A dynamic model for the plant canopy microclimate

Asaeda, Takashi
Ca, Vu Thanh
Fujino, Takeshi
Kodama, Housou

(Citation)
神戸大学都市安全研究センター研究報告. 特別報告,1:309-314

(Issue Date)
1998-07

(Resource Type)
departmental bulletin paper

(Version)
Version of Record

(JaLCDOI)
https://doi.org/10.24546/00044747

(URL)
https://hdl.handle.net/20.500.14094/00044747

A Dynamic Model for the Plant Canopy Microclimate

Takashi ASAEDA [1], VU Thanh Ca[2], Takeshi FUJINO [3] and Housou KODAMA[4]

[1] Associate Professor, Graduate School of Science and Engineering, Saitama University (255 Shimo-okubo, Urawa, Saitama 338, Japan)

[2] Associate Professor, Dept. of Civil and Environmental Engineering, Saitama University(255 Shimo-okubo, Urawa, Saitama 338, Japan)

[3] Research Associate, Graduate School of Science and Engineering, Saitama University (255 Shimo-okubo, Urawa, Saitama 338, Japan)

[4] Pulic Work Research Institute, Ministry of Construction (Asahi 1 Tsukuba, Ibaraki 305, Japan)

A numerical model has been developed for the simulation of heating and evapo-transpiration processes in the plant canopy. Heat and moisture fluxes at the soil surface are evaluated by solutions of equations coupling subsurface heat and moisture transfer, and the evaporation at the ground surface. The heating and transpiration processes in the plant canopy are computed using a model coupling the foliage heating and water transport in the soil-plant system. The plant canopy is divided into layers with LAI in each layer equal or less than 0.1; and stomatal conductance and photosynthesis of leaves in each layer were simulated. The model for transpiration in the plant canopy includes a submodel for the absorption of water in the soil by root, a submodel for the transport of water in the stem, and a submodel for the transpiration at the leaves. Details of the air temperature, specific humidity and wind velocity inside the plant canopy are also investigated.

A verification of the model using a field observational data at Tsukuba, Japan reveals that the model can simulate satisfactorily the mass and heat transfer processes in the plant canopy. Due to its general type, the model can be used to predict the heating

Key Words : *Plant Canopy, field observation, numerical model, evapotranspiration*

1. INTRODUCTION

Modelling of heating and evapo-transpiration processes in the plant canopy requires knowledge about plant physiology, which includes water uptake by the root, water transport in the stem to the leaf, and transpiration at the leaf; and also the knowledge of radiation and heat transfer processes in the plant canopy. The temperature and water content of the soil are also important for the root water uptake. Much studies in the vegetation-atmospheric interaction is conducted based on the employment of the Penman-Monteith equation where the canopy acts as a ``big leaf" with a canopy conductance equal to the parallel sum of the leaf stomatal conductances. Big leaf models are belong to the family of one-layer-canopy models.

Kanda and Hino (1989, a,b) developed a multilyer model for the simulation of the heating and evapo-transpiration at the plant canopy. However, the assumption of constant soil moisture restricts the model to the computation for only a short period.

Kondo and Watanabe (1992) and Watanabe (1994) developed and tested a multi-layer model for the plant canopy microclimate. The valuability of this model is that it provide a method for estimating bulk transfer coefficients inside the plant canopy. In this model, leaf stomatal resistance was assigned by a given value, and the dynamics of subsurface heat and moisture transfer was not included.

This paper presents a new model for the heating and vapor transfer in the plant canopy. The model consists of a submodel for radiation transfer in the plant canopy, a submodel for the heating of the canopy, a submodel for the transport of water in the root-stem-leaf system, a submodel for the coupling of heat and moisture transfer in the soil, and a submodel for the evapo-transpiration in the plant.

