NOTES AND CORRESPONDENCE

Determination of the Mean Wind Speed and Momentum Diffusivity Profiles above Tall Vegetation and Forest Canopies Using a Mass Conservation Assumption

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ABSTRACT

A semianalytical method based on a mass conservation principle is presented for describing the transition-layer profiles of mean wind speed and momentum diffusivity and for estimating the aerodynamic characteristics of forest and tall vegetation canopies. This method incorporates density and vertical structure of the canopy and assumes that the transition-layer mean wind speed profile can be expressed in a polynomial form having second-order osculation. It is also suggested that canopy structure has a major influence on the transition-layer mean wind speed and momentum diffusivity profile. The proposed methodology may help in simulating airflow for use in large-scale models of plant–atmosphere exchanges.

1. Introduction

The strict applicability of the modified logarithmic wind profile to the measured distribution of the mean wind speed just above the roughness elements has always been an area of doubt. Deviations from the log law have been observed in the wind tunnel (e.g., Raupach et al. 1980) and in atmospheric observations over forest (e.g., Garratt 1980). In general, these profile deviations are consistent with the physical picture of surface-generated wakes producing enhanced vertical mixing in the layer immediately above the canopy; this being termed the transition layer above which wake effects are negligible and the inertial-layer relations apply (Garratt 1980).

Molion and Moore (1983), DeBruin and Moore (1984), and Lo (1990), took into consideration the existence of a transition layer (between the forest canopy and the inertial boundary layer) in determining the zero-plane displacement d and roughness length z_0 during their analysis of the Thetford Forest Experiment profile data. As stated in DeBruin and Moore (1984), the basic assumption is made that d is chosen such that the logarithmic wind profile $u_L(z)$, extrapolated to $z = d + z_0$, transports the same amount of mass as the actual $u_m(z)$ wind profile. Assuming that the air is incompressible and that density is constant with height, this condition can be written in neutral stability:

$$\int_{d+z_0}^{z_f} u_L(z)dz = \int_0^{z_f} u_m(z)dz, \qquad (1)$$

where z_f represents a level within the logarithmic regime. As suggested by Lo (1990), it would be desirable to extend measured wind profiles to some higher levels in order to ascertain that the top level z_f is within the logarithmic profile regime (e.g., DeBruin and Moore proposed that the mass conservation idea requires measurements within and over an extensive forest up to at least five times the tree height). Extending the measured velocity profile $u_m(z)$ to higher levels ($z_f \leqslant z \leqslant z_*$), from Eq. (1) yields (Zoumakis 1993):

$$\int_{d+z_0}^{z_*} u_L(z)dz = \int_0^{z_f} u_m(z)dz + \int_{z_f}^{z_*} u_T(z)dz, \qquad (2)$$

where $u_T(z)$ is the empirical modification of the wind speed profile in the transition layer suggested by Garratt (1980) and z_* is the transition-layer depth. The principle of mass conservation [Eq. (1)] leads to a relationship between the aerodynamic characteristics of the canopy [Eq. (2)], which allows estimates of z_0, d, and z_* without assumptions on the structure of the canopy. Moreover, this method uses semiempirical modifications of the wind profile in the transition layer, eliminating the need for measured wind data extending into the logarithmic regime. However, it is reasonable to believe that the few previous empirical modifications $u_T(z)$ of the transition-layer wind speed profile (e.g., Garratt 1980) are specific to the particular physical characteristics of the underlying canopy and the plan-

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ning of the experiment (e.g., Thetford Forest Experiment, United Kingdom, the Koorin Expedition, Australia, etc.), and are, in general, not uniquely related to z_0, d, and z_*, for the different wind profile shapes within a variety of forest and tall vegetation canopies.

The present study proposes that instead of using an empirical formula for $u_T(z)$, which tends to be site specific (e.g., Raupach et al. 1980; Garratt 1980), a general relationship linking the logarithmic wind profile $u_L(z)$ with the underlying canopy characteristics is more desirable. In particular, it is suggested that in the transition layer the mean wind speed profile can be expressed as a fifth-order polynomial having second-order osculation. Also, the methodology presented here uses theoretical canopy wind profiles $u_C(z)$, eliminating the need for measured (within and above canopy) wind data extending into the logarithmic regime.

2. Methodology

The method described by DeBruin and Moore (1984) and used by Lo (1990), which is based on a mass conservation hypothesis (taking into consideration a transition layer between the forest canopy and the inertial boundary layer), is mathematically simple as well as consistent with the physics of the flow (e.g., Lo 1990). In this study, a semianalytical method based on the same mass conservation assumption as that of DeBruin and Moore (1984) is presented for describing the transition-layer mean wind speed and momentum diffusivity profiles and for estimating the aerodynamic characteristics of forest and tall vegetation canopies.

a. Basic equations

Substituting the low {and probably erroneous [e.g., see Molion and Moore (1983), 119–125; DeBruin and Moore (1984), 46–48]} wind speed measurements $u_m(z)$ within the forest canopy by a theoretical canopy wind profile $u_C(z)$ [see Eqs. (11)–(14)] (e.g., see also Molion and Moore 1983), from Eq. (2) yields:

$$\int_{d+z_0}^{z_*} u_L(z)dz = \int_0^h u_C(z)dz + \int_h^{z_*} u_T(z)dz, \quad (3)$$

where h is the mean height of roughness elements.

