An Approach for Calculation of Turbulent Transfer Coefficient for Momentum inside Vegetation Canopies

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(Manuscript received 9 November 2004, in final form 15 June 2005)

ABSTRACT

A method for calculating the profile of turbulent transfer coefficient for momentum inside a vegetation canopy for use in land surface schemes is presented. It is done through the following steps. First, an equation for the turbulent transfer coefficient for momentum inside a vegetation canopy using the "sandwich" approach for its representation is derived. Second, it is examined analytically to determine whether its solution is always positive. Third, the equation for the turbulent transfer coefficient is solved numerically, using an iterative procedure for calculating the attenuation factor in the expression for the wind speed inside a vegetation canopy that is assumed to be a linear combination of an exponential function and a logarithmic function. The proposed method is tested using 1) the observations for the wind profiles in a Japanese larch plantation and a pine forest and 2) the outputs for surface fluxes and total soil water content obtained by the Land–Air Parameterization Scheme (LAPS) with the forcing data and observations in a soybean field at the Caumont site in France during the 1986 growing season. Also, a test is performed that compares the proposed method with the method for calculating the turbulent transfer coefficients for momentum inside a vegetation canopy commonly used in land surface schemes.

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1. Introduction

Considerable recent research addresses various aspects of modeling many complex land–atmosphere processes at small, medium, or large scales, using new methodologies and approaches, numerical methods, and software techniques (Walko et al. 2000; Xiu and Pleim 2001; Mihailovic et al. 2004). In many of these models, calculating the turbulent fluxes inside and above a vegetation canopy requires the specification of turbulent transfer coefficients for momentum, heat, and water vapor inside the canopy. In the last two decades their parameterization has been considered by many authors (Sellers et al. 1986; Munley 1991; Brutsaert and Sugita 1996; Lalic et al. 2003; Mihailovic et al. 2004, among others). These works have remarkably improved the parameterization of energy, mass, and momentum exchange inside different plant communities in land surface schemes, making them more relevant for a broad range of practical and scientific activities in environmental and closely related sciences like biophysical parameterization of vegetation in atmospheric, ecological, and agricultural models of all scales (Lalic and Mihailovic 2004; Pingtong and Hidenori 2000; Pinard and Wilson 2001). Many current vegetation–atmosphere, and environmental models, however, require a more reliable approach for modeling turbulent fluxes inside vegetation canopies, particularly in the case of sparse vegetation canopies [i.e., those in which the plant spacing is on the order of the canopy height or larger (Wyngaard 1988; Kondo and Watanabe 1992)]. For instance, suppose that a certain land surface scheme that is used to calculate the energy balance of a sparsely vegetated surface under conditions of strong radiation then describes an erroneously small transport of water within the soil. Under the specified conditions, the bare soil surface will soon dry out, which shows up as a strong increase of the soil surface temperature, which affects net radiation and reduces the aerodynamic resistances owing to the stability correction, which perhaps enhances the evaporation from the canopy component, which will lead to an increase of the atmospheric humidity, and so on, as conjectured by van den Hurk (1996).

In this note, we suggest a method for calculating the turbulent transfer coefficient for momentum inside a vegetation canopy in land–atmosphere schemes for numerical modeling. Section 2 describes the method proposed, including its numerical aspects. Section 3 summarizes all results of the numerical tests.

2. Calculation of turbulent transfer coefficient for momentum inside vegetation canopies

For the canopy, consider a block of constant-density porous material placed between two heights h_c (the canopy height) and h (the canopy bottom height) (Sellers et al. 1986; Mihailovic and Kallos 1997). The differential equation describing the wind profile within such canopy architecture can be written in the form (Mihailovic et al. 2004)

$$\frac{d}{dz}\left(K_m\frac{du}{dz}\right) = \sigma_f\frac{C_d\overline{L}_d(h_c-h)}{h_c}u^2, \tag{1}$$

where the fractional vegetation cover σ_f (a measure of how sparse the vegetation canopy is) is considered. In this equation, z is the vertical coordinate, K_m is the turbulent transfer coefficient for momentum inside the canopy, u is the wind speed inside the canopy, C_d is the leaf drag coefficient, and $\overline{L}_d$ is the area-averaged stem and leaf area density (also called canopy density), which is related to leaf area index (LAI) as LAI $= \overline{L}_d(h_c - h)$. In the case of dense vegetation ($\sigma_f = 1$), Eq. (1) reduces to the well-known equation for dense vegetation (Mihailovic et al. 2004). Otherwise, when $\sigma_f = 0$, Eq. (1) leads, by a proper choice of integration constant, to the wind profile over bare soil. We can use Eq. (1) for calculating the wind speed inside a vegetation canopy after we have assumed a functional form of K_m as is usually done. The inadequacy of this approach, however, is in the fact that the behavior of K_m must be given a priori; that is, it must be presupposed by experience.