2. THE NEW MODEL

(1) Main equations of the model

As this model is a unsteady, uni-dimensional in the vertical direction, a horizontally uniform canopy is assumed. Assuming uniform wind blow over an otherwise horizontally uniform plant canopy, the heating processes at a point in the plant canopy is described by the following equation

$$\rho_{cp} c_{cp} \frac{dT_{cp}}{dt} = R_n - a(z)H_c(z) - a(z)Le_c(z), \qquad (1)$$

and the transport of water vapor in the plant canopy, including stem and root is evaluated as

$$C_p \frac{\partial \psi_p}{\partial t} = \frac{\partial}{\partial z}\left(K_p \frac{\partial(\psi_p + z)}{\partial z}\right) - S_p(z), \qquad (2)$$

where ρ_{cp}, c_{cp} and T_{cp} are density, specifc heat and temperature of the leaves, respectively; t is time; R_n is the net radiation; $a(z)$ is the leaf area density (one sided), H_c(z) is the sensible heat exchange between leaves and the air; L is the latent heat of evaporation; $e_c(z)$ is the transpiration rate at the canopy, which is identical to $S_p(z)$ for $z>0$; C_p is the water capacity of the plant; ϕ_p is the total pressure head in the root-stem; K_p is the hydraulic conductivity in the root-stem; z is the vertical coordinate; and S_p is the source or sink of water due to root water uptake or leaf evapo-transpiration.

The vertical structure of wind velocity in the plant canopy is described by the following equation

$$\frac{\partial u}{\partial t} - \frac{\partial}{\partial z}\left[(\nu + \nu_m(z))\frac{\partial u}{\partial z}\right] = \begin{cases} -a(z)\tau_c(z)/\rho_a & 0 \le z \le h_c \\ 0 & z > h_c. \end{cases} \qquad (3)$$

The air temperature inside the plant canopy is computed by solution of the equation

$$\frac{\partial T_a}{\partial t} - \frac{\partial}{\partial z}\left[(\kappa_h + K_h(z))\frac{\partial T_a}{\partial z}\right] = \begin{cases} a(z)H_c(z)/c_p\rho_a & 0 \le z \le h_c \\ 0 & z > h_c, \end{cases} \qquad (4)$$

and the equation for water vapor transfer in the canopy

$$\frac{\partial q_a}{\partial t} - \frac{\partial}{\partial z}\left[(\kappa_m + K_m(z))\frac{\partial q_a}{\partial z}\right] = \begin{cases} a(z)e_c(z)/\rho_a & 0 \le z \le h_c \\ 0 & z > h_c, \end{cases} \qquad (5)$$

where u is the wind velocity; τ_c is the momentum flux to leaves; ν and ν_m are the molecular and turbulent viscosities, respectively; $\tau_c(z)$ is the shear stress due to the presence of leaves; ρ_a is the air density; h_c is the height of the canopy; κ_h and K_h are the molecular and turbulent heat diffusivities, respectively; T_a is air temperature; c_p is specific heat of the air under constant pressure; and κ_m and K_m are the molecular and turbulent vapor diffusivities, respectively; and q_a is the specific moisture content of the air.

The turbulent viscosity and diffusivities for heat and water vapor in the neutral conditions are modelled follows the K-theory of Kondo and Watanabe (1990, 1992). Effects of atmospheric instability inside and near the top of the plant canopy are accounted for following Goudriaan (1977) and Businger (1971).

(2) Modelling the momentum, heat and mass exchange between leaves and the air

Equations for momentum, heat and water vapor exchange between leaf surface and the air are as (Kondo and Watanabe, 1992)

$$\tau_c(z) = \rho_a c_d u^2, \qquad (6)$$

$$H_c(z) = c_p \rho_a c_h u (T_{cp} - T_a), \qquad (7)$$

$$e_c(z) = \rho_a c_e (q_{*cp} - q_a), \qquad (8)$$

where c_e and c_h are, respectively, coefficients for exchange of water vapor and heat between leaves and the air; q_{cp} is the saturation vapor pressure at leaf temperature.