1) Transition zone

Garratt (1980) suggested that the gradient of wind speed in the transition zone over forest is well represented by

$$\frac{\partial u_T}{\partial z} = \frac{u_*}{k(z-d)} \Phi\left(\frac{z}{z_*}\right), \quad z < z_*,$$

where $\Phi(z/z_*) \equiv \gamma \exp\{\gamma_1[(z-d)/z_*]\}$, $\gamma = 0.5$, $\gamma_1 = 0.7$, u_* is the friction velocity, and k is von Kármán constant. On the other hand, Raupach et al. (1980) suggested that the diffusivity within the transition layer is constant with the height. However, such approaches assume that $u_T(z)$ is independent of the canopy structure (e.g., the shape of the canopy wind profile) and give discontinuities (in both direction and curvature) in $u_T(z)$ and $\partial u_T/\partial z$ at $z = h$ and $z = z_*$ (e.g., see Garratt 1980, 811–813).

The methodology presented here assumes that vertical structure of the canopy, for example, the shape of the mean wind profile (at least) in the upper canopy, has a major influence on the shape of the mean wind profile (at least) in the lower part of the transition layer. Moreover, the present study proposes that instead of using an empirical formula for $u_T(z)$, which tends to be site specific (e.g., Raupach et al. 1980; Garratt 1980), a general relationship linking the logarithmic wind profile $u_L(z)$ with the underlying canopy characteristics is more desirable. Furthermore, it is supposed that the actual within- and above-canopy mean wind profile $u_m(z)$ can be fitted with a theoretical curve $u(z)$ to provide a smooth and continuous profile, for which direction and curvature are free of discontinuities. For example, DeBruin and Moore (1984) assume a mean neutral wind speed profile (presented in their Fig. 1) measured within and above Thetford Forest, designed to give equal mass flows between ground and z_f (as indicated by equal areas A and B), for which direction and curvature are free of discontinuities [e.g., see also the mean neutral wind speed profile measured within and above an extensive forest presented in Fig. 1 of Oliver (1971), Fig. 2 of Meyers and Paw U (1986), Fig. 4 of Lo (1990), etc.]. The above considerations, together with background discussion in the Introduction, provide support for using a tentative (theoretical) modification $u_T(z)$ for the transition-layer mean wind speed profile joining positions $[h, u_C(h)]$ and $[z_*, u_L(z_*)]$, for which direction and curvature are free of discontinuities. Therefore, the corresponding curve $u_T(z)$ has what is called contact of second order. Thus for the second-order osculation, we require:

$$u_T(h) = u_C(h), \quad (4)$$

$$u_T(z_*) = u_L(z_*), \quad (5)$$

$$\left[\frac{\partial u_T(z)}{\partial z}\right]_{z=h} = \left[\frac{\partial u_C(z)}{\partial z}\right]_{z=h}, \quad (6)$$

$$\left[\frac{\partial u_T(z)}{\partial z}\right]_{z=z_*} = \left[\frac{\partial u_L(z)}{\partial z}\right]_{z=z_*}, \quad (7)$$

$$\left[\frac{\partial^2 u_T(z)}{\partial z^2}\right]_{z=h} = \left[\frac{\partial^2 u_C(z)}{\partial z^2}\right]_{z=h}, \quad (8)$$

$$\left[\frac{\partial^2 u_T(z)}{\partial z^2}\right]_{z=z_*} = \left[\frac{\partial^2 u_L(z)}{\partial z^2}\right]_{z=z_*}, \quad (9)$$

where $u_L(z)$ is the logarithmic wind profile in neutral stability conditions:

$$u_L(z) = \left(\frac{u_*}{k}\right)\ln\left(\frac{z-d}{z_0}\right).$$

The problem is considerably simplified if a polynomial may be used as a substitute for the unknown function. Tentatively taking an osculating polynomial path as a substitute for the transition-layer mean wind speed profile $u_T(z)$, the method of undetermined coefficients can be used to obtain the corresponding fifth-degree polynomial form having second-order osculation:

$$u_T(z) \approx \left(\frac{u_*}{k}\right)\sum_{i=0}^{5} A_i\left(\frac{z}{h}\right)^i, \tag{10}$$

where the dimensionless coefficients A_0, A_1, A_2, A_3, A_4, and A_5 are dependent on z_0, d, z_*, and the canopy wind profile extinction coefficients [see Eqs. (11)–(14)]. Moreover, the friction velocity u_* is assumed to be constant above the canopy (e.g., Massman 1987). According to the existence and uniqueness theorem, the suggested relationship, Eq. (10), is the unique polynomial approximation $u_T(z)$ linking the logarithmic wind profile $u_L(z)$ with the canopy wind profile $u_C(z)$, for which direction and curvature are free of discontinuities.

