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B. Lalic

Dragutin T. Mihailović

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A new approach in parameterisation of momentum transport inside and above forest canopy under neutral conditions

B. Lalić[a,b] **and D.T. Mihailović**[a,b]

[a]*Faculty of Agriculture, University of Novi Sad, Dositej Obradović Sq. 8, Novi Sad, Yugoslavia*
(branka@polj.ns.ac.yu; guto@polj.ns.ac.yu)
[b]*Center for Meteorology and Environmental Modeling, University of Novi Sad, Dositej Obradovi} Sq. 5,*
Novi Sad, Yugoslavia

Abstract: The forest as an underlying surface is often met in atmospheric models of different scales. Experimental evidence indicates that there is a significant departure of the wind profile within the forest and in the so-called transition layer above it. In the forest environment, the observed values are rather different than the values of the wind speed profile obtained by: a) the logarithmic relationship in the transition layer and b) K theory within the forest. This situation can seriously disturb the real physical picture concerning the transfer of momentum, heat and water vapour from the surface into the atmosphere. In order to minimise the foregoing problems we have suggested an empirical expression for the wind profile in the transition layer above the forest as well as the expressions for the wind profile and turbulent momentum transfer coefficient within the forest. The validity of the proposed expressions was checked using the micrometeorological measurements from the two experimental sites: a) the Scots pine forest at Thetford, Norfolk, United Kingdom and b) the ponderosa pine forest at Shasta Experimental Forest, California, USA.

Key words: forest; wind profiles; momentum transfer;

1. INTRODUCTION

Wind is an important factor in meteorological, agricultural and ecological models for calculation of heat, momentum, water vapour and carbon dioxide fluxes from ground to canopy air space and free atmosphere [Cowan, 1968; Thom, 1971]. During the last century the scientific community emphasised the importance of wind behaviour for the rate of spread of forest fires. Ecological and financial effects of forest fires have revealed a definite need for better understanding of wind profiles within and above forest [Curry and Fons, 1938]. Also, the movement of spores, pollen and particles within and just above the vegetation canopy is strongly affected by wind [Pingtong and Hidenori, 2000; Pinard and Wilson, 2001].

In dynamic environmental models (atmospheric, hydrological and ecological) the definition of the lower boundary condition is of great importance, especially in the presence of vegetation. The forest as an underlying surface is important for models of all scales because the atmosphere ‘feels’ the presence of trees up to a few hundred meters from the ground, depending on tree height. In this transition layer between the forest and free atmosphere, the wind profile differs from the standard logarithmic profile. For that reason, the forest should not be treated as a porous material sandwiched between two air layers, which is a broadly used approximation in surface schemes for grasses and so-called tall grasses (wheat, maize and corn) [Mihailović, 1996].

A number of numerical models for calculating the wind flow within vegetation have been developed [Cowan, 1968; Thom, 1971). However, accurate parameterisation of wind profile within the forest is much more difficult then for short vegetation due to complexity in tree structure and presence of two specific layers, crown and stands. Transport of momentum between the ground, crown and stand air space, and atmosphere is rather complex. Absorption of momentum between crown top and bottom is 70-90%, depending on crown depth and density. Attenuation of momentum, below the bottom of the crown, is rather small up to the roughness layer, where the rest of the air momentum is transferred to the ground due to molecular transport.

The object of this paper is to propose a new approach for parameterisation of momentum transport inside and above the forest. Consequently, a new empirical expression for the wind profile in the transition layer above the forest as well as the expressions for the wind profiles and turbulent momentum transfer coefficient within the forest is suggested. Additionally, for the proposed wind profiles, the expressions for: displacement height, roughness length and derived profile parameters, as functions of the forest morphological characteristics are determined from the continuity conditions and mass conservation hypothesis. Simulations of the wind profiles in Scots pine forest at Thetford (Norfolk, United Kingdom) and the ponderosa pine at Shasta Experimental Forest (California, USA) were compared with the observations.

