# An Approach for Calculating the Turbulent Transfer Coefficient Inside the Sparse Tall Vegetation

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**Abstract:** The sparse tall grass significantly affects the heat and moisture exchange in the lower atmosphere through the turbulent transfer coefficient inside its environment. Common approaches for calculation of turbulent transfer coefficient inside the tall grass environment are based on the assumption that it depends either on wind speed or mixing length inside the canopy. In this paper we suggested a new approach for calculating the turbulent transfer coefficient inside the sparse tall vegetation. In that sense we first derived an equation for the turbulent transfer coefficient inside the sparse tall grass using the "sandwich" approach for representation of vegetation, then we examined analytically whether its solution is always positive. Next, we solved the equation numerically using an iterative procedure for calculating the attenuation factor in the expression for the wind speed inside the canopy assumed to be a linear combination of an exponential and a logarithmic function. The proposed calculation of turbulent transfer coefficient is tested using the Land-Air Parameterization Scheme (LAPS). Model outputs of air temperature inside the canopy for 11-13 July 2002 are compared with micrometeorological measurements inside a sunflower field at the Rimski Sancevi experimental site (Serbia).

***Keywords**:* Turbulence inside the tall sparse vegetation; Turbulent transfer coefficient; Mixing length; Land surface schemes; Environmental modeling

## 1. INTRODUCTION

Many complex environmental features at small, medium, or large scales involve processes that occur both within and between environmental media (e.g., air, surface water, groundwater, soil, biota). Considerable recent research work addresses various aspects of modeling these processes using new methodologies/approaches, numerical methods, and software techniques (e.g., Walko et. al. 2000; Brandmeyer and Karimi 2001; Lalic et al. 2003; Mihailovic et al. 2001; and references herein). In environmental models, calculating turbulent fluxes inside and above a vegetation canopy requires the specification of air temperature, water vapor pressure, and turbulent transfer coefficients inside the canopy. The calculation of these quantities inside a tall grass canopy has been considered by many authors (e.g., Sellers and Dorman [1987]; Sellers et al. [1986]; Mihailovic et al. [1993]; Raupach et al. [1996]). Their work has remarkably improved the parameterization of turbulent fluxes inside tall grass canopies in land surface schemes. However, there is not yet a complete approach for modeling the turbulent fluxes inside tall grass canopies, particularly in the case of sparse tall grass canopies (i.e., those in which the plant spacing is of the order of the canopy height or larger, Wyngaard [1988]). Such an approach is needed because tall grass canopies, through key variables like friction velocity and internal air temperature, can significantly affect heat and moisture exchange in the lower atmosphere.

The objective of this paper is to suggest a new method for calculating the turbulent transfer coefficient inside tall grass canopies in land-atmosphere schemes for environmental modelling.

Section 2 includes derivation of (i) equation for wind profile inside the canopy in the “sandwich” approach (Section 2.1) and (ii) equation for turbulent transfer coefficient profile inside the sparse tall canopy (2.2). Section 3 is devoted to a numerical test. Section 3.1 includes description of numerical procedure for calculating the turbulent transfer coefficient inside the sparse vegetation; and (ii) numerical simulation of the air temperature inside a sunflower field for a three-day period, performed using a land surface scheme, and its comparison with observations (Sections 3.2 and 3.3). Section 3.4 summarizes results.

## 2. TURBULENT TRANSFER COEFFICIENT INSIDE THE TALL CANOPY

### 2.1 Derivation of Equation for Wind Profile Inside the Canopy in the “Sandwich” Approach

Let us consider an element of the canopy volume having an area $S$ and height $H$. The loss of air particles’ momentum due to close contact with the plant leaves comes from the drag force arising on the leaf surface. This drag force $F_d$ produces a shearing such that $d\tau / dz$, the vertical gradient of shear stress, $\tau$, is equal to the drag force per volume $V$, i.e.,