2) CANOPY

Canopy wind speed profiles can often be represented by an exponential function:

$$u_C(z) \approx u_h \exp\left[-\alpha\left(1-\frac{z}{h}\right)\right], \quad z \leqslant h, \tag{11}$$

where $u_h = u_C(h)$ is the mean horizontal wind speed at the top of the canopy, h is the mean height of the canopy, and α is the wind profile extinction coefficient. Experience has shown that Eq. (11) can describe (at least) the upper part of most canopy wind profiles when α is suitably chosen (Raupach and Thom 1981). As a working hypothesis, it is also assumed that the hyperbolic cosine (cosh) canopy wind profile,

$$u_C(z) \approx u_h\left[\frac{\cosh(\beta z/h)}{\cosh\beta}\right]^{1/2}, \quad z \leqslant h; \tag{12}$$

the power-law canopy wind profile,

$$\frac{u_C(z)}{u_h} \approx \left(\frac{z}{h}\right)^{a/\ln h};$$

or, equivalently,

$$u_C(z) \approx u_h \exp\left[-a\left(1-\frac{\ln z}{\ln h}\right)\right], \quad z \leqslant h; \tag{13}$$

and the hyperbolic sine (sinh) canopy wind profile,

$$u_C(z) \approx u_h\left[\frac{\sinh(bz/h)}{\sinh b}\right]^{1/2}, \quad z \leqslant h \tag{14}$$

can model the canopy wind speed, when the extinction coefficients β, a, and b are suitably chosen.

b. *Solving procedure*

By requiring that the transition-layer mean wind speed profile can be expressed in a second-order osculating polynomial form, $u_T(z)$, and adopting an exponential variation of the canopy wind speed $u_C(z)$ with height [Eq. (11)], from the condition of mass conservation [Eq. (3)] and from Eqs. (4)–(10) yields:

$$\int_{d+z_0}^{z_*} u_L(z)dz = z_0\left(\frac{u_*}{k}\right)[x(\ln x - 1) + 1], \tag{15}$$

$$\int_0^h u_C(z)dz = u_h\left(\frac{h}{\alpha}\right)[1-\exp(-\alpha)], \tag{16}$$

$$\int_h^{z_*} u_T(z)dz \approx \left(\frac{u_*}{k}\right)\sum_{i=0}^{5}\frac{A_i}{h^i}\left(\frac{z_*^{i+1}-h^{i+1}}{i+1}\right), \tag{17}$$

$$\left(\frac{u_*}{k}\right)\sum_{i=0}^{5} A_i = u_h, \tag{18}$$

$$\left(\frac{u_*}{k}\right)\sum_{i=0}^{5} A_i\left(\frac{z_*}{h}\right)^i = \left(\frac{u_*}{k}\right)\ln\left(\frac{z_*-d}{z_0}\right), \tag{19}$$

$$\left(\frac{u_*}{k}\right)\sum_{i=0}^{5} A_i\left(\frac{i}{h}\right) = \left(\frac{\alpha}{h}\right)u_h, \tag{20}$$

$$\left(\frac{u_*}{k}\right)\sum_{i=0}^{5} A_i\left(\frac{i}{h}\right)\left(\frac{z_*}{h}\right)^{i-1} = \left(\frac{u_*}{k}\right)\frac{1}{(z_*-d)}, \tag{21}$$

$$\left(\frac{u_*}{k}\right)\sum_{i=0}^{5} A_i\left[\frac{i(i-1)}{h^2}\right] = \left(\frac{\alpha}{h}\right)^2 u_h, \tag{22}$$

$$\left(\frac{u_*}{k}\right)\sum_{i=0}^{5} A_i\left[\frac{i(i-1)}{h^2}\right]\left(\frac{z_*}{h}\right)^{i-2} = -\left(\frac{u_*}{k}\right)\frac{1}{(z_*-d)^2}, \tag{23}$$

where $x = (z_* - d)/z_0$ and $u_L(z)$ is the logarithmic wind profile in neutral stability conditions.

We observe that Eqs. (18)–(23) are linear in each of the unknown variables A_0, A_1, A_2, A_3, A_4, and A_5. Therefore, using the method of undetermined coefficients, that is, solving the system of linear equations (18)–(23), the parameters A_0, A_1, A_2, A_3, A_4, and A_5 can be expressed as unique analytical functions of z_0, d, z_*, h, α, and u_*/u_h:

$$A_i \equiv A_i(z_0, d, z_*, h, \alpha, u_*/u_h), \quad i = 0, 1, 2, 3, 4, 5. \tag{24}$$