2. WIND PROFILE ABOVE AND INSIDE THE FOREST

Under thermally neutral conditions, the well-known logarithmic law can describe steady-state flow over uniform vegetative surfaces

$$u(z) = \frac{u_*}{k} \ln \frac{z-d}{z_0} \tag{1}$$

where: $u(z)$ is the horizontal wind velocity at height z, k is von Karman's constant taken to be 0.41 [Hogstrom, 1985], d is the displacement height, z_0 is the roughness length and u_* is the friction velocity over the vegetated surface. According to this expression, the wind speed is numerically zero at height $d+z_0$ but in practice the logarithmic profile is inapplicable that far downwards.

The experimental evidence indicate that above the vegetation there is a transition layer where the wind profile predicted by the Eq. (1) gives greater values compared to the observed one. Consequently, the use of Eq. (1) in this layer may lead to serious miscalculations of the surface fluxes in atmospheric models. Analysing wind profiles above the different communities of vegetation [Morgan et al., 1971; Jacobs and van Boxel, 1988; de Bruin and Moore, 1985], we have found that the wind profile $u(z)$, in the transition layer can be more appropriately described by the power dependence:

$$u(z) = \frac{u_*}{k} a \left(\frac{z}{z_k} - 1 \right)^n \quad h < z < z_t \tag{2}$$

where: z_k is height within canopy where the extrapolated wind profile $u(z)$ reaches zero value, n is the power number used to be 1/10 for the forest, a is the profile parameter depending on the morphological characteristics of vegetation, h is the canopy height and z_t is the height of transition layer above which the wind profile becomes again the logarithmic one. Following estimations introduced by Tennekes [1982] and De Bruin and Moore [1985], we have assumed that the height of the transition layer is located at

$$z_t = d + m z_0 \tag{3}$$

where m is a constant.

The quantities z_k, z_t, n, m and a are derived from a physical assumption which will be shortly elaborated. We followed an idea introduced by Thom [1971] that is later included in the paper by De Bruin and Moore [1985]. Namely, in calculating the aerodynamic characteristics of the Scots pine forest, they employed the mass conservation hypothesis assuming that the logarithmic wind profile extrapolated to $z=z_0+d$, transports the same amount of mass as the observed wind profile. We have slightly modified this idea assuming that the logarithmic wind profile [Eq. (1)] extrapolated to $z=z_0+d$, transports the same amount of mass as the wind profile through the whole layer from the ground beneath the forest up to the top of the transition layer. Combining this assumption with continuity conditions (continuity of the wind speed, momentum transfer coefficient and continuity of their first derivative at: transition layer top, forest top and crown bottom) and Eq. (3) we have obtained the system of nine transcendental equations. Solving this system we could determine the quantities: z_k, z_t, a, u_*, z_0, d, m, C_h and σ_d. Here, C_h denotes the constant which is included in the expressions for the wind profile and momentum transfer coefficient within the canopy, while σ_d is another constant appearing in the expression for the momentum transfer coefficient within the canopy.

In order to put into the process the previously described procedure, it is necessary to define a wind profile within the forest which may significantly deviate from the profile proposed by Cowan (1968) that is intensively exploited by the numerical modellers as well as other micrometeorological specialists. On the basis of the detailed analysis of the observed wind profiles within the forest, Lalić [Lalić, 1997; Lalić and

Mihailović, 1998] suggested the wind profile in the form

$$u(z)=\begin{cases} u_h\left[\dfrac{\cosh\beta\left(\dfrac{z-z_d}{h}\right)}{\cosh\beta\left(1-\dfrac{z_d}{h}\right)}\right]^{\frac{5}{2}} & z_d < z \le h \\ C_h u_h & z_0 < z \le z_d \end{cases} \qquad (4)$$

where: z_d is the crown bottom height, u_h is the wind speed at the top of the forest and β is the extinction factor that is equal to $4C_dLAI/(\alpha^2k^2)$ according to Massman (1987). Here, α is a dimensionless constant describing the roughness of the underlying vegetative surface, having the value between 1.0 and 2.0 [Raupach and Thom, 1981]. In creating the foregoing profile, the evidences that come from the observations of the wind profile within the forest were taken into account. Namely, around 90 % of momentum above the forest is absorbed by the forest′s crown, thus below the crown bottom the vertical wind gradient is very close to zero. As a result of that corresponding wind speed below the crown is 5-10 % of the forest top wind speed u_h.