$$\frac{d\tau}{dz} = \frac{F_d}{V} \,. \tag{1}$$

The drag force per leaf unit area, $S_l$, is proportional to the wind speed, $u$, i.e., the volumetric kinetic energy $1/2\rho u^2$ with the coefficient of proportionality $C_d$, the leaf drag coefficient. So,

$$\frac{F_d}{S_l} = \frac{1}{2} C_d \rho u^2 \,, \tag{2}$$

where $\rho$ is the air density. Note that $S_l$ is the area of all leaves in the considered volume. Following the definition of leaf area index $(LAI)$, we can write $LAI = S_l/(2S)$, since it is defined in terms of only one side of the leaf ($S$ is the ground surface covered with plants). Using $\tau = \rho K_s du/dz$, Eqs. (1) and (2), and keeping in mind that the volume occupied by plants is $S(H-h)$, after some manipulation we arrive at

$$\frac{d}{dz}\left(K_s \frac{du}{dz}\right) = \frac{C_d \overline{L}_d (H-h)}{H} u^2 \,, \tag{3}$$

where $z$ is the vertical coordinate, $K_s$ the turbulent transfer coefficient inside the canopy, $\overline{L}_d$ the area- averaged stem and leaf area density, related to $LAI$ as $\overline{L}_d (H-h)$, while $h$ is the canopy bottom height [Sellers et al., 1986; Mihailovic and Kallos, 1997].

In a sparse tall grass canopy (one in which the plant spacing is of the order of the canopy height or larger), $K_s$ is strongly affected by processes in the environmental space, including the plants and the space above the bare soil fraction. Therefore, Eq. (3) can be slightly modified taking into account fractional vegetation cover, $\sigma_f$ (a measure of how sparse the tall grass is). The modified equation has the form

$$\frac{d}{dz}\left(K_s \frac{du}{dz}\right) = \sigma_f \frac{C_d \overline{L}_d (H-h)}{H} u^2 \,. \tag{4}$$

In the case of dense vegetation ($\sigma_f$ = 1), Eq. (4) reduces to Eq. (3). Otherwise, when $\sigma_f$ = 0, Eq. (4) represents the turbulent transfer coefficient over bare soil. We use Eq. (4) to derive the equation for turbulent transfer coefficient inside the sparse tall canopy.

### 2.2 Derivation of Equation for Turbulent Transfer Coefficient Profile Inside the Sparse Tall Canopy

A number of assumptions are offered about the variation of $K_s$ inside the canopy, as used in Eqs. (3) and (4). For example, according to Sellers et al. [1986] they are: (i) $K_s$ is proportional to the wind speed $u$, i.e, $K_s = \sigma u$ with the length scale, $\sigma$, as an arbitrary constant; the data of Legg and Long [1975] and of Denmead [1976] qualitatively support this relationship that is often exploited in environmental modeling, (ii) Jarvis [1976] found that assumption $K_s = K_s(H)$ is a representative one for the upper part of a coniferous canopy, and (iii) $K_s = l_m^2 du/dz$ where $l_m$ is a mixing length. Instead to keep the length scale, $\sigma$ constant, Lalic et al. [2003] assumed its dependence on z vertical coordinate, i.e., $\sigma = \sigma(z)$ that can be obtained from an ordinary differential equation. Inadequacy of these approaches lies in the fact that the behavior of $K_s$ must be given *a priori*, i.e. presupposed by experience.

In this paper we shall change the order of steps in calculation of the turbulent transfer coefficient inside the sparse vegetation, i.e. we shall solve Eq. (4) for $K_s$ after assuming a functional form of solution for wind speed over the sparse tall vegetation, containing an attenuating parameter $\beta$

that will be obtained iteratively. After taking the derivative of Eq. (4) over $z$, we obtain a differential equation of first order and first degree, where $K_s$ is an unknown function, i.e.,

$$\frac{du}{dz}\frac{dK_s}{dz}+\frac{d^2u}{d^2z}K_s=\sigma_f\frac{C_d\overline{L}_d(H-h)}{H}u^2 . \quad (5)$$