Here we propose changing the order of the steps in the calculation of the turbulent transfer coefficient for momentum inside the vegetation. We shall solve Eq. (1) for K_m after assuming a functional form of solution for wind speed inside the vegetation canopy, containing an attenuating parameter α that will be obtained iteratively. After taking the derivative of Eq. (1) over z, we obtain a differential equation of the first order and first degree, where K_m is an unknown function; that is,

$$\frac{du}{dz}\frac{dK_m}{dz} + \frac{d^2u}{dz^2}K_m = \sigma_f\frac{C_d\overline{L}_d(h_c-h)}{h_c}u^2. \tag{2}$$

Solution of this equation can be found if the wind speed is expressed as a linear combination of two terms that express the behavior of the wind speed over dense and sparse vegetation. Thus,

$$u(z) = \sigma_f u(h_c)\exp\left[-\frac{1}{2}\alpha\left(1-\frac{z}{h_c}\right)\right] + (1-\sigma_f)\frac{u_*}{k}\left[\ln\frac{z}{z_b} - \psi_m(z/L)\right], \tag{3}$$

where α is an unknown constant to be determined, $u(h_c)$ is the wind speed at the canopy height, u_* is the friction velocity, k is the von Kármán constant, z_b is the roughness length over the nonvegetated surface, $\psi_m(z/$

L) is the stability function, and L is Monin–Obukhov length (Paulson 1970). The function $\psi_m(z/L)$ is given for stable conditions ($z/L > 0$) by $\psi_m(z/L) = 4.7z/L$ and is given for unstable conditions ($z/L < 0$) by

$$\psi_m(z/L) = -2\ln\left[\frac{(1+x)}{2}\right] - \ln\left[\frac{(1+x^2)}{2}\right] + 2\tan^{-1}(x) - \frac{\pi}{2}, \tag{3a}$$

where $x = [1 - (15z/L)]^{1/4}$. The first term in Eq. (3) is used to approximate the wind profile inside the vegetation canopy (Brunet et al. 1994; Mihailovic et al. 2004), and the second term simulates the shape of the wind profile above bare soil. After we introduce Eq. (3) into Eq. (2) and rearrange, we reach

$$\frac{dK_m}{dz} + a(z)K_m = b(z), \tag{4}$$

where

$$a(z) = \frac{\dfrac{1}{4h_c^2}\alpha^2\sigma_f u(h_c)\exp\left[-\dfrac{1}{2}\alpha\left(1-\dfrac{z}{h_c}\right)\right] + (1-\sigma_f)\dfrac{u_*}{k}\left[-\dfrac{1}{z^2} + \psi''_m(z/L)\right]}{\dfrac{1}{2h_c}\alpha\sigma_f u(h_c)\exp\left[-\dfrac{1}{2}\alpha\left(1-\dfrac{z}{h_c}\right)\right] + (1-\sigma_f)\dfrac{u_*}{k}\left[\dfrac{1}{z} + \psi'_m(z/L)\right]} \tag{5}$$

and

$$b(z) = \left\{\sigma_f u(h_c)\exp\left[-\frac{1}{2}\alpha\left(1-\frac{z}{h_c}\right)\right] + (1-\sigma_f)\frac{u_*}{k}\left[\ln\frac{z}{z_b} + \psi_m(z/L)\right]\right\}^2 \times \frac{\sigma_f\dfrac{C_d\overline{L}_d(h_c-h)}{h_c}}{\dfrac{1}{2h_c}\alpha\sigma_f u(h_c)\exp\left[-\dfrac{1}{2}\alpha\left(1-\dfrac{z}{h_c}\right)\right] + (1-\sigma_f)\dfrac{u_*}{k}\left[\dfrac{1}{z} + \psi'_m(z/L)\right]}, \tag{6}$$

with $\psi'_m(z/L) = d\psi_m(z/L)/dz$ and $\psi''_m(z/L) = d^2\psi_m(z/L)/dz^2$.