The wind profile defined by Eq. (4) requires additional assumption in defining the momentum transfer coefficient, K_m within the forest, which we need for continuity conditions. Instead of commonly used assumption $K_m(z) = \sigma u(z)$, describing the turbulence through the whole environment occupied by plants, we have introduced another one. For simplicity, σ is often assumed to be constant regardless of the structure of the canopy vegetation. However, in the case of the forest this idea can be applied just in some part of its environment. Thereby, we have assumed that in the crown of the forest ($h > z \ge z_d$) σ can be considered as a function of height z, i.e. $\sigma = \sigma(z)$, while below it ($z_d > z \ge z_0$) σ remains constant. Thus, the momentum transfer coefficient can be written in the form

$$K_m(z)=\begin{cases} \sigma(z)u_h\left[\dfrac{\cosh\beta\left(\dfrac{z-z_d}{h}\right)}{\cosh\beta\left(1-\dfrac{z_d}{h}\right)}\right]^{\frac{5}{2}} & z_d < z \le h \\ \sigma_d C_h u_h & z_0 < z \le z_d \end{cases} \qquad (5)$$

where σ_d is assumed to be a constant.

The functional form of $\sigma(z)$ may be found as the solution of the differential equation describing the shear stress within the canopy

$$\frac{d}{dz}\left(K_c\frac{du}{dz}\right)=\frac{C_d LAI}{h}u^2 . \qquad (6)$$

where C_d is the leaf drag coefficient and LAI the leaf area index. Using expressions (4) and (5) for u(z) and K_m(z) solution of Eq.(6) has the following form

(4)

$$\sigma(z)=\frac{2C_d LAI\ h}{7\beta^2 ch^6\beta\left(\dfrac{z-z_d}{h}\right)}\left[1+\sinh^2\beta\left(\frac{z-z_d}{h}\right)+\right.$$
$$\left.+\frac{3}{5}\sinh^4\beta\left(\frac{z-z_d}{h}\right)+\frac{1}{7}\sinh^6\beta\left(\frac{z-z_d}{h}\right)\right] \qquad (7)$$