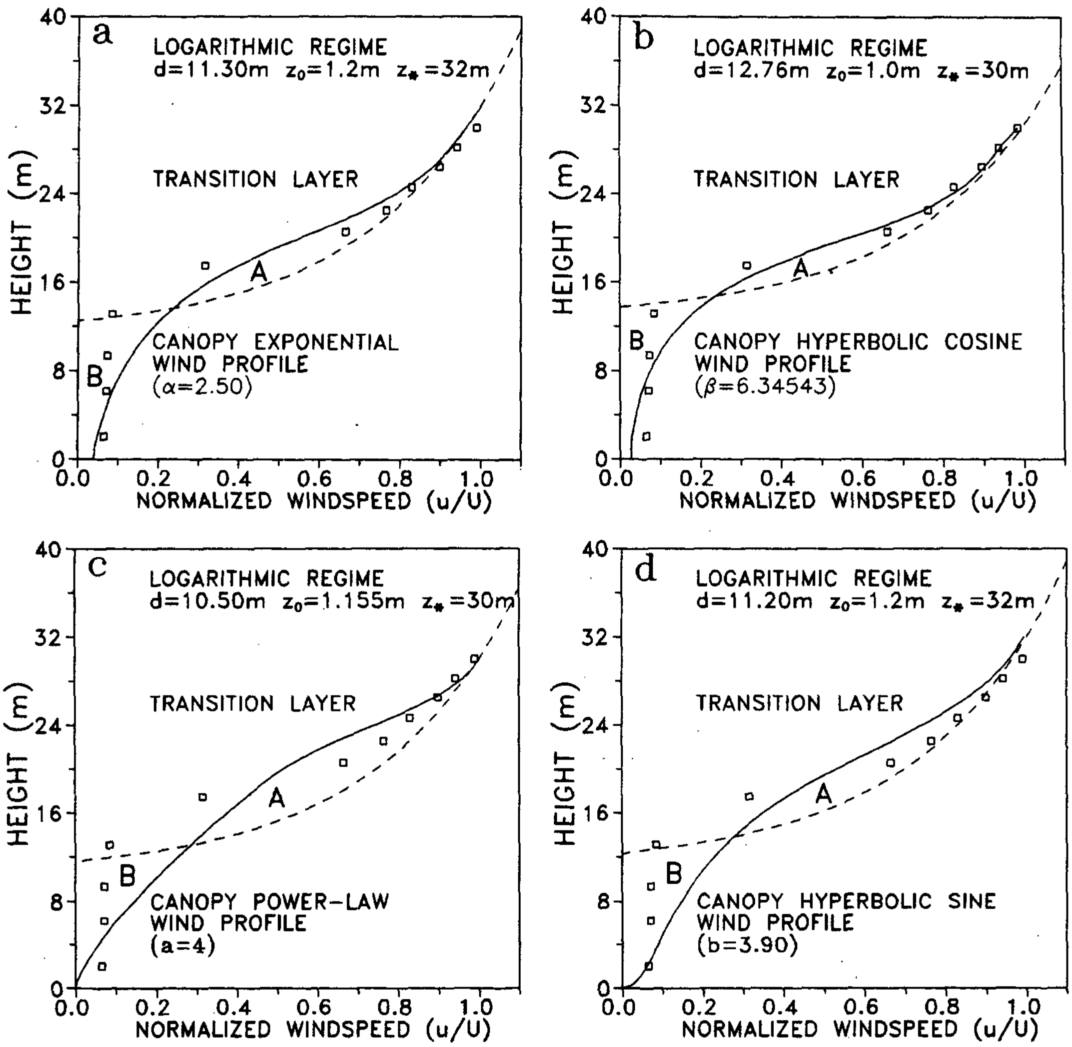

FIG. 1. Normalized mean neutral wind speed profiles $[u(z)/u_L(z_*)]$ in and above a forest canopy (solid lines) [from Eqs. (4)–(10)], associated with the: (a) exponential [Eq. (11)], (b) cosh [Eq. (12)], (c) power-law [Eq. (13)], and (d) sinh [Eq. (14)] canopy wind profiles and with the theoretical logarithmic law $u_L(z)$ above z_* (dashed lines), designed from the principle of mass conservation [Eq. (3)] to give equal mass flows between ground and z_*, as indicated by equal areas A and B. Observations are taken from DeBruin and Moore (1984).

Substituting the specified analytic expressions of A_0, A_1, A_2, A_3, A_4, and A_5 [from Eq. (24)] and Eqs. (15)–(17) into Eq. (3), leads to a single equation for z_0, d, z_*, h, α, and u_*/u_h. Consequently, the condition of mass conservation, Eq. (3), makes it possible to analyze the relationships between z_0, d, z_*, h, and the extinction coefficient.

The canopy exponential wind profile, Eq. (11), was adopted, with $h = 18.5$ m and $\alpha = 2.5$ (e.g., Molion and Moore 1983). Then, tentatively assuming that $z_0 = 1.2$ m, $d = 11.30$ m, and the ratio $u_*/u_h = 0.31623$, solving the system of linear equations (18)–(23), the unknown parameters A_0. A_1, A_2, A_3, A_4, and A_5 can be expressed as unique analytical functions of the transition-layer depth z_*. Substitution of Eqs. (15)–(17) and (24) into Eq. (3), the system of seven equations has therefore been reduced to the single Eq. (3) to be solved by numerical iterations for the sole unknown, z_* [and from Eq. (3) finally yields $z_* = 32$ m].

Relationships associated with the cosh, power-law, and sinh canopy wind profiles are not shown because they are quite similar to those presented above. Different analytical expressions [e.g., Eqs. (12)–(14)] for the canopy wind profile $u_C(z)$ require minor modifications of the suggested equations (16), (18), (20), and (22). The canopy cosh wind profile was adopted, with $h = 18.5$ m and $\beta = 6.34543$. Assuming that $z_0 = 1.0$ m, $d = 12.76$ m, and the ratio $u_*/u_h = 0.31623$, from the condition of mass conservation [Eq. (3)], finally yields $z_* = 30$ m. With the assumption of a power-law variation of the canopy wind speed profile with height [Eq. (13)] (taking that $a = 4$, $z_0 = 1.155$ m, $d = 10.50$ m, and $u_*/u_h = 0.31623$) from Eq. (3) yields $z_* = 30$ m. Finally, using the canopy sinh wind profile [Eq. (14)] and assuming that $b = 3.9$, $z_0 = 1.2$ m, $d = 11.20$ m, and $u_*/u_h = 0.31623$, from Eq. (3) yields $z_* = 32$ m.

