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FIELD OBSERVATION AND ESTIMATION OF URBAN AIR TEMPERATURE IN SURFACE BOUNDARY LAYER USING A METHOD FOR REGIONAL SURFACE ENERGY BALANCE INCLUDING VEGETATION EFFECTS

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SYNOPSIS

This paper estimates the air temperature of the atmospheric surface boundary layer in urban and suburban areas using a model for regional surface energy balance including vegetation effects. Applying the Monin-Obukhov similarity theory in those areas, the model is based on the assumption that evapotranspiration in urban areas is primarily due to vegetation. The present paper assumes that the evapotranspiration is controlled by such three factors as an evapotranspiration area index (i.e., effective leaf area index), vapor pressure deficit at leaf temperature, and stomatal opening. The relation between NDVI and the air temperature estimated by the vegetation model has a mitigation effect due to vegetation on air temperature in urban areas. The mitigation effect amounts to 1 ℃ for an increase of 0.1 in NDVI.

INTRODUCTION

There has been various studies so far on heat island phenomena, but difficulties to observe mitigation effects of vegetation on air temperature in regional areas is why research on the mitigation is scarce. One of a limited number of examples is a simulation on the mitigation effect (1) and another is a field observation by Kanda and Hino (2). On the other hand, although studies on vegetation effects against radiometric surface temperature are reported using vegetation coverage ratio derived from Landsat TM (3), there exists no regional research on vegetation effects on air temperature in the atmospheric surface boundary layer. Speaking of researches on urban heat environment by one dimensional model of surface energy balance using remotely sensed data, the examples are specified as Carlson et al.(4) in Los Angeles and St. Louis by Heat Capacity and Mapping Mission (HCMM), and Taconet et al.(5) at Beauce in France with a model including vegetation effects. The Carlson's model considered no vegetation effects, while Taconet applied a one-dimensional boundary layer/vegetation/soil model to homogeneous vegetation of dense crop fields. No studies exist, on authors' knowledge, about surface energy balance including non-homogeneous vegetation in regional area as well as estimation of the mitigation effect on air temperature using remotely sensed data.

Methods to estimate latent heat flux using remotely sensed data so far are indirect evaluation of the flux by subtracting sensible heat flux from net radiation. Since the authors' method estimates latent heat flux directly using evapotranspiration indices, the presented method can evaluate vegetation effects on air temperature in urban environments from the relation between the estimated air temperature and normalized difference vegetation index (NDVI).

This paper proposes a method for estimating regional surface energy balance assuming that the Monin-Obukhov similarity theory is consistent in the test area. The lowering of air temperature by vegetation effects can be estimated as follows:

Friction velocity U_* and Obukhov length L are calculated using NDVI derived from Landsat TM on the application of the Monin-Obukhov similarity theory. Friction velocity U_* and friction temperature θ_* determine the air temperature in the surface boundary layer, after θ_* is obtained from U_* and Obukhov length L. The relation between the estimated air temperature and NDVI enables to evaluate the vegetation's effect on air temperature. The value of the effect on air temperature increases with effective leaf area index α_{NDVI}. The drop amounts 1 ℃ for an increase of 0.1 in NDVI (i.e., 0.17 increase in effective LAI) on the assumption that the heat convection effect can be neglected.

ESTIMATION OF AIR TEMPERATURE

Estimation Method

Applying the Monin-Obukhov similarity theory in the atmospheric surface boundary layer, the latent heat flux is expressed as

$$E = -\rho\, l U_* q_* \qquad (1)$$

where ρ = density of air; U_* = friction velocity; l = latent heat of evaporation; q_* = friction specific humidity, defined by

$$q_* = -\overline{wq}/U_* \qquad (2)$$

where $\overline{wq}$ = specific humidity flux.

The sensible heat flux is written as

$$H = -C_p\, \rho\, U_* \theta_* \qquad (3)$$

where C_p = specific heat of air; θ_* = friction temperature. The friction velocity, specific humidity and friction temperature are estimated by using Landsat TM and meteorological routine data on the assumption that the Monin-Obukhov similarity theory is consistent.