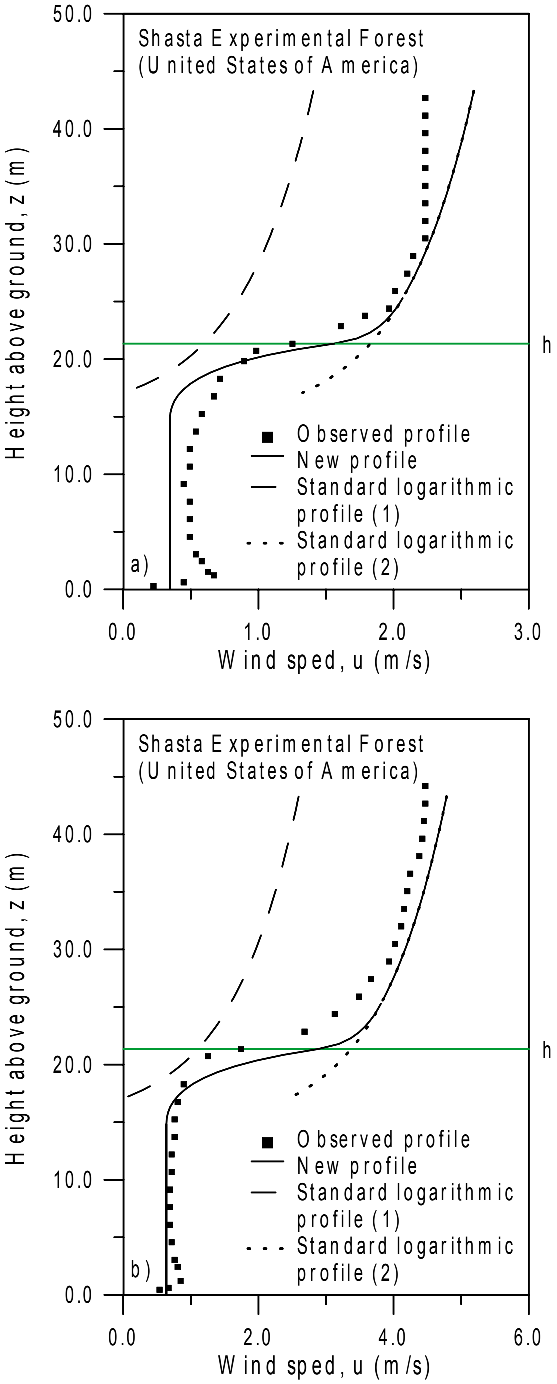
3. COMPARISON WITH OBSERVED DATA AND CONCLUSION

Two sites of moderately dense ponderosa pine forest were selected for the study — one in the McCloud flat area on the Shasta Experimental Forest, northern California, USA (in further text SEF) and one in Thetford Scots pine forest in Great Britain (in further text TSP).

At the SEF site the average height of the stand was 21.34 m. the measurements of wind speed were obtained for several series of 15- to 90-minute periods during July, August and September 1935. The wind speed was measured at eleven levels. Wind profiles for wind velocities of 2.74, 5.05 and 7.51 m s^{-1} measured 43.28 m above the ground were represented by black squares on Figures 1a-1c, respectively.

At the TSP site the average height of the stand was 18.3 m, the wind speed was measured at fifteen levels within the forest and at the six levels above the forest. Averaging the measured values over the 20 minutes interval performed the measurements. The values of the observed profile were normalised by the wind speed measured at 29.93 m. That profile consisting of observed values, indicated by the black squares, is shown on Figure 2.

The standard logarithmic profile calculated for $d = 0.8h$ and $z_0 = 0.1h$, which is the commonly



used approach, is indicated by dashed line on Figures 1 and 2 (standard logarithmic profile (1)). Logarithmic profile obtained for values of d and z_0 calculated using the procedure described above is indicated by dotted line on all graphs (standard logarithmic profile (2)).

In Figure 1 the solid line represents the new wind profile within the forest and above it obtained with Eqs. (1), (2) and (4), where the parameters are needed have the values: $a = 4.47$, $z_k = 21.1$ m, $u_*/u_h = 0.14$, $C_h = 0.22$ and the height of the transition layer was $z_t = 25.3$ m.

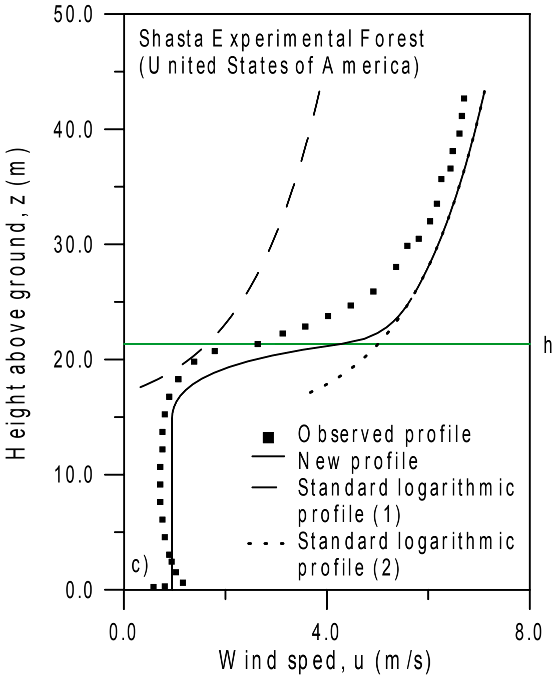


Figure 1. Comparison of the new wind profile and old logarithmic profile with wind profile observed within and above pine forest for wind velocities of 2.74 m s^{-1} (a), 5.05 m s^{-1} (b) and 7.51 m s^{-1} (c) measured 43.28 m above the ground.