Solution of this equation can be found if the wind speed is used to be a linear combination of two terms, expressing behavior of the wind speed over dense and sparse vegetation. Thus,

$$u(z)=\sigma_f u(H)e^{-\frac{1}{2}\beta\left(1-\frac{z}{H}\right)}+(1-\sigma_f)\frac{u_*}{k}\ln\frac{z}{z_g} , \quad (6)$$

where $u(H)$ is the wind speed at the canopy height, $\beta$ is an unknown constant to be determined, $u_*$ the friction velocity, $k$ the von Karman constant supposed to be 0.41 and $z_g$ the roughness length over non-vegetated surface. The first term in the expression (6) is used because it fairly well approximates the wind profile within the dense tall grass canopy [Brunet et al., 1994; Mihailovic et al., 2004], while the second term simulates the shape of wind profile inside the tall sparse vegetation. After we introduce the expression (6) into Eq. (5), and rearrange it, we reach

$$\frac{dK_s}{dz}+a(z)K_s=b(z) , \quad (7)$$

where

$$a(z)=\frac{\frac{1}{4H^2}\beta^2\sigma_f u(H)e^{-\frac{1}{2}\beta\left(1-\frac{z}{H}\right)}-(1-\sigma_f)\frac{u_*}{k}\frac{1}{z^2}}{\frac{1}{2H}\beta\sigma_f u(H)e^{-\frac{1}{2}\beta\left(1-\frac{z}{H}\right)}+(1-\sigma_f)\frac{u_*}{k}\frac{1}{z}} \quad (8)$$

and

$$b(z)=\left[\sigma_f u(H)e^{-\frac{1}{2}\beta\left(1-\frac{z}{H}\right)}+(1-\sigma_f)\frac{u_*}{k}\ln\frac{z}{z_g}\right]^2\times\frac{\sigma_f\frac{C_d\overline{L_d}(H-h)}{H}}{\frac{1}{2H}\beta\sigma_f u(H)e^{-\frac{1}{2}\beta\left(1-\frac{z}{H}\right)}+(1-\sigma_f)\frac{u_*}{k}\frac{1}{z}} . \quad (9)$$

Let us analyze the nature of the solution, $K_s$, of the Eq. (6) with the initial condition defined as $K_s(z_0)=K_s^0>0$, where $z_0$ is some certain height inside the canopy: (i) The solution is unique and defined over the interval $[z_0,\infty)$, that follows from the fact that the functions $a(z)$ and $b(z)$ are defined and continuous over the interval indicated; (ii) The solution is positive, that comes from the analysis of the field of directions of the given equation or more precisely due to $b(z)>0$; (iii) The solution is stable that can be seen from the following analysis. When $z\to\infty$ we have $a(z)\approx\beta/(2H)$ and $b(z)\approx B\exp[\beta z/(2H)]$. Now, Eq. (7) takes the form

$$\frac{dK_s}{dz}+\frac{\beta}{2H}K_s=Be^{\frac{\beta z}{2H}} , \quad (10)$$

where

$$B=\frac{2\sigma_f^2u^2(H)C_d\overline{L}_d(H-h)}{\beta H} . \quad (11)$$

The particular solution of this equation has the form $A\exp[\beta z/(2H)]$, where $A$ is a constant, that can be obtained after replacing the particular solution in Eq. (10). If we follow this procedure we get $A=BH/\beta$. So, in this case, i.e., $z\to\infty$, the solution of Eq. (7) is asymptotically stable, it behaves as $A\exp[\beta z/(2H)]$ for any given $A$.

## 3. NUMERICAL EXPERIMENTS

To examine how successfully the foregoing proposed method for calculation of the turbulent transfer coefficient parameters support simulation of the air temperature within a tall grass canopy, a test was performed using the LAPS land surface scheme described in Mihailovic [1996]. LAPS outputs of air temperatures inside the canopy for three days (11-13 July 2002) were compared with single-point micrometeorological measurements over a sunflower field at the Rimski Sancevi experimental site in Serbia. In the numerical experiments we used a data set from a measurement program that examined the exchange processes of heat, mass, and momentum just above and inside a sunflower canopy during its growing season.