Let us analyze the nature of the solution K_m of Eq. (4) with the initial condition defined as $K_m(z_I) = K_m^0 > 0$, where z_I is some certain height inside the canopy: 1) the solution is unique and is defined over the interval $[z_I, \infty)$, which follows from the fact that the functions $a(z)$ and $b(z)$ are defined and are continuous over the interval indicated, 2) the solution is positive, which comes from the analysis of the field of directions of the given equation or more precisely because $b(z) > 0$, and 3) the solution is stable, which can be seen from the following analysis. When $z \to \infty$ we have $a(z) \approx \alpha/(2h_c)$ and $b(z) \approx B\exp[\alpha z/(2h_c)]$. Now, Eq. (4) takes the form

$$\frac{dK_m}{dz} + \frac{\alpha}{2h_c}K_m = B\exp\left(\frac{\alpha z}{2h_c}\right), \tag{7}$$

where

$$B = \frac{2\sigma_f^2 u^2(h_c)C_d\overline{L}_d(h_c-h)}{\alpha h_c}. \tag{8}$$

The particular solution of this equation has the form $A\exp[\alpha z/(2h_c)]$, where A is a constant, that can be obtained after replacing the particular solution in Eq. (7). If we follow this procedure we get $A = Bh_c/\alpha$. So, in this case ($z \to \infty$), the solution of Eq. (4) is asymptotically stable; it behaves as $A\exp[\alpha z/(2h_c)]$ for any given A.

For the fixed α, Eq. (4) can be solved using the finite-difference scheme

$$K_m^{n-1} = K_m^n - \Delta z[b^n(z) - a^n(z)K_m^n], \tag{9}$$

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

$$K_s^N(h_c) = k^2u(h_c)\left[\frac{\sigma_f(h_c-d)}{\ln\left(\dfrac{h_c-d}{z_0}\right)} + \frac{(1-\sigma_f)h_c}{\ln\left(\dfrac{h_c}{z_b}\right)}\right], \tag{10}$$

where d is the displacement height and z_0 is the canopy roughness length calculated according to Mihailovic et al. (1999). The procedure then goes backward down to the canopy bottom height h that is defined according to Mihailovic et al. (2004). To obtain parameter α we use an iterative procedure that is not finished until the condition