It has been well documented that the value of the coefficient for exchange of water vapor between leaves and the air depends on many environmental factors such as air humidity, leaf water content conditions and radiation (Jones, 1992)

$$c_e = g_0 f(I) f(\delta e_l) f(\psi_p), \tag{9}$$

g_o is the maximum leaf water conductivity; $f(I)$ $f(\delta e_l)$ and $f(\psi_p)$ are functions which have values between 0 and 1 and expressesd as Jones (1992). I and δe_l are respectively the PAR values and the difference in vapor pressure between the leaf surface and the air. The coefficient c_h should depend on turbulent in the plant canopy, i.e. on wind velocity and atmospheric stability. However, due to uncertainty about this, in this study, are assumed not depend on these factors.

(3) Radiation transfer in the plant canopy

The submodel for the radiation transfer in the plant canopy used in this model is essential the same as that of Goudriaan (1977). For the computation of longwave radiation in the plant canopy, it is assumed that the emissivity of leaves equal to 1. Assuming the canopy is divided into layers, numbered from the top to the ground surface, the downward longwave radiation at the lower end of a canopy layer j is computed as

$$\begin{aligned} R_{Ld}(j) = {} & R_{Ld}(j-1)[1 - L_s(j-1)] \\ & + \sigma T_{cp}^4(j-1) L_s(j-1), \end{aligned} \tag{10}$$

and the upward longwave radiation at the upper end of a canopy layer j is computed as

$$\begin{aligned} R_{Lu}(j) = {} & R_{Lu}(j+1)[1 - L_s(j)] \\ & + \sigma T_{cp}^4(j) L_s(j), \end{aligned} \tag{11}$$

where $R_{Ld}(j)$ and $R_{Lu}(j)$ are the downward and upward longwave radiation at the lower end of the canopy layer j, respectively; $L_s(j)$ is the leaf area index in the canopy layer j; and σ, is the Stefan-Boltzman constant.

(4) The root water uptake model

In this study, the root water uptake model of Herkelrath et al (1977) is employed. This model was subjected to the most rigorous derivation and test independent of some other mathematical model of the calibration type; also, the root soil contact resistance is accounted for (Molz, 1981). The equation for root water uptake is as

$$S_p = \frac{\theta}{\theta_s} \zeta_r l_r (\psi_s - \psi_r), \tag{12}$$

where θ is the soil water content; θ_s is the maximum soil water content upon rewetting; ψ_s and ψ_r are the water potential of the soil and inside the root membrane, respectively; ζ_r is the root membrane permeability per unit length of root; and l_r is the total root length per unit volume of soil (m/m^3).

The value of the root membrane permeability should change with type of plant. However, since lack of information, in this model the value proposed by Herkelrath et al (1977) is adopted.

(5) The subsurface heat and moisture transfer model

The subsurface heat and moisture transfer model used in this study is essential the same as that of Asaeda and Vu (1993). The equations coupling water and heat transfer inside the soil are integrated numerically using a finite element scheme. With the assumption of local equilibrium between the liquid and vapor phases, the vapor density inside soil pores and at the soil surface is evaluated and is used for the computation of evaporation rate at the soil surface.The hysteretic soil water retention process can be evaluated following Mualem (1974). The dependence of hydraulic conductivity of the soil upon the soil water potential and soil temperature is calculated following Mualem (1976a,b).

(6) Boundary and Initial Conditions and Numerical Scheme

Boundary conditions at the top of the computational domain, which is several meters above the plant canopy, are meteorological conditions such as air temperature, relative humidity, wind velocity, and downward shortwave and longwave radiation. In case the data of downward shortwave and longwave radiation are not available, cloud data can be used for the computation of radiation follows Asaeda and Vu (1993).

The lower boundary conditions for the soil domain are constant temperature and matric head at large depth.

From the experiment data, the values of temperature and matric head in the soil domain can be determined at given depths. These will be used as the initial conditions for the temperature and matric head in the soil domain.The initial leaf and air temperatures are specified by measurement on leaf temperature and air temperature distribution in the vertical direction. In case of no measurement data, the initial pressure head in the plant canopy is considered constant in the vertical direction and equal to a specified value. In this study, in order to save computational time, a finite element scheme, which allows fine mesh near surface where a strong variation of soil temperature and moisture content with time and depth is observed, and coarse mesh at large depth where physical properties of soil change slowly, is adopted. A finite volume scheme, which allows a nonuniform mesh and is easy for implementation in the numerical code, is employed to integrate equations (1-5) in the canopy layer and air domain.