Based on Eqs. (4)–(10), Fig. 1 shows the (discussed above) typical examples of the normalized mean neutral wind speed profiles $[u(z)/U]$, with $U = u_L(z_*)$, in and above a forest canopy (solid lines) associated with the exponential [Eq. (11)], cosh [Eq. (12)], power-law [Eq. (13)], and sinh [Eq. (14)] canopy wind profiles and with the theoretical logarithmic law $u_L(z)$ above z_* (dashed lines), designed from the principle of mass conservation [Eq. (3)] to give equal mass flows between ground and z_*, as indicated by equal areas A and B. All profiles presented in Fig. 1 assume that the ratio $(u_*/u_h)_{z=h}$ (for the neutrally stable conditions) is a constant (e.g., Albini 1981) and von Kármán's constant is taken $k = 0.41$. The plots indicate that the theoretical profiles compare reasonably with the Thetford Forest experimental data published by DeBruin and Moore (1984).

c. Discussion and sensitivity tests

Based on Eqs. (3)–(10), Fig. 2a shows the relationship between the normalized roughness length, z_0/h, and the extinction coefficient, for the wind speed profiles discussed in Fig. 1. All the profiles presented here produce the expected unimodal structure for the roughness length (e.g., Seginer 1974; Shaw and Pereira 1982; Massman 1987). Roughness length initially increased with increasing extinction coefficient, reached a peak, and then declined. Figure 2b shows the normalized zero-plane displacement, d/h, as a function of the extinction coefficient, for the same wind speed profiles as used in the previous figure. The predicted d/h corresponding to the cosh and power-law canopy wind speed profiles presents a monotonically increasing behavior, which qualitatively agrees with the deductions of Shaw and Pereira (1982) and Massman (1987). Then, for different values of the extinction coefficient, the plots in Figs. 3a and 3b were constructed expressing the relation between z_* and z_0 for the exponential and cosh canopy wind speed profiles, discussed in Figs. 1a and 1b, respectively. Garratt (1980) found that $z_*/z_0 \approx 35$ and 150 for wind at a dense and a less dense underlying forest canopy surface, respectively [a similar conclusion was drawn from a wind tunnel study by Raupach et al. (1980)], while Tennekes (1982) suggested that $z_* \approx d + 20z_0$. However, it follows from Figs. 3a and 3b that z_* is strongly dependent on the different types of canopy wind speed profiles [e.g., Eqs. (11)–(14)]. Moreover, the salient feature of Figs. 3a and 3b is the increase in z_* with z_0 for small values of the extinction coefficient (dashed lines) and the decrease in z_* with z_0 for large values of the extinction coefficient (solid lines) for both the exponential and cosh canopy wind speed profiles.

The description of the wind profile through the concept of a transition layer requires determination of the quantity z_*. Therefore, it is important to establish a scheme for determining z_*, in terms of the particular physical characteristics of the canopy. Based on Eqs. (3)–(10), Fig. 4a presents z_* as a function of the extinction coefficient for the exponential (solid lines) and power-law (dashed lines) canopy wind speed profiles, for different values of d and z_0. With the assumption of an exponential variation [Eq. (11)] of the canopy wind speed with height, Figs. 4b and 4c show the relation between z_* and h, and between z_0 and h, respectively (for various values of d), and Fig. 4d presents d as a function of h (for different values of z_0). It follows

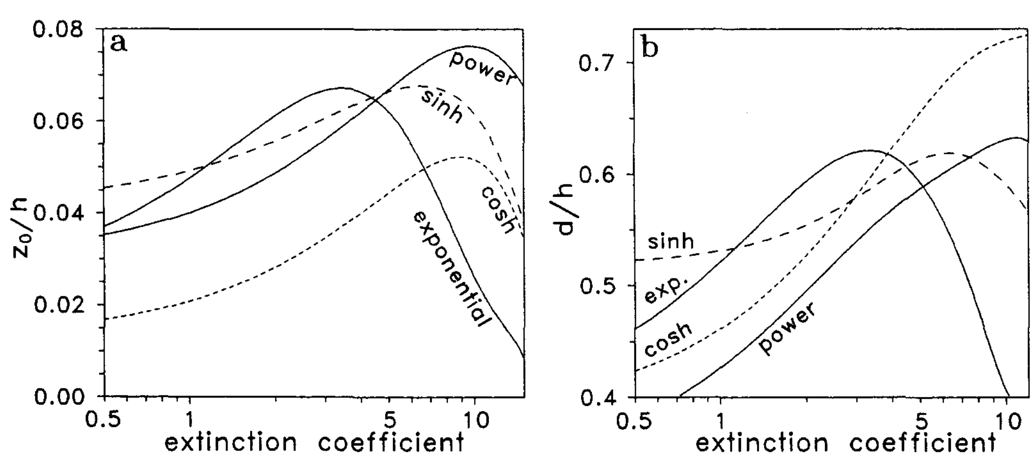

FIG. 2. Normalized (a) roughness height z_0/h and (b) zero-plane displacement height d/h as functions of the profile extinction coefficient, for the wind speed profiles shown in Fig. 1.