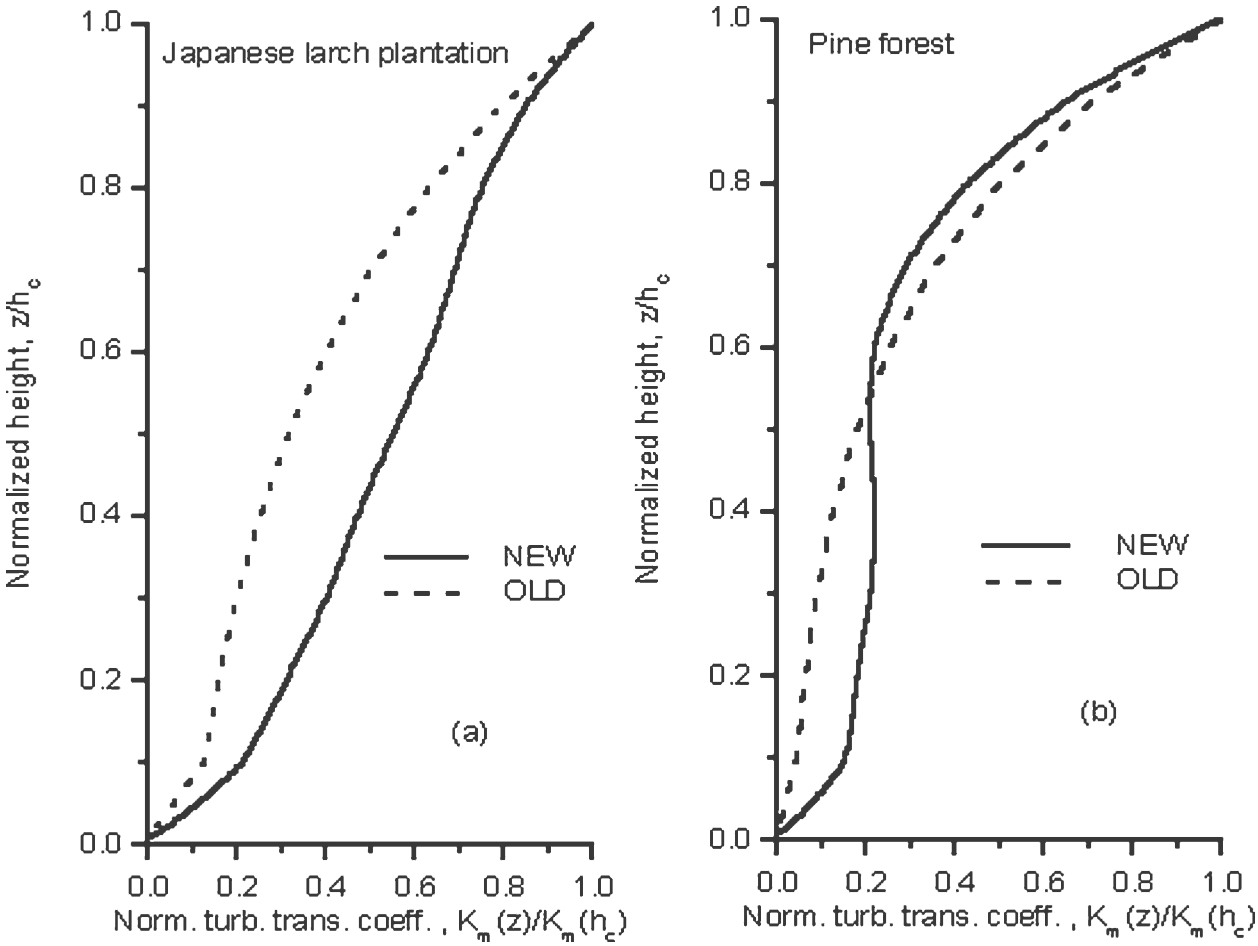

FIG. 1. Profiles of K_m inside (a) a Japanese larch plantation and (b) a pine forest.

$$\left|\sum_{i=1}^{N} u_i^{m+1} - \sum_{i=1}^{N} u_i^{m}\right| < \mu \tag{11}$$

is reached, where m is the number of the iteration while μ is less then 0.001. Having this parameter, we can calculate the wind profile on the interval $[h_c, h]$ according to Eq. (2). Beneath the canopy bottom height, the wind profile has the logarithmic shape (Sellers et al. 1986; Mihailovic et al. 2004); that is,

$$u(z) = u(h_c)\left\{\frac{\sigma_f \exp\left[-\frac{1}{2}\alpha\left(1-\frac{h}{h_c}\right)\right]}{\ln\frac{h}{z_b}} + \frac{1-\sigma_f}{\ln\frac{h_c}{z_b}}\right\}\ln\frac{z}{z_b}. \tag{12}$$

3. Evaluation of proposed method and comments

This section is devoted to tests for comparison between the proposed method (hereinafter called the new method) and the conventional method (hereinafter called the old method) for calculating the profile of turbulent transfer coefficient for momentum K_m inside a vegetation canopy. The methods are compared and assessed using 1) the wind speed data measured in a Japanese larch plantation (JLP) and pine forest (PF) and 2) simulation of the surface fluxes and total soil water content (TWC) in a soybean field performed by running the land surface Land–Air Parameterization Scheme (LAPS). In the old method the proportionality between K_m and the wind speed u inside the canopy is assumed as in the commonly used approach (see, e.g., Legg and Long 1975; Denmead 1976; Sellers et al. 1986); that is,

$$K_m = \sigma u, \tag{13}$$

where the scaling length σ is an arbitrary, unknown constant. Combining Eqs. (1) (for $\sigma_f = 1$) and (13) produces an equation for the wind speed inside the canopy:

$$\frac{d^2u}{dz^2} = \frac{2C_d\overline{L}_d(h_c - h)}{\sigma h_c}u^2. \tag{14}$$