Relations concerning air temperature, wind speed and specific humidity in the surface boundary layer consist of eight formulae as follows:

The relation between dimensionless height ζ and universal functions is written as

$$\zeta = B \cdot \phi_m^2(\zeta) / \phi_h(\zeta) \qquad (4)$$

where ϕ_m = universal function for wind speed; ϕ_h = universal function for atmospheric temperature.

B is the bulk Richardson number expressed as

$$B = \frac{g(T_a - T_s)}{\overline{\theta}\; U^2}(z - d_o) \qquad (5)$$

where g = acceleration of gravity; T_a = atmospheric temperature; κ = von Karman constant; T_s = surface temperature observed by TM; $\overline{\theta}$ = smoothed surface temperature; U = wind speed; z = observation height of U, T_a and q_a ; d_o = zero-plane displacement. ζ is the dimensionless height defined by

$$\zeta = (z - d_o)/L \qquad (6)$$

Monin-Obukhov length L is written by the following form

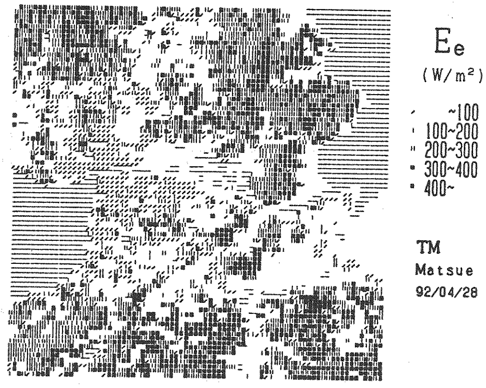


Fig. 1 Horizontal distribution of latent heat flux *Ee* in urban and suburban areas of Matsue city.

Fig. 2 Horizontal distribution of sensible heat flux *He* .

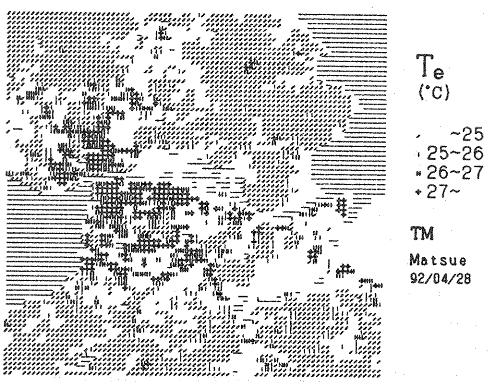


Fig. 3 Horizontal distribution of estimated air temperature *Te* .

$$L = \frac{\overline{\theta}\ U_*^2}{\kappa\ g_*\ \theta} \tag{7}$$

Integral of the universal function ϕ_h in the Monin-Obukhov theory yields the following equations

$$T_e - T_s = \frac{\theta_*}{\kappa}\ \Psi_h(\xi), \tag{8}$$

where

$$\Psi_h = \int_{\xi_o}^{\xi} \frac{\phi_h}{\xi}\ d\xi, \tag{8a}$$

$$\xi_{oh} = z_{oh}/L, \tag{8b}$$

$$U = \frac{U_*}{\kappa}\ [\Psi_m(\xi) - \Psi_m(\xi_o)], \tag{9}$$

where

$$\Psi_m = \int_{\xi_o}^{\xi} \frac{\phi_m}{\xi}\ d\xi, \tag{9a}$$

$$q - q_o = \frac{q_*}{\kappa}\ [\Psi_m(\xi) - \Psi_m(\xi_o)] \tag{10}$$

where q_o = specific humidity on earth surface. The present paper proposes the expression of specific humidity deficit ($q - q_o$) in terms of the specific humidity deficit ($q - q_c$) between saturation specific humidity q_c at leaf temperature and air flow specific humidity q using two evapotranspiration indices, as follows,