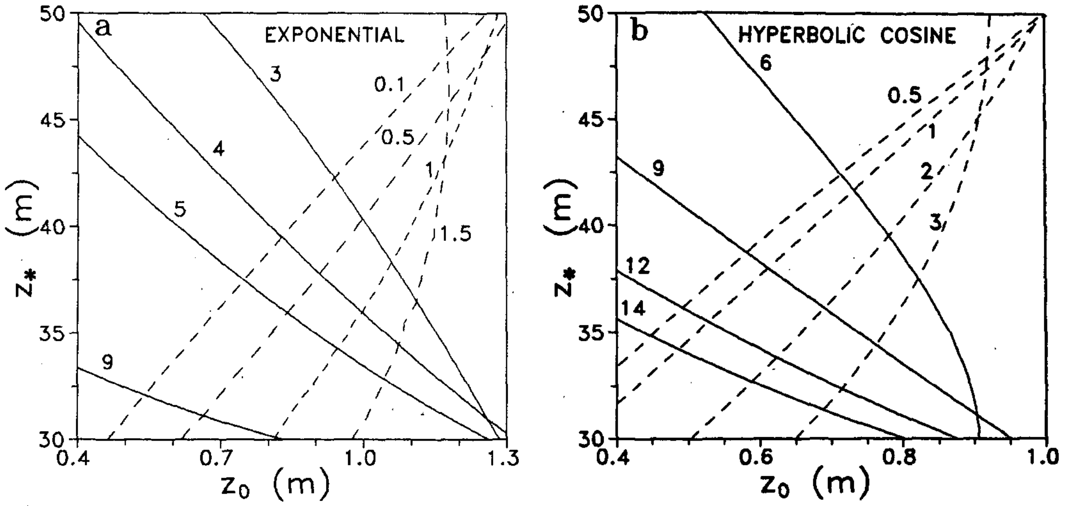

FIG. 3. (a) Transition-layer depth z_* as a function of z_0 (for the exponential canopy wind profile discussed in Fig. 1a), for different values of the profile extinction coefficient, (b) same as (a) for the cosh canopy wind profile discussed in Fig. 1b.

from Figs. 4a and 4b that z_* decreases with the increasing extinction coefficient and z_* increases with increasing h. Finally, Figs. 4c and 4d show the expected linear increase in z_0 and d with h (e.g., Oke 1978). In conclusion, by the requirement that the transition-layer mean wind speed profile can be expressed in an osculating polynomial form $u_T(z)$ [Eqs. (4)–(10)], the mass conservation principle [Eq. (3)] makes it possible to analyze the relationships between z_0, d, z_*, h, and the extinction coefficient. The important point to be mentioned here is that canopy structure has a major influence on the transition-layer mean wind structure and significantly affects the analysis of the parameters d, z_0, and z_*.

The transition-layer profile of the eddy diffusion coefficient K for momentum transfer may be obtained by using the diffusivity equation (flux-gradient approach):

$$K\frac{\partial u_T}{\partial z} = u_*^2. \tag{25}$$

By introducing Eqs. (3)–(10) into Eq. (25), we obtain the transition-layer profiles of the momentum diffusivity ratio $K(z)/K(h)$ (illustrated in Fig. 5 as dashed lines), for each of the four different canopy types [Eq. (11)–(14)] discussed in Fig. 1. It follows from Fig. 5 that the momentum diffusivity decreases within the lower part of the transition layer, but increases in the upper layers. Also it is seen that despite the separate models of canopy mean wind structure, the predicted diffusivity profiles are broadly consistent. However, the suggested mass conservation methodology presents a view that is radically different from the (traditionally) expected behavior of the momentum diffusivity ratio $K(z)/K(h)$ within the transition layer. For example, Raupach et al. (1980) assume that the diffusivity within the transition layer is constant with the height. On the other hand, Garratt (1980) suggested a transition-layer momentum diffusivity profile equivalent to

$$K = \frac{ku_*(z-d)}{\Phi(z/z_*)}. \tag{26}$$

Consequently, Garratt's approach suggests a monotonically increasing behavior of the momentum diffusivity ratio $K(z)/K(h)$ within the transition zone (shown in Fig. 5 as solid line). In contrast, it follows from Fig. 5 that canopy mean wind structure has a major influence on the shape of the transition-layer diffusivity profile for momentum transfer. Moreover, the salient feature of the predicted diffusivity profiles (from the suggested mass conservation methodology) is (i) the (monotonically) increasing behavior of $K(z)$ in the upper part of the transition layer and (ii) the relatively small variation of the momentum diffusivity ratio, with $K(z)/K(h) < 1$, within the lower part of the transition layer. This is seen to be in excellent agreement with the behavior of $K(z)$: (i) in the logarithmic regime, where $K(z) = ku_*(z-d)$, and (ii) in the upper layers of the canopy, where $K(z)/K(h) > 1$, as reported by Tohm (1971), Landsberg and Jarvis (1973), and Bache (1986). It is obvious then, that the theoretical cusp at $z = h$ in the K profile (described in Bache 1986) may be removed by adopting the osculating polynomial $u_T(z)$ from Eqs. (4)–(10) as a substitute for the transition-layer mean wind speed profile. In conclusion, the tendency to produce transition-layer mean wind speed and momentum diffusivity profiles consistent with the expected structure of $u(z)$ and $K(z)$ within the forest canopy and the expected $u(z)$ and