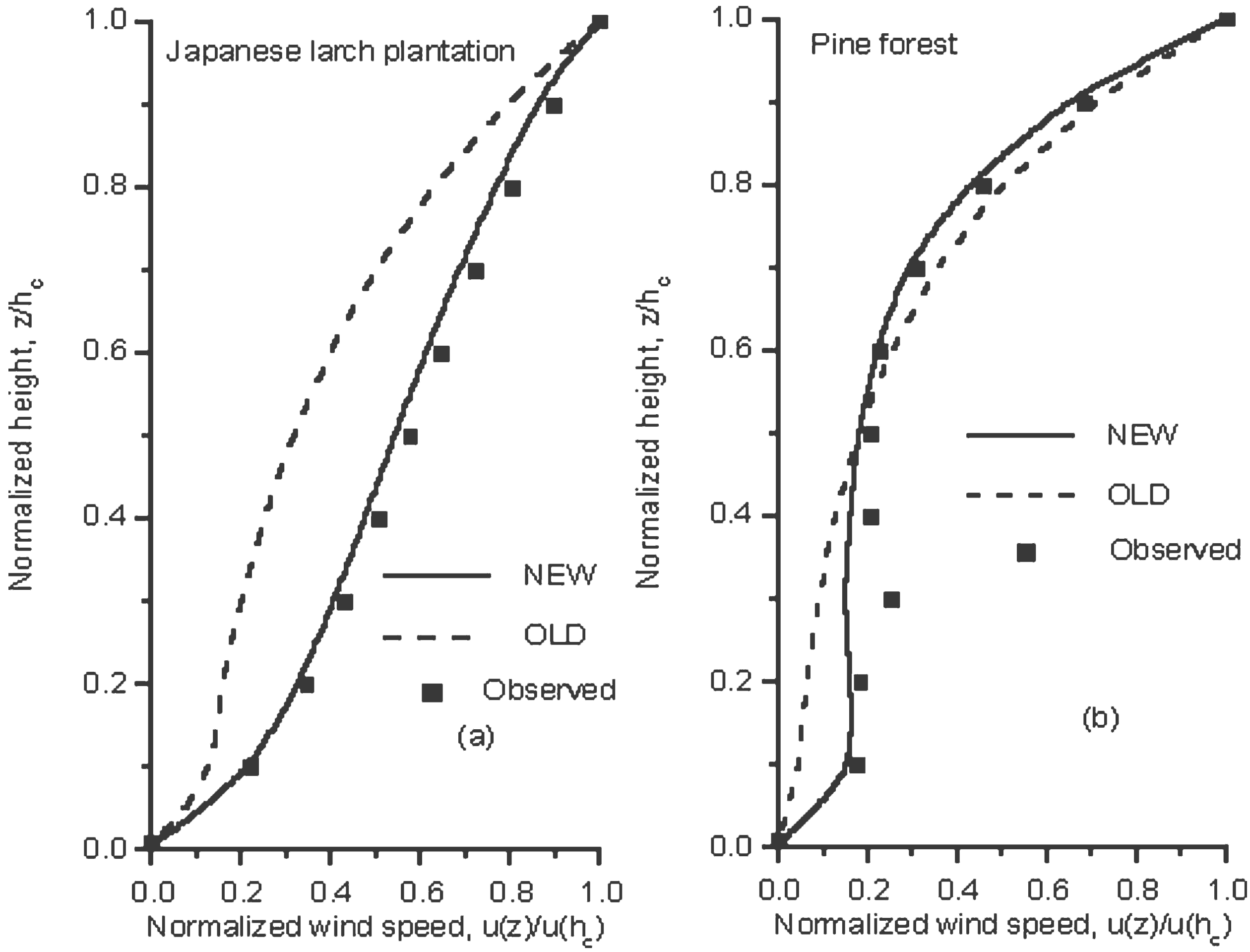

FIG. 2. Profiles of wind speed inside (a) a Japanese larch plantation and (b) a pine forest. The black squares are observations from Allen (1968) and Oliver (1971), respectively.

A particular solution of this equation can be found in a form that approximates the wind profile within the tall grass canopy fairly well (Brunet et al. 1994):

$$u(z) = u(h_c) \exp\left[-\frac{1}{2}\beta\left(1 - \frac{z}{h_c}\right)\right], \tag{15}$$

where β is the extinction parameter, defined as

$$\beta^2 = \frac{2C_d\overline{L}_d(h_c - h)h_c}{\sigma}. \tag{16}$$

According to Mihailovic et al. (2004), the value of the scaling length σ is defined as

$$\sigma = \frac{2C_{dg}^2 h_c}{C_d\overline{L}_d(h_c - h)}, \tag{17}$$

where C_{dg} is the leaf drag coefficient estimated from the size of the roughness elements of the ground (Sellers et al. 1986; Mihailovic et al. 2004).

To illustrate how well the values calculated by the new and old methods agree with observations, we compared profiles of wind speed with values observed inside a Japanese larch plantation and a pine forest that were taken from Allen (1968) and Oliver (1971), respectively. In these papers can be found more details about the used wind speed measuring technique, sampling and averaging periods, and other experimental details. The observations of plant height h_c, LAI, friction velocity u_*, and estimated leaf drag coefficient C_d can be also found in these papers and in Dubov et al. (1978), and the canopy bottom height h and leaf drag coefficient C_{dg} were estimated following Mihailovic et al. (2004). The parameters β and σ were calculated using Eqs. (17) and (16). Figure 1 depicts the calculated curves of K_m as a function of the normalized height z/h_c for the Japanese larch plantation (Fig. 1a) and pine forest (Fig. 1b), using the old and new methods. The curve of the turbulent transfer coefficient for momentum K_m within the Japanese larch plantation obtained by the old method approaches zero faster than does the curve calculated by the new method. Within the upper part of the pine forest (Fig. 1b), the curves of K_m closely follow each other. However, in the lower part of the canopy the curve calculated by the old method tends to zero faster than does the K_m profile obtained by the new method. Figures 2a and 2b compare the calculated and observed wind speed values inside the Japanese larch plantation and pine forest. For both plant communities the shape of the calculated wind speed profile curves is closer to observations when the new method is applied.