2. FIELD OBSERVATION AND COMPUTATIONAL RESULTS

Field observations has been carried out to investigate the influence of various environmental factors such as solar radiation, air temperature, air humidity, wind velocity etc. to the heating and evapo-transpiration processes at the plant canopy. The experiment site is located in a forest in Tsukuba City, Ibaraki, Japan. There are many plant species such as *Cyptomeria japonica, Chamaecyaris obtusa, Querucus acuisima, Oak, Fagus crenata, Prunus*, and others. The dominant species are *Cyptomeria japonica and Chamaecyaris obtusa*. A tower with the height of 10 m was set up inside a *Cyptomeria japonica* area with a canopy height of 12m. A perch was mounted on the tower, which enables the measurement of wind velocity, air temperature and relative humidity at the height of 15m. During the observations, wind velocity was measured by anemometers; air temperature and relative humidity at some heights from the ground surface were measured by thermo-hygrometer; solar radiation and albedo of the canopy top were measured by pyranometer and albedometer, respectively; and soil temperature at the surface and different depths in the soil were also measured. Foliage surface temperature at some levels was measured using hand thermography (thermoflow). The LAI of the canopy was measured by a plant canopy analyzer.

The chosen observational site provides favorable conditions for the application of the one-dimensional model for the heating and evapo-transpiration at the plant canopy.

Fig. 1 depicts the leaf area density, evaluated from the measured LAI. It can be seen that leaves of the trees concentrate at the top of the canopy, from 10.5m to 12m with a maximum leaf area density of about $1m^2/m^3$. Lower than 10.5m, the leaf area density decreases rapidly to the value of about $0.25m^2/m^3$ at the height of 6m from the ground surface. Lower than this height, the leaf area density remain constant due to the presence of small trees near the ground surface.

Figure 2 depicts the turbulent mixing length inside and outside the plant canopy, computed by the model of Watanabe and Kondo (1990). As in the figure, the turbulent mixing length increases with the distance from the ground surface, then decreases due to the increase of the leaf area density. Above the plant canopy, the turbulent mixing length increase again with the distance from the plant canopy.

Figure 3 depicts the observed and computed time variation of air temperature at the height of 12m, just the top of the plant canopy, and 6m, the mid-point of the plant canopy. As indicated in the figure, the days were fine and hot days with the air temperature at the top of the canopy at 12 a.m. reaching 33.5 ^{o}C. At this time, the difference in air temperature between that at the top of the plant canopy and that at the mid-point reaches more than 2 ^{o}C. This difference is due to

