: Integrated value of universal function (-),
g: gravitational acceleration (=9.8 m/s^2),
H: anthropogenic heat production (W/m^2),
J_s: solar radiation (W/m^2),
K: coefficient of cloud height (=0.62),
l: latent heat of vaporization (=2,512 kJ/kg),
L: Monin-Obukhov length (m),
lE: latent heat flux (W/m^2),
P_{wa}: water vapor pressure in the air (kPa),
q: specific humidity (kg/kg),
Q_l: long wave radiation (W/m^2),
Q_s: short wave radiation (W/m^2),
r: albedo (-),
R: net radiation (W/m^2),
T: absolute air temperature (K),
u: wind velocity (m/s),
u*: friction velocity (m/s),
V: convective heat flux (W/m^2),
w: evaporative efficiency (-),
z: height (m),

Subscripts

a: upper air,
0: earth surface or near earth surface,

Greek character

α_c: convective heat transfer coefficient (W/(m^{2}K)),
α_r: radiative heat transfer coefficient (W/(m^{2}K)),
α_w: moisture transfer coefficient (kg/(m^{2}h(kg/kg))),
Δz_g: depth in soil (m),
ε: emmisivity (-),
θ: air temperature (C),
κ: von Karman constant (=0.35),
λ_g: thermal conductivity of soil (W/(mK)),
ρ_a: density of air (=1.2 kg/m^3),
ρ_g: density of soil (kg/m^3),
σ: Stefan-Boltzmann constant (=5.67x10^{-8} W/(m^{2}K^4))