To examine how successfully the foregoing proposed method for calculating the turbulent transfer coefficient K_m inside a vegetation canopy supports the calculating of heat and water fluxes above the canopy, a simulation of 1) the surface fluxes over a soybean field and 2) TWC under a soybean field was performed. In the simulation we used the LAPS. This land surface scheme is designed as a software package that can be run as a part of an atmospheric model or as a stand-alone model. The processes parameterized in LAPS are divided into three parts that fully describe subsurface thermal and hydraulic processes, bare-soil transfer processes, and canopy transfer processes. The version of LAPS used for these experiments has been comprehensively described in Mihailovic et al. (1995, 1998, 2004), Mihailovic and Kallos (1997), and Pielke (2002). The model has seven prognostic variables: three temperatures (canopy, ground, and deep soil), interception store for canopy, and three soil water contents. In the hydrological module the direct loss of liquid water across the scheme domain boundaries is considered as separate processes that can be summarized as follows: overland flow (when a precipitation excess is over infiltration capacity or when the surface becomes saturated), subsurface runoff (horizontal drainage from unsaturated flow), and a vertical drainage through the lower scheme boundary. Moving from top to bottom of the soil water column, there are three layers in which the vertical water flow is considered according to Darcy's law.

Model outputs of 1) surface fluxes [latent heat flux (LHF) and sensible heat flux (SHF)] over the canopy for day of year (DOY) 150–155 and 2) the TWC under the canopy for DOY 120–273 during 1986, for both the new and old methods, were compared with measurements in a soybean field at Coumont, France, where plants start to grow in May and are harvested at the end of September. The dataset used includes a full year of atmospheric forcing that is described in numerous papers (Goutorbe et al. 1989; Goutorbe 1991; Goutorbe

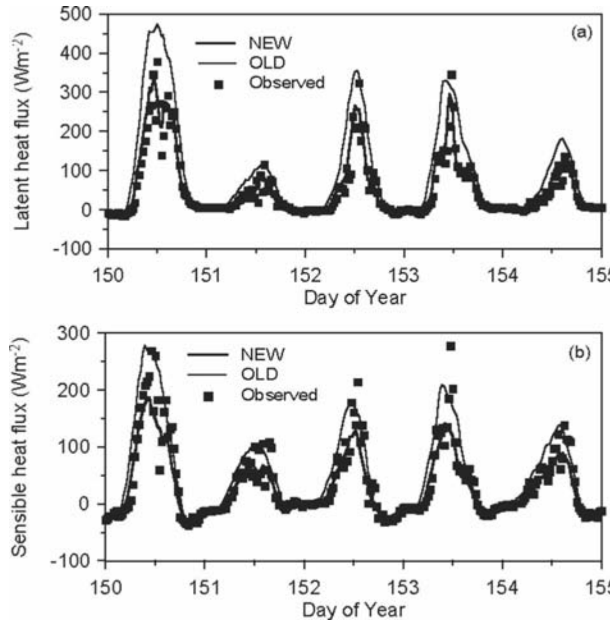

FIG. 3. Temporal variation of (a) latent heat flux and (b) sensible heat flux (for DOY 150–155) obtained by LAPS compared with the observations over a soybean field in the Caumont site during its growing season in 1986. The simulations were performed using the new and old methods for the calculation of K_m inside the vegetation canopy.

and Tarrieu 1991). The parameters used for characterizing the land surface, monthly LAI, vegetation fractional cover σ_f, morphological and aerodynamic parameters, and simulation details used in integration were taken from Mihailovic et al. (1998).

Figure 3 depicts a comparison between the calculated diurnal variations (new method and old method) of LHF (Fig. 3a) and SHF (Fig. 3b) for DOY 150–155. In

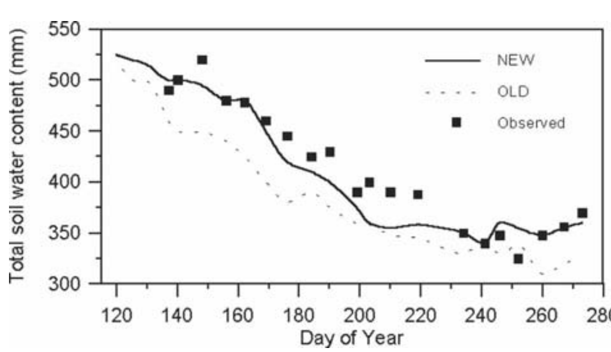

FIG. 4. Daily averages of the total soil water content (mm) over a depth of 1.6 m simulated by LAPS compared with weekly measurements under a soybean field at the Caumont site during its growing season in 1986. The simulations were performed using the new and old methods for calculation of K_m inside the vegetation canopy.