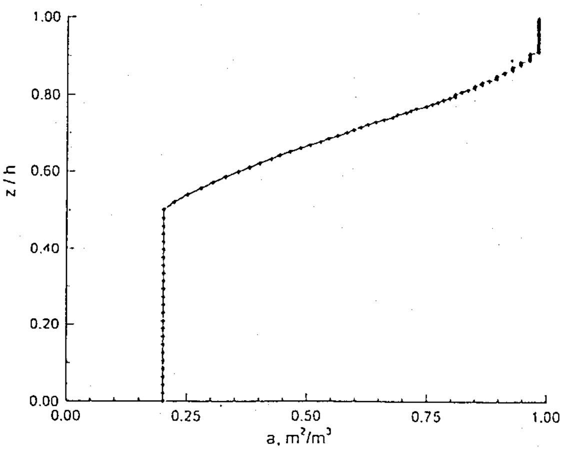

Figure 1: Distribution of leaf area density in the plant canopy

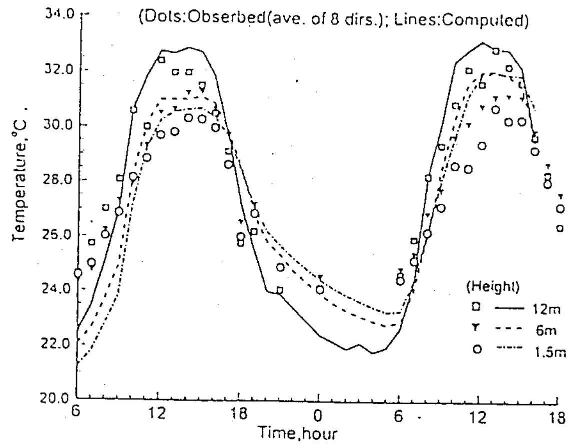

Figure 4: Observed and computed foliage temperature in the plant canopy (Sept. 1-2, 1997).

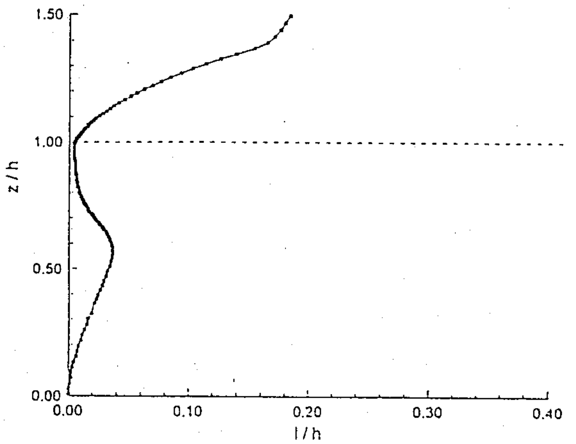

Figure 2: Distribution of the computed mixing length in the plant canopy.

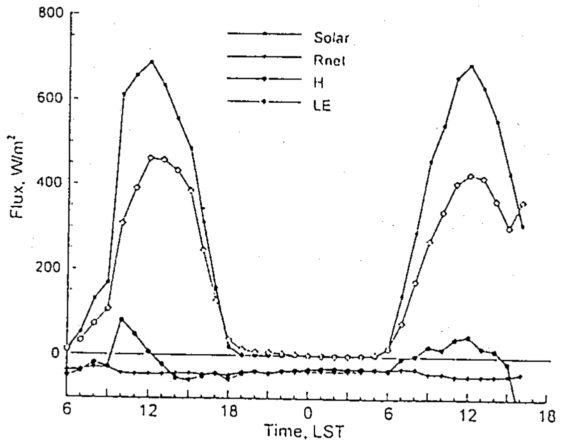

Figure 5: Computed heat balance in the plant canopy (Sept. 1-2, 1997).

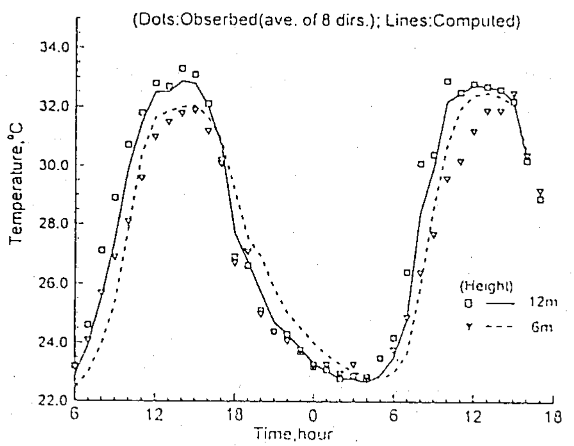

Figure 3: Observed and Computed air temperature in the plant canopy (Sept. 1-2, 1997).

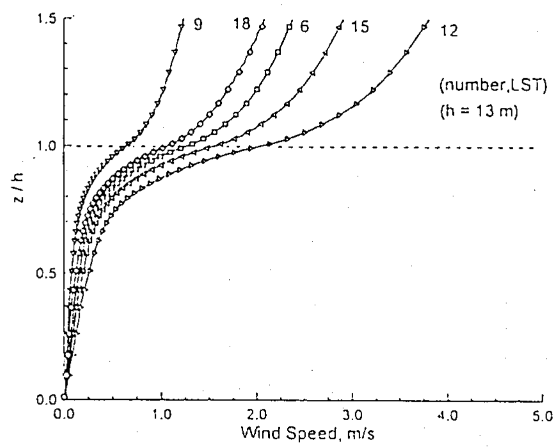

Figure 6: Computed wind velocity profile in the plant canopy (Sept. 1, 1997)

the excessive heating at the top of the plant canopy and the densely distributed leaves near the top of the canopy prevents the exchange of air inside and outside the plant canopy. The difference in air temperature inside and outside the plant canopy decreases with time and becomes almost diminished at 7p.m.