$$q - q_o = a_c\ \alpha_{NDVI} \cdot \beta\ (q_s - q_c) \tag{11}$$

where α_{NDVI} = index of effective leaf area; β_s = index of stomatal opening; a_c = conversion coefficient. Given variables derived from TM are smoothed surface temperature $\overline{\theta}$, radiometric surface temperature T_s and saturated specific humidity q_c. Meteorological routine data at an observatory provide other given variables such as wind speed U and specific humidity q. The index of stomatal opening β_s (Kaneko and Hino, 1994) is also the given variable derived from remotely sensed data and meteorological data. Unknown variables are bulk Richardson number B, dimensionless height ξ, Obukhov length L, friction velocity U_*, friction specific humidity q_*, friction temperature θ_*, and specific humidity at earth surface q_o. Since eight formulae exist against eight unknown variables, the distribution of non-homogeneous air temperature T_e can be obtained by assuming that two variables of wind speed U and specific humidity q among three kinds of meteorological routine data T_a, U and

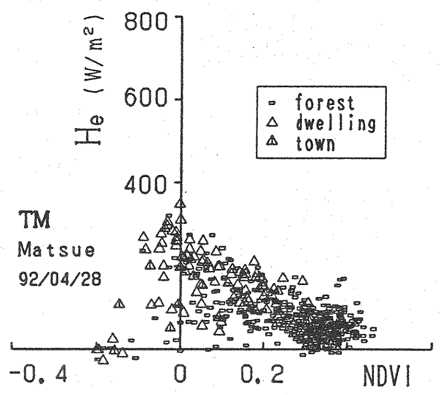


Fig. 4 Relation between sensible heat flux *He* and NDVI.

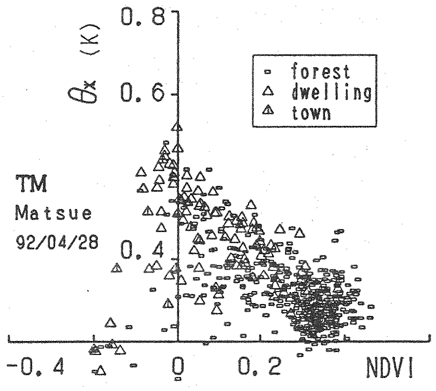


Fig. 5 Relation between friction temperature θ_* and NDVI

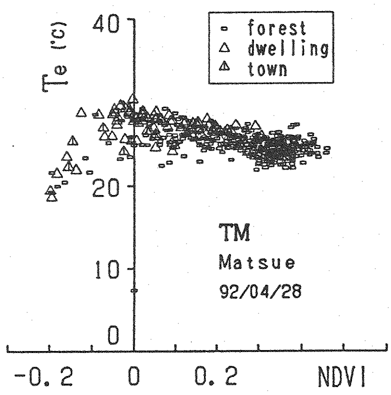


Fig. 6 Relation between estimated air temperature *Te* and NDVI.

q are uniform as the first approximation in the test area. The estimated air temperature T_e is at the height of z=26.7 m at which the wind speed is observed at Matsue Observatory.

Horizontal Distribution of Latent Heat and Sensible Heat Fluxes

The present research aims to estimate air temperature at the land-use sites of towns and dwellings where urban heat island issues are concerned in the test area of Matsue City as well as forested sites having opposite characteristics to the urban area. Fig.1 shows the horizontal distribution of latent heat flux E_e estimated by Eq.(1) .

Latent heat flux E_e in the urban area has a small value of less than 100 W/m ^{2} due to the lack of transpiration effect by vegetation, while E_e in the forested areas and Matsue suburbs amounts to a large value of more than 400 W/m ^{2} . The fact that the sensible heat flux increases with the decrease in NDVI makes the air temperature in the urbanized area to rise due to the decrease of transpiration from vegetation. NDVI is defined by Eq.(12) as

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}} \qquad (12)$$

where NIR = digital count of near infrared band (0.76-0.90 μ m);
R = digital count of red band (0.63-0.69 μ m).

The horizontal distribution of estimated sensible heat flux H_e by means of Eq.(3) is shown in Fig.2 corresponding to the horizontal distribution data obtained by TM.