In these calculations, the values of d and z_0, obtained from the continuity and mass conservation conditions are $d = 14.24$ m and $z_0 = 0.25$ m. In all three cases, presented on Figures 1a - 1c, value for friction velocity, u_* was calculated using wind speed measured at 43.28 m above the ground supposing that that far from the ground the standard logarithmic profile is good enough. Also, wind speed at the top of the crown, u_h was calculated using this value for u_* and calculated value for u_*/u_h. The solid line in Figure 2 also represents the new wind profile within and above the forest but normalised by values of the wind speed at z = 29.93 m. The parameters are needed for these calculations have the values: $a = 4.01$, $z_k = 18.27$ m, $u_*/u_h = 0.16$, $C_h = 0.30$ and the height of the transition layer was $z_t = 22.25$ m. Calculated values of d and z_0 are $d = 10.7$ m and $z_0 = 0.37$ m. For both, SEF and TSP sites, we suppose that drag coefficient, C_d is 0.2 and the leaf area index, LAI was 2.3 what is commonly used value for pine forest (Amiro, 1990).

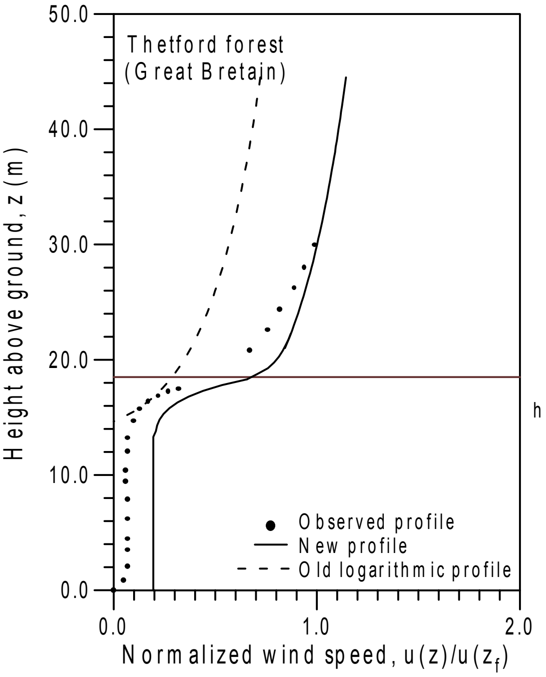


Figure 2. Comparison of the new wind profile and old logarithmic profile with wind profile observed within and above the Scots pine forest in Thetford (GB) (normalised values) and profiles obtained by the method proposed.

Short inspection of the figures presented shows that the old logarithmic profile with the usual values for aerodynamic characteristics, d and z_0, does not represent properly the behaviour of wind speed from the crown top to the free atmosphere. It can be caused by two reasons: a) in the transition layer, between the crown and free atmosphere, logarithmic function is not appropriate to represent behaviour of wind with height; b) values for d and z_0 (0.8h and 0.1h, respectively) are not good enough in case of forest.

Looking at the Figures 1 and 2, it is clearly seen that the new wind profile, through the whole forest environment from its bottom up to the free atmosphere, is very close to the observed wind profile following it more realistically then the other profiles. Practically, it means that in the new representation the wind is more damped by the forest than it is in the conventional representation. Apparently, this better treatment of the wind profile, in the space occupied by forest and just above it, will contribute to better calculation of the momentum, heat and water vapour transfer from the underlying surface into the atmosphere.

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