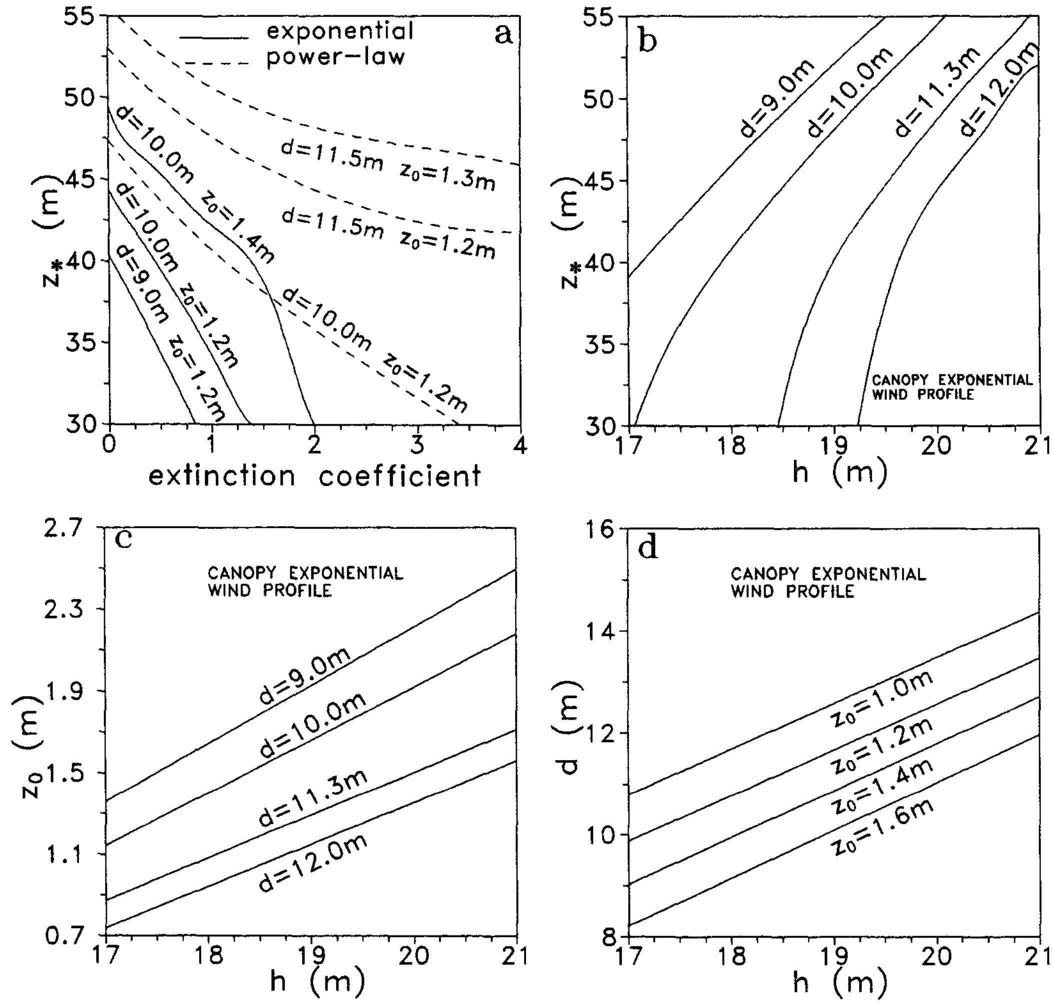

FIG. 4. The relation from Eqs. (3)–(10) between: (a) z_* and profile extinction coefficient, for the exponential (solid line) and power-law (dashed line) canopy wind profiles, for different values of d and z_0; (b) z_* and h, for different values of d; (c) z_0 and h, for different values of d; and (d) d and h, for different values of z_0 (for the exponential canopy wind profile discussed in Fig. 1a).

$K(z)$ profiles within the logarithmic regime is also clearly shown in Figs. 1 and 5.