Estimation of Friction Temperature

Eq.(7) gives friction temperature θ_* using the following computation process:
Assuming that the air temperature is uniform in the test area as a first approximation, i.e. the constant of T_a obtained by Matsue Observatory, Obukhov length L is estimated using the bulk Richardson number B and the dimensionless height ξ calculated iteratively by means of Eqs.(4) and (5). The value of friction temperature θ_* can be obtained from the friction velocity U_* calculated from Eq.(9) and Obukhov length L.
The universal function ϕ proposed by Businger-dyer was applied.

$$\left.\begin{aligned}\phi_m &= (1-16\,\xi)^{-4/4}\\ \phi_h &= (1-16\,\xi)^{-1/2}\end{aligned}\right\}\ \xi < 0 \qquad (13a)$$

$$\phi_m = \phi_h = 1+5\,\xi \qquad \xi \geqq 0 \qquad (13b)$$

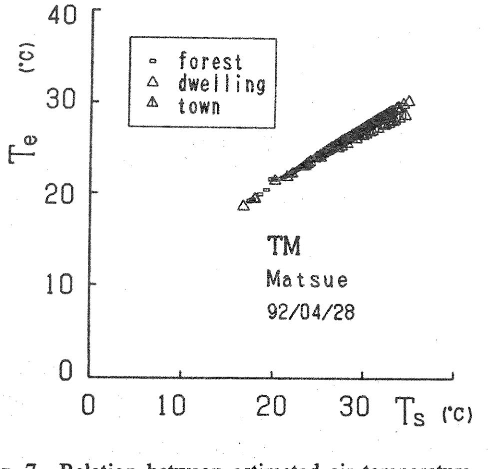


Fig. 7 Relation between estimated air temperature and surface temperature Ts derived by TM.

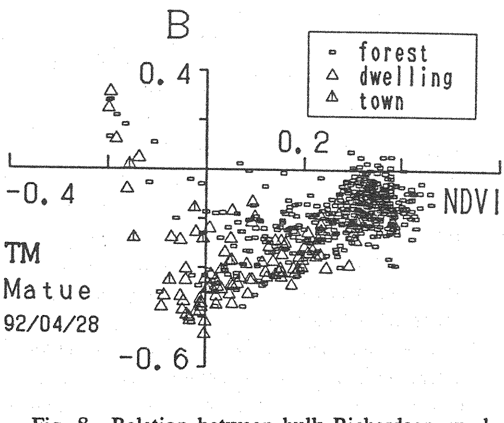


Fig. 8 Relation between bulk Richardson number and NDVI.

Estimation of Air Temperature

The values of air temperature at every spot corresponding to TM pixels are determined by Eq.(7) using the values of friction temperature θ_* by means of Eq.(7) and the surface temperature T_s obtained by TM. Eq. (13) gives beforehand integral Ψ_h of the universal function since Obukhov length L has been already calculated.

Relation between Friction Temperature and NDVI

The surface temperature decreases with the increase in NDVI by the effect of latent heat flux due to the transpiration from vegetation. Fig.5 presents the effect of NDVI through the temperature decrease onto the friction temperature θ_* by comparing with Fig.4 concerning the relation between sensible heat flux H_e and NDVI . The trend that the friction temperature decreases with increase in NDVI means that the vegetation restrains the increase of air temperature in the atmospheric surface boundary layer.

Horizontal Distribution of Estimated Air Temperature

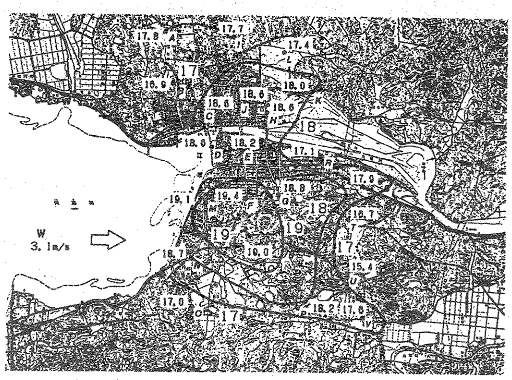
Fig.3 illustrates the horizontal distribution of air temperature estimated by Eq.(7) in the test area of Matsue City, comparing with Figs.1 and 2 concerning the distributions of E_e and H_e . While the values of air temperature T_e at forested areas in the suburbs of Matsue City are less than 23 ℃ , the urbanized areas maintain an air temperature of more than 28 ℃ which is 6 ℃ higher than that in the suburbs. The highest area was the center part of the city in such areas as building and shopping streets or dense housing zones around Matsue railway station.