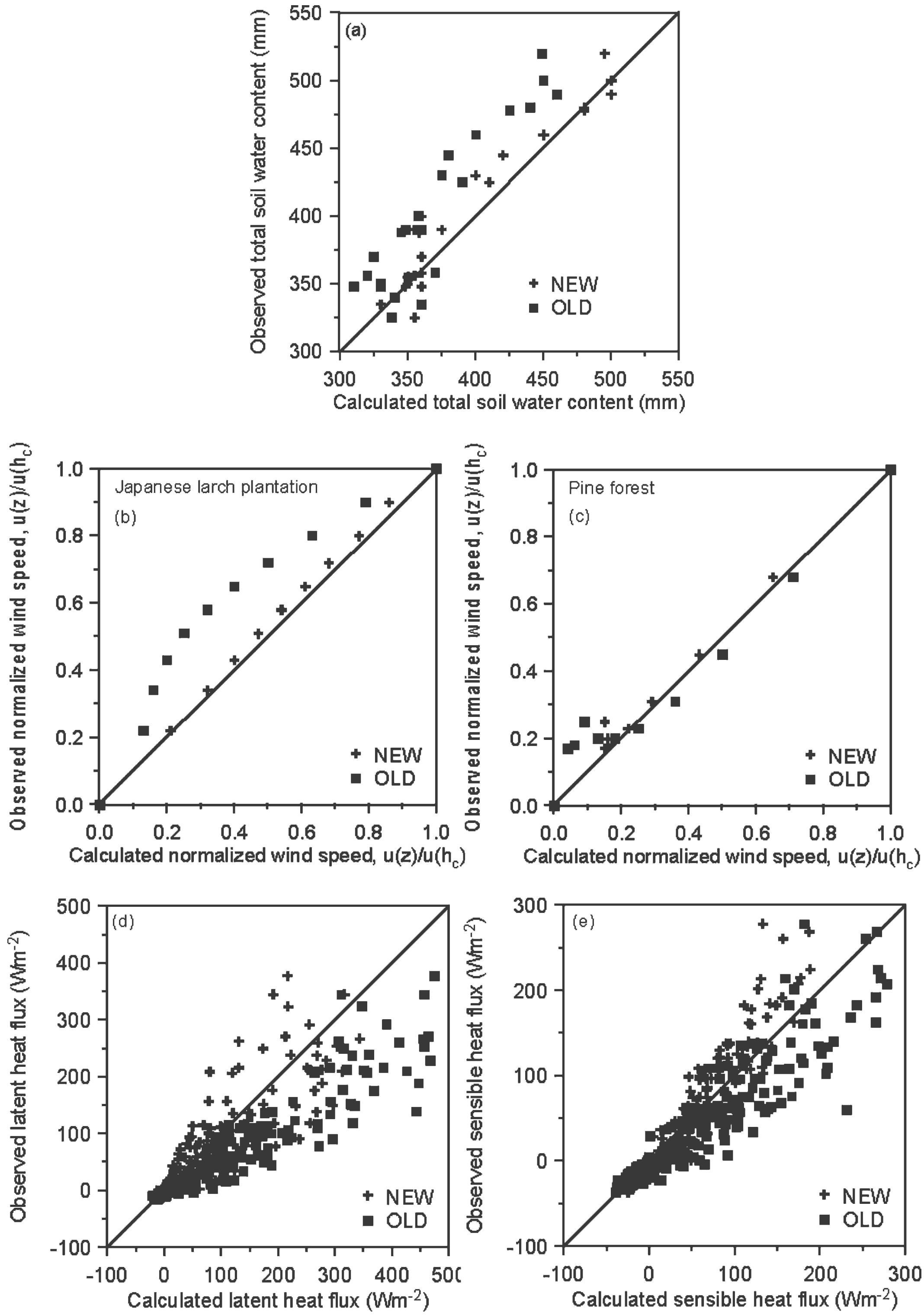

FIG. 5. Values of (a) total soil water content, (b) wind speed in a Japanese larch plantation, (c) wind speed in a pine forest, (d) latent heat flux, and (e) sensible heat flux obtained by the new and old methods, plotted against the observations.

TABLE 1. Error analysis of the simulated total soil water content, wind speed, latent heat flux, and sensible heat flux using the new and old methods.