### 3.1 Numerical Procedure

For the fixed $\beta$ Eq. (7) can be solved using the finite-difference scheme

$$K_s^{n-1}=K_s^n-\Delta z\left\{b^n(z)-a^n(z)K_s^n\right\}, \quad (12)$$

where $n$ is the number of the spatial step in the numerical calculating on the interval $[H,h]$, while $\Delta z$ is the grid size defined as $\Delta z=(H-h)/N$ where $N$ is a number indicating an upper limit in number of grid sizes used. The turbulent transfer coefficient calculation starts from the canopy top with an initial condition defined as

$$K_s^N(H)=k^2\sigma_f(H-d)\frac{u(H)}{\ln\frac{H-d}{z_g}}+k(1-\sigma_f)u_*H \quad (13)$$

then goes backward up to the canopy bottom height, $h$, that is defined according to Mihailovic et al. [2004]. To obtain parameter $\beta$ we use an iterative procedure for this parameter that is not finished until the condition

$$\left|\sum_{i=1}^{N} u_i^{k+1} - \sum_{i=1}^{N} u_i^{k}\right| < \mu \qquad (14)$$

is reached, where $k$ is number of iteration while $\mu$ is less then 0.001. Having this parameter we can calculate the wind profile on the interval $[H,h]$ according to the expression (6). Beneath the canopy bottom height, the wind profile has the logarithmic shape [Sellers et al., 1986; Mihailovic et al., 2004], i.e.,

$$u(z) = u(H)\left[\frac{\sigma_f e^{-\frac{1}{2}\beta\left(1-\frac{h}{H}\right)}}{\ln\frac{h}{z_g}} + \frac{1-\sigma_f}{\ln\frac{H}{z_g}}\right]\ln\frac{z}{z_g} . \qquad (15)$$

## 3.2 Calculating the Air Temperature Inside the Sunflower Canopy

The temperature inside the sunflower air space, $T_a$, was determined diagnostically from the energy balance equation. This procedure comes from the equality of the sensible heat flux from the canopy to some reference level in the atmosphere, and the sum of the sensible heat fluxes from the ground and from the leaves to the canopy air volume [Sellers et al., 1986; Mihailovic, 1996], i.e.,

$$T_a = \frac{\frac{2T_f}{r_b} + \frac{T_g}{r_d} + \frac{T_r}{r_a}}{\frac{2}{r_b} + \frac{1}{r_d} + \frac{1}{r_a}} , \qquad (16)$$

where $T_f$ is the foliage temperature, $T_g$ the ground surface temperature, $T_r$ the temperature at reference level, $r_b$ the bulk boundary-layer aerodynamic resistance, $r_d$ the aerodynamic resistance to water vapor and heat flow from the soil surface to air space inside the canopy, and $r_a$ the aerodynamic resistance representing the transfer of heat and moisture from the canopy to the reference level, $z_r$.

The aerodynamic resistance $r_a$ between $z_r$ and $h_a$, the water vapor and sensible heat source height [Sellers et al., 1986], can be defined as

$$r_a = \int_{h_a}^{H} \frac{1}{K_s} dz + \int_{H}^{z_r} \frac{1}{K_s} dz . \qquad (17)$$

The aerodynamic resistance in canopy air space, $r_d$, can be written in the form

$$r_d = \int_{z_g}^{h} \frac{1}{K_s} dz + \int_{h}^{h_a} \frac{1}{K_s} dz , \qquad (18)$$

while the area-averaged bulk boundary layer resistance, $\overline{r_b}$, has the form [Sellers et al., 1986]

$$\frac{1}{\overline{r}_b} = \int_{h_a}^{H} \frac{\overline{L}_d \sqrt{u(z)}}{C_s P_s} dz , \qquad (19)$$

where $C_s$ is the transfer coefficient [Sellers et al., 1986] and $P_s$ the leaf shelter factor. The values for these parameters were taken from Mihailovic and Kallos [1997]. Eqs. (17)-(19) can be modified to take into account the effects of nonneutrality. According to Sellers et al. [1986], the position of the canopy source height, $h_a$, can be estimated by obtaining the center of gravity of the $1/\overline{r}_b$ integral.