Relation Between Surface Temperature and Estimated Air Temperature

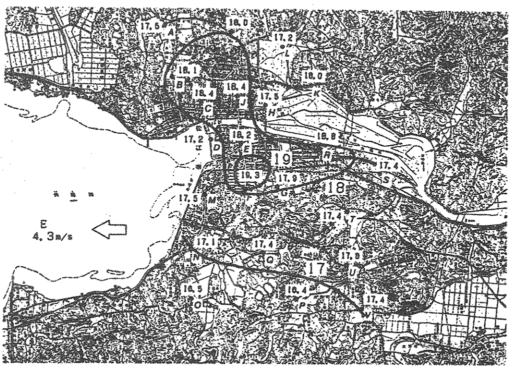
Fig.7 shows the relation between TM-derived surface temperature T_s and the estimated air temperature T_e in Matsue City. The air temperature increases with surface temperature T_s by the effect of sensible heat flux.

Relation between Air Temperature and NDVI

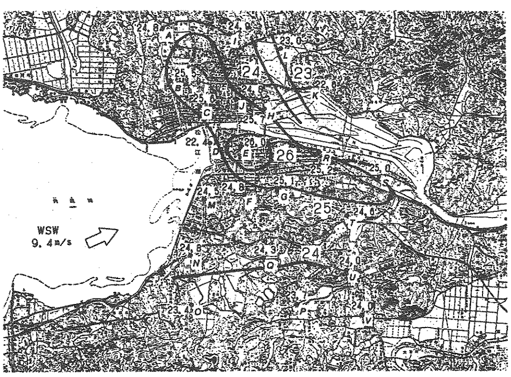
To evaluate the mitigation effect of vegetation on air temperature regarding the heat island phenomena, Fig.6 presents the relation between NDVI and the estimated air temperature T_e obtained by Eq.(8) in the test area around the center part of Matsue City. The air temperature T_e is less than 23 ℃ in vegetated areas where the values of NDVI are more than 0.4. The



(a) On 15 May 1993.



(b) On 16 May 1993.



(c) On 25 May 1993.

Fig. 9 Horizontal distribution of air temperature by field observation.

comparison of the air temperature of 23 ℃ with that more than 29 ℃ in urban areas gives a decrease of 6 ℃. The mitigation effect due to vegetation diminishes with the decrease in NDVI at such urbanized sites as buildings and dwellings. This phenomenon means that the air temperature increases with decrease of latent heat flux due to the effect of diminishing evapotranspiration in less vegetated areas as shown in Fig.(1). The vegetation effect of temperature mitigation amounts to 2 ℃ in urban areas having a value of NDVI = 0.1, i.e. 1 ℃ temperature drop for an increase of 0.1 in NDVI (or in other words, 17 % increase of the area ratio of evapotranspiration).

Relation between Bulk Richardson Number and NDVI

Fig.8 shows the relation between NDVI and the bulk Richardson number B obtained by Eq.(5). The effect of NDVI on atmospheric stability is explained as follows: The bulk Richardson number is scarcely positive, i.e. the atmosphere is stable in the quite limited areas of NDVI more than 0.4. The atmosphere was unstable over almost all pixels of urban areas where the surface temperature T_s increases with the decrease in NDVI. The average value of dimensionless height ξ estimated by Eq.(6) was -0.209 which is a similar value to the averaged value of bulk Richardson number $\overline{B}$= -0.156, since the averaged universal functions for momentum ϕ_m = 1.016 and that for heat ϕ_h = 0.832 result in the value of $\phi_m^2(\xi)/\phi_h(\xi)$ =1.19.