A satisfactory agreement between the computed air temperature and the observed air temperature in the plant canopy is observed.

Figure 4 depicts the comparison between the computed and observed time variation of foliage temperature at the heights of 12m (top of the plant canopy), 6m (mid-point of the plant canopy) and 1.5m (near the ground surface). The measurement of foliage temperature at a height was conducted at 8 points in 8 different directions around the observational tower and the values in all directions were averaged to get the observational values, plotted in the figure. Here, a difference in foliage temperatures at the top of the canopy and near the ground surface of up to 3°C at noon was observed. This difference is due to the diminished of solar radiation inside the plant canopy because of the presence of tree leaves. Again, a satisfactory agreement between the observed and computed foliage temperature was observed.

The agreement between computed and observed air and foliage temperature at points inside the plant canopy suggests that the proposed numerical model is capable of simulating the heating and evapo-transpiration processes in the plant canopy.

Figure 5 depicts the time variation of heat balance at the plant canopy. In the figure, *Solar* and *Rnet* denote the net downward solar and longwave radiation at the top the plant canopy, respectively. *H* and *LE* denote the total sensible heat and latent heat for the whole plant canopy. Since it was a fine day, the maximum net solar radiation at the top of the plant canopy reaches 700W/m^2. Due to a strong transpiration at the top of the plant canopy, with the maximum of total latent heat for the plant canopy reaching 450W/m^2, even with such large value of the solar radiation, the foliage temperature at the canopy top does not exceed the air temperature much. Inside the plant canopy, due to the diminish of the solar radiation, the foliage temperature is generally lower than the air temperature. Thus, for almost all day, the total sensible heat is transported from the air to the tree.

Figure 6 depicts the profiles of wind velocity inside the plant canopy. Near the top of the plant canopy, a sudden decrease of the wind velocity is observed. This variation of wind velocity has been well documented by other researchers (Watanabe and Kondo, 1990)

3. CONCLUSION

A one-dimensional model for the plant canopy climate has been developed. The model took into account all complex and up-to-date knowledge of plant physiology and dynamic processes in the soil, the plant canopy and the air. Verification of the model using field observational data reveals that the model is capable of simulating the heating and evapo-transpiration processes at the plant canopy.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Mr. Tadasi HIKE(Landowner of the field), Prof. J. KOBATAKE(Guma University), Assoc. Prof. A. KONDO(Chiba University), and many students for their contributions to the field observation.

REFRENCES

Asaeda T., and Vu T. C. (1993) Boundary-Layer Meteorol.65, 159-179.

Businger J.A., J.C. Wijngaard, Y.I. Izumi and E.F. Bradley (1971) J. Atmos. Sci.28, 181-189.

Goudriaan, J. (1977) Crop micrometeorology: a simulation study PUDOC, Wageningen

Jones H.G. (1992) Plants and Microclimate. Cambridge University Press, 323pp.

Kanda M. and M. Hino (1990) J. Japan Soc. Hyd. Water Resour. 3 37-46.

Kondo J. and T. Watanabe (1992) J. Atmos. Sci. 49, 2183-2199.

Herkelrath W.N., E.E. Miller and W.R. Gardner (1977) Soil. Sci. Am. J., 41, 1039-1043.

Molz F.J. (1981) Water Resour. Res. 17, 1245-1260.

Watanabe T. (1994) Boundary-Layer Meteorol. 66, 13-35.

Watanabe T. and J. Kondo (1990) J. Meteor. Soc. 227-235.