## 3.3 Experimental Site and Details

The experimental site (270 m x 68 m) is located in the northern part of Serbia (45.3°N, 19.8°E) on a chernozem soil of the loess terrace of southern Backa with the following physical and water properties: Clapp-Hornberger constant “B”: 6.50; ground emissivity: 0.97; heat capacity of the soil fraction: 780 J kg$^{-1}$°C$^{-1}$; saturated hydraulic conductivity: 32x10$^{-6}$ m s$^{-1}$; soil moisture potential at saturation: -0.036 m; soil density: 1290 kg m$^{-3}$; ratio of saturated thermal conductivity to that of loam: 1.0; volumetric soil moisture content at saturation: 0.52 m$^3$ m$^{-3}$; volumetric soil moisture content at field capacity: 0.36 m$^3$ m$^{-3}$; wilting point volumetric soil moisture content: 0.17 m$^3$ m$^{-3}$; and effective ground roughness length: 0.01 m. The experimental site was surrounded by other agricultural fields also sown with sunflowers. The sunflower rows were oriented north to south, with row spacing of 0.70 m. This data set was chosen because it was considered typical and representative of a fully developed sunflower crop. For the 11-13 July period the mean estimated $LAI$ was 3.0 m$^2$ m$^{-2}$; the crop height, $H$, was around 1.99 m; and the canopy bottom height, $h$, was 0.100 m. The extinction factor, $\beta$, was calculated using a numerical procedure that is described in the previous subsection. While the zero plane displacement, $d$, and roughness length, $z_0$, were calculated according to Mihailovic and Kallos [1997]. The scaling length, $\sigma$, was derived following Mihailovic et al. [2004]. In these calculations the area-averaged stem and leaf area density, $\overline{L}_d$, had a value of 1.59 m$^2$ m$^{-3}$, while a value of 0.2 was used for the leaf drag coefficient, $C_d$. Since the minimum stomatal resistance was not measured, we assumed it to be 40 s m$^{-1}$. The fractional vegetation cover was 0.90. Other parameters used in the simulation can be found in Mihailovic et al. [2000]. Canopy source height, $h_a$, was calculated following Mihailovic et al.

[2004]. Using the above parameter values, we obtained a value of 1.1 m.