Statistical parameter according to Eqs. (18)–(21):		ν	ν_{BR}	η	$\hat{\eta}$
TWC (mm)	New method	19.59	0.20	57.78	59.05
	Old method	42.84	1.45	47.56	59.05
Normalized wind speed inside a Japanese larch plantation	New method	0.03	0.01	0.28	0.28
	Old method	0.18	0.09	0.29	0.28
Normalized wind speed inside a pine forest	New method	0.03	0.02	0.27	0.26
	Old method	0.07	0.07	0.30	0.26
LHF (W m^{-2})	New method	40.05	40.78	83.02	80.15
	Old method	74.16	59.11	126.36	80.15
SHF (W m^{-2})	New method	24.29	23.61	50.54	65.58
	Old method	35.64	31.27	77.90	65.58

both cases the values simulated by the old method are higher than the observations. In contrast to that result, the new method gives values that are closer to the observations, particularly around local noon. For comparing the predicted TWC with the observations, we had weekly TWC measurements through the year based on neutron sounding probes for the top 1.6-m soil layer at 0.1-m intervals. A comparison of the predicted TWC with the measurements, for both methods, is plotted in Fig. 4. The curve, representing the values of the TWC over 1.6-m depth, obtained by simulation using the new method is much closer to the observations than when the old method is used. Figure 5 depicts the calculated values of total water content, wind speed, LHF, and SHF obtained using both methods for calculation of K_m plotted against observed ones. From this figure it is seen that the new method gives evidently better values for all of the above-listed quantities than the old method does.

To quantify the simulated values of the TWC, wind speed inside a Japanese larch plantation and a pine forest, LHF, and SHF we have performed an error analysis of the outputs obtained, based on a method discussed in Pielke (2002) and later used by Mahfouf (1990). Following them we computed several statistical quantities as follows:

$$\nu = \left[\frac{1}{N}\sum_{i=1}^{N}(\Gamma_i - \hat{\Gamma}_i)^2\right]^{1/2}, \qquad (18)$$

$$\nu_{BR} = \left\{\frac{1}{N}\sum_{i=1}^{N}[(\Gamma_i - \overline{\Gamma}) - (\hat{\Gamma}_i - \overline{\hat{\Gamma}})]^2\right\}^{1/2}, \qquad (19)$$

$$\eta = \left[\frac{1}{N}\sum_{i=1}^{N}(\Gamma_i - \overline{\Gamma})^2\right]^{1/2}, \quad \text{and} \qquad (20)$$

$$\hat{\eta} = \left[\frac{1}{N}\sum_{i=1}^{N}(\hat{\Gamma}_i - \overline{\hat{\Gamma}})^2\right]^{1/2}. \qquad (21)$$

Here, Γ is the variable of interest (aforementioned variables in this study) and N is the total number of data. An overbar indicates the arithmetic average, and a caret refers to an observation. The absence of a caret indicates a simulated value; ν is the rmse, and ν_{BR} is rmse after a bias is removed. Root-mean-square errors give a good overview of a dataset, with large errors being weighted more than many small errors (Mahfouf 1990). The standard deviations in the simulations and the observations are given by η and $\hat{\eta}$. An rmse that is less than the standard deviation of the observed value indicates skill in the simulation. Moreover, the values of η and $\hat{\eta}$ should be close if the prediction is to be considered realistic. The statistics for the values of the TWC, wind speed, LHF, and SHF are listed in Table 1. It indicates that the unbiased rmse for all analyzed variables is always lower for the new method than for the old method.

A comparison of η and $\hat{\eta}$ shows that the difference between them for all variables is evidently smaller when the new method is employed [TWC (1.77 mm), JLP (0.00), PF (−0.01), LHF (−2.87 W m^{-2})] instead of the old method [TWC (11.49 mm), JLP (−0.10), PF (−0.04), LHF (−46.21 W m^{-2})]. The only exceptions from these statistics are the values for the sensible heat flux, which are very close (−15.04 W m^{-2} for the new method vs −12.32 W m^{-2} for the old method). This analysis shows that in the simulation of the TWC, the use of the proposed method for calculation of K_m gives better results than when K_m is calculated in the conventional way.

Acknowledgments. The research work described in this paper has been funded by the Serbian Ministry of Science and Environmental Protection under the project “Modelling and Numerical Simulations of Complex Physical Systems,” ON141035 for 2006–10. This research was partly supported by the New York State Energy Research and Development Authority under

Contractual Agreement NYSERDA 4914-ERTER-ES-99. The investigators thank Dr. S. T. Rao for his support and Dr. Mirko Budincevic for his valuable comments.

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