Since the purpose of this paper is to demonstrate a search approach rather than a model development, simple and popular parameterizations of the canopy wind speed profile [such as Eqs. (11)–(14)] were used for all calculations. For progress, if we accept Eq. (10) as a valid basis for analysis, then the accuracy of the estimates of z_0, d, and z_* via Eq. (3) reflects the ability of Eqs. (11)–(14) to fit the observed in-canopy wind profiles. However, the simplifications and assumptions used in the derivation of Eqs. (11)–(14) are such that one may wonder if $u_C(z)$ could represent the observed $u_m(z)$ wind profiles in plant canopies. Physically, one can argue that a unique wind profile shape may exist for each of the different canopy types. Moreover, it should be noted that a variety of wind profile shapes may be found in reality canopies. On the other hand, Hanna (1971) found that local pressure gradients within a forest canopy may be overwhelmed by the effect of synoptic pressure gradients. Therefore, by the incorporation of a more appropriate analytical expression for the canopy wind profile $u_C(z)$ into the set of equations (3)–(10), it may be possible to represent properly the effects of the underlying canopy on the atmospheric boundary layer [different analytical expressions for $u_C(z)$ require minor modifications of the resultant equations discussed above]. However, despite the fundamental criticisms of Eqs. (11)–(14), experience has shown that a number of observed canopy wind profiles do agree with Eqs. (11)–(14) when the profile extinction coefficients α, β, a, and b are suitably chosen (e.g., Raupach and Thom 1981; Molion and Moore 1983; Bache 1986; Massman 1987).

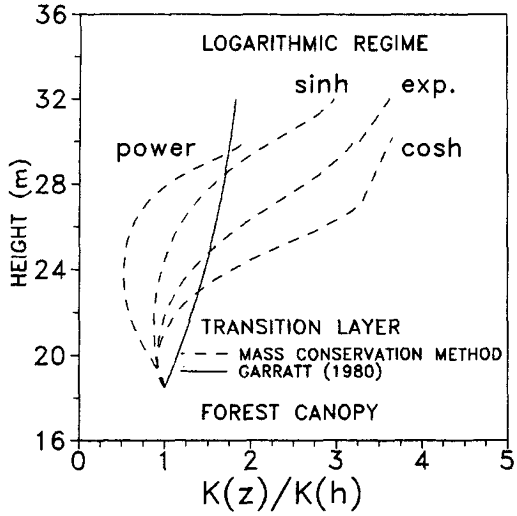

FIG. 5. Transition-layer profiles of the momentum diffusivity ratio (dashed lines) predicted from the mass conservation method, for each of the four different canopy types discussed in Fig. 1. Garratt's approach [see Eq. (26)] is illustrated as solid line.

Moreover, Raupach and Thom (1981) comment that the different canopy wind profile shapes tend to be rather similar in the upper canopy.

3. Conclusions

In summary, the present method is adapted from DeBruin and Moore (1984), Lo (1990), and Zoumakis (1993). An important difference, however, is that the proposed methodology uses simple parameterizations of the mean wind speed profiles in and above a canopy, eliminating the need for measured (within- and above canopy) wind data extending into the logarithmic regime. It is also suggested that the actual $u_m(z)$ mean wind profile within and above a canopy can be fitted with a theoretical curve $u(z)$ to provide a smooth and continuous profile, for which direction and curvature are free of discontinuities. This hypothesis provides support for using a second-order osculating curve $u_T(z)$ as a substitute for the unknown actual wind profile within the transition zone. For the purposes of this study, it is assumed that in the transition layer the mean wind speed profile $u_T(z)$ can be expressed as a fifth-order polynomial form (having second-order osculation) linking the logarithmic wind profile $u_L(z)$ with the canopy wind profile $u_C(z)$. It can be concluded that (i) the present method has eliminated the need of using an empirical formula for $u_T(z)$ that tends to be site specific, (ii) the parameters z_0, d, and z_* can be expressed in quantities that, in principle, can be measured (e.g., the mean height h of roughness elements, the ratio u_*/u_h, and the profile extinction coefficient) and (iii) the predicted transition-layer profiles of mean wind speed and momentum diffusivity seem broadly consistent with the in-canopy $u(z)$ and $K(z)$ profiles, as well as consistent with $u(z)$ and $K(z)$ profiles within the logarithmic regime. Finally, the suggested methodology may be profitably used for simulating airflow for use within large-scale plant–atmosphere exchange models.

The accuracy of the estimates of the aerodynamic characteristics of the canopy via Eq. (3) reflects the ability of the osculating polynomial from Eqs. (4)–(10) to fit the observed mean wind speed profiles within the transition zone. We realize that this idea needs further verification. Therefore, the purpose of a future work is to examine and compare against wind tunnel and atmospheric observations (over representative plant canopy types) the transition-layer profiles of mean wind speed and momentum diffusivity, as predicted from the proposed mass conservation principle, before the validity of the new approach can be fully established. Moreover, the conventional regression techniques (e.g., Lo 1979; Kramm 1989) can be compared with our method. However, for several reasons, the traditional least-squares methods generally used to determine d and z_0 from the measured wind profile are frequently not applicable to tall vegetation (e.g., see Molion and Moore 1983; DeBruin and Moore 1984; Lo 1990). There is, therefore, a need for an alternative regression technique to determine d, z_0, and z_* above tall vegetation and forest canopies. Consequently, by taking into consideration the existence of a transition layer between the canopy and the inertial boundary layer, and fitting the measured wind profiles simultaneously to the theoretical profile relations adopted here [Eqs. (3)–(10)] (i.e., assuming a regression curve having second-order osculation together with the principle of mass conservation), it may be possible to improve the regression technique to determine the aerodynamic characteristics of tall vegetation and forest canopies. Here again we must conclude that more work has to be done. Meanwhile, our mass conservation assumption may be used as a reasonable working hypothesis.

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