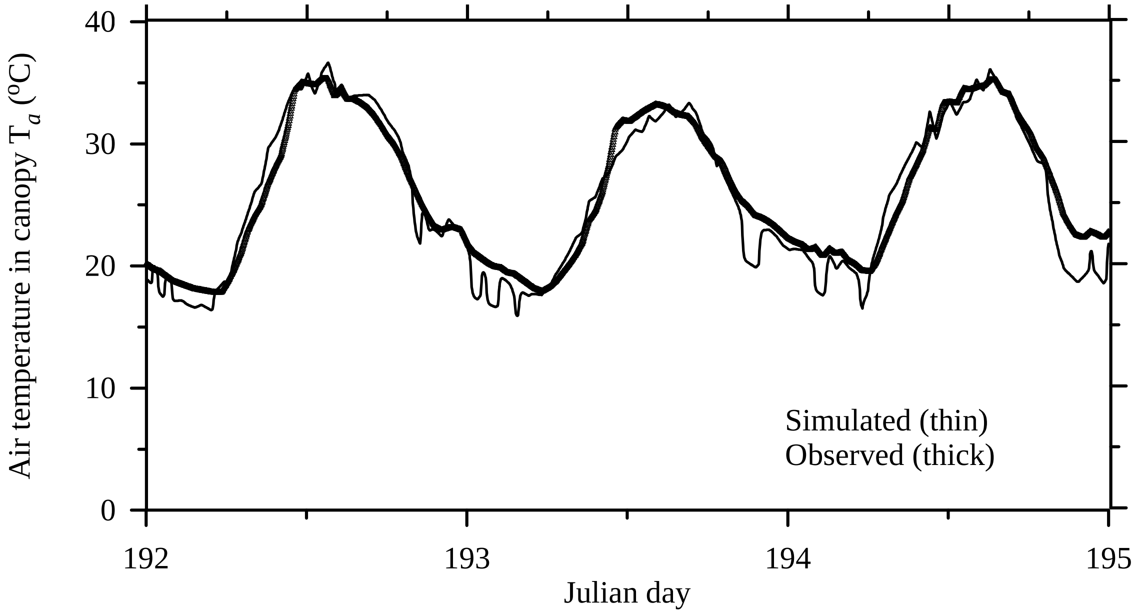


**Figure 1.** The comparison of three-day variation (11-13 July 2002) of the air temperature simulated by LAPS and observed inside a sunflower canopy at the Rimski Sancevi site.

Temperatures were measured using platinum resistance thermometers (Pt-100) set at 0.95 and 2.1 m above the ground. The wind speed at the reference level of $z_r$ = 2.1 m was measured using a Vector Instruments anemometer. A Kipp Zonen CM5 solarimeter was used to measure incoming solar radiation, while relative humidity was recorded using a Greisinger sensor set at 2.1 m. Precipitation was measured by an electronic rain gauge manufactured at the Institute of Physics in Belgrade. Soil temperature was measured at 0.05-, 0.1-, and 0.2-m depths. In all data sets, the atmospheric boundary conditions at $z_r$ = 2.1 m were derived from measurements of global radiation, precipitation, relative humidity, and wind for 24 hours from 0000 LST at 30-min intervals. The longwave atmospheric counter--radiation was calculated via an empirical formula described in Mihailovic et al. [1995], including a correction for the amount of cloudiness. Cloudiness data were taken at 30-min intervals from the nearest standard meteorological station, Rimski Sancevi, which is 500 m away from the experimental site. These values were interpolated to the beginning of each time step ($\Delta t$ = 120 s). The thicknesses of soil layers were defined as $D_1$ = 0-0.1 m, $D_2$ = 0.1-0.5 m, and $D_3$ = 0.5-1 m. The initial conditions for the volumetric soil moisture contents corresponding to these layers were $w_1$ = 0.1552 $m^3\ m^{-3}$, $w_2$ = 0.1484 $m^3\ m^{-3}$, and $w_3$ = 0.1348 $m^3\ m^{-3}$. At the initial time the ground temperature was 292.68 K. The initial condition for atmospheric pressure was 100.53 kPa.

### 3.4 Comments and Further Plans

The validity of the LAPS-simulated air temperature inside the canopy was tested against the observations recorded by the platinum resistance thermometer located at 0.95 m at 30-min intervals during 11-13 July 2002. Figure 1 shows the calculated and observed diurnal variations of air temperature inside the sunflower canopy at the experimental site. After midnight, the simulated values are lower than the observations, while in the early afternoon the simulated values are slightly higher than the observed ones. This situation occurs because at night LAPS simulates less heat transfer from the ground into the canopy air space than the observations indicate. In contrast, during the afternoon, the scheme calculates a lower amount of evapotranspiration, which for some days results in a higher leaf temperature and consequently a higher air temperature inside the sunflower canopy [Eq. (17)]. Apparently, the calculation of air temperature inside the tall grass canopy strongly depends on the resistances given by Eqs. (17)-(19), i.e., on the resistances' sensitivity to morphological and aerodynamic parameters, which can be sources of uncertainty in their calculation. In the future we plan to check the proposed method using more specific tests including three-dimensional simulations.

**Acknowledgments**

This research was supported by the New York State Energy Research and Development Authority under contractual agreement NYSERDA 4914-ERTER-ES-99. The research was also supported by the Serbian Ministry for Science and Technology under contracts BTR.S.02.0401.B and BTR.S.02.0427.B. The investigators would like to thank Dr. S.T. Rao for his support.