FIELD OBSERVATION OF AIR TEMPERATURE IN HEAT ISLAND AREAS AND OBSERVATION METHOD

Air temperature and humidity are observed simultaneously by Assmann's aspiration psychrometers at 22 observation points around Matsue City shown in Fig.9. The observation height is 1.5 m above ground. Five psychrometers provided data at the same time within 30 minutes moving and sharing each other's several observation spots of the 22 points around the city.

Horizontal Distribution of Air Temperature by Field Observation

Fig.9(a) presents the horizontal distribution of the air temperature observed by the method described above at 10:00 A.M. on 15 May 1993 around Matsue urban areas. The wind speed and direction were 3.1 m/s and westerly respectively, while the air temperature was 17.6 ℃ at Matsue meteorological observatory. The air temperature at the center part of Matsue City was over 19 ℃ and about 2 ℃ higher than that of paddy and farm fields in the suburbs. The horizontal distribution of high air temperature on 15 May 1993 spread toward the east by thermal convection effects due to sea breezes from Japan Sea on the west side of Matsue City. In the case of 16 May 1993, however, the horizontal distribution of air temperature coincides with that calculated by Eq.(1) as shown in Fig.3, since the wind speed U = 2.2 m/s is weak with the direction ENE which means that the thermal convection effect by wind from cool surfaces of sea and Lake Shinji is negligible. The case of 25 May 1993 is another example of the negligible thermal convection.

CONCLUSION

The proposed model for regional surface energy balance including vegetation effects estimates the air temperature of the atmospheric surface boundary layer in urban and suburban areas. Mitigation effect of vegetation on the air temperature in urban areas was evaluated. Conclusions are summarized as follows:

1) Air temperature in regional urban areas is estimated using the proposed model for regional surface energy balance based on the similarity theory of Monin-Obukhov using such remotely sensed data as vegetation index NDVI and surface temperature derived from Landsat TM.

2) The relation that the air temperature decreases due to latent heat effect with increase in NDVI enables us to evaluate mitigation effects of vegetation on air temperature in urban heat island where vegetated areas are mixed in the city.

3) The horizontal distribution of air temperature can be determined by a model using the horizontal distribution of surface temperature and NDVI derived from Landsat TM.

4) The maximum mitigation effect of vegetation on air temperature amounts 6 ℃ in densely forested areas. The effect is 1 ℃ for an increase of 0.1 in NDVI. The 0.1 increase in NDVI means that the evapotranspiration area index increases by 17% whose physical and hydrologic meaning is that the area covered by forest increases by 17% in the test pixel.

5) The horizontal distribution of air temperature in a small city is affected by thermal convection by wind when cool water surface exists on the windward side.

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APPENDIX - NOTATION

The following symbols are used in this paper:

ρ = density of air;
C_p = specific heat of air;
U_* = friction velocity;
q_* = friction specific humidity;
θ_* = friction temperature;
ϕ_m = universal function for wind speed;
ϕ_h = universal function for atmospheric temperature;
Ψ_m = integral of the universal function ϕ_m ;
Ψ_h = integral of the universal function ϕ_h ;
g = acceleration of gravity;
T_a = atmospheric temperature;
κ = von Karman constant;
B = bulk Richardson number;
T_s = surface temperature derived from Landsat TM;
T_e = estimated air temperature;
$\overline{\theta}$ = averaged surface temperature;
U = wind speed;
z = height at which the values of air temperature T_a and wind speed U are measured;
d_o = zero-plane displacement;
ζ = dimensionless height;
L = Monin-Obukhov length;
q_o = specific humidity on ground surface;
q = specific humidity of air flow;
q_c = saturation specific humidity at leaf temperature;
a_c = conversion coefficient;
$NDVI$ = normalized difference vegetation index;
α_{NDVI} = index of effective leaf area; and
β_s = index of stomatal opening.

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