**REFERENCES**

Brandmeyer, J., and H.A. Karimi, Coupling methodologies for environmental models, *Environ. Modeling & Software*, *15*(5), 479-488, 2001.

Brunet, Y., J.J. Finnigan, and M.R. Raupach, A wind tunnel study of air flow in waving wheat: Single-point velocity statistics, *Boundary-Layer Meteorol*., *70*, 95-132, 1994.

Denmead, O.T., *Temperate cereals*. In: Vegetation and the atmosphere- 2nd., J. L. Monteith (Ed.), Academic Press, pp. 1-31, New York, 1976.

Jarvis, P.G., The interpretation of leaf water potential and stomatal conductance found in canopies in the field, *Phil. Trans. R. Soc. London*, Ser. B, *273*, 593-610, 1976.

Lalic, B., D.T Mihailovic, B. Rajkovic, I.D. Arsenic, and D. Radlovic, Wind profile within the forest canopy and in the transition layer above it, *Environ. Modeling & Software*, 18, 947-950, 2003.

Legg, B. J., and I. F. Long, Turbulent diffusion within a wheat canopy II, *Quart. J. Roy. Meteor. Soc.*, *101*, 611-628, 1975.

Mihailovic, D.T., Description of a land-air parameterization scheme (LAPS), *Global Planet. Change*, 13, 207-215, 1996.

Mihailovic, D.T., and G. Kallos, A sensitivity study of a coupled soil-vegetation boundary layer scheme for use in atmospheric modeling, *Boundary-Layer Meteorol.*, *82*, 283-315, 1997.

Mihailovic, D.T., B. Rajkovic, B. Lalic, and LJ. Dekic, Schemes for parameterizing evaporation from a non-plant-covered surface and their impact in on partitioning the surface energy in land-air exchange parameterization, *J. Appl. Meteor*., 34, 2462-2475, 1995.

Mihailovic, D.T., R.A. Pielke, B. Rajkovic, T.J. Lee, and M. Jeftic, A resistance representation of schemes for evaporation from bare and partly plant-covered surfaces for use in atmospheric models, *J. Appl. Meteor*., *32*, 1038-1054, 1993.

Mihailovic, D.T, I. Koci, B. Lalic, I. Arsenic, D. Radlovic, and J. Balaz, The main features of BAHUS-biometeorological system for messages on the occurrence of diseases in fruits and vines, *Environ. Modeling & Software*, *16*(8), 691-696, 2001.

Mihailovic, D.T., K. Alapaty, B. Lalic, I. Arsenic, B**.** Rajkovic, and S. Malinovic, Turbulent transfer coefficients and calculation of air temperature inside tall grass canopies in land-atmosphere schemes for environmental modelling, *J. Appl. Meteor.*, 2004. (In revision)

Mihailovic, D.T., T.J. Lee, R.A., Pielke, B. Lalic, I. Arsenic, B. Rajkovic, and P.L Vidale, Comparison of different boundary layer schemes using single point micro-meteorological field data, *Theor. Appl. Climatol.*, 67, 135-151, 2000.

Raupach, M.R., J.J. Finnigan, and Y. Brunet, Coherent edies and turbulence in vegetation canopies: The mixing-layer analogy, *Boundary-Layer Meteorol.*, *78*, 351-382, 1996.

Sellers, P.J., and J.L Dorman, Testing the simple biosphere model (SiB) using point micrometeorological and biophysical data, *J. Clim. Appl. Meteorol*., 26, 622-651, 1987.

Sellers, P. J., Y. Mintz, Y. Sud, A. Dalcher, A simple biosphere model (SiB) for use within general circulation model, *J. Atmos. Sci.*, *43*, 506-531, 1986.

Walko, R. L., and Coauthors, Coupled atmosphere-biophysics-hydrology models for environmental modeling, *J. Appl. Meteor.*, *39*, 931-944, 2000.

Wyngaard, J.C., *Convective processes in the lower atmosphere*, In: Flow and transport in the natural environment: Advances and applications, W.L. Steffen and O.T. Denmead (Eds.), Springer, Berlin, 240-260, 1988.