NOTES AND CORRESPONDENCE

Estimating the Zero-Plane Displacement and Roughness Length for Tall Vegetation and Forest Canopies Using Semi-empirical Wind Profiles

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ABSTRACT

A simple method based on a mass-conservation principle is presented for estimating the aerodynamic characteristics of forest and tall vegetation canopies. The method uses semi-empirical modifications of the profiles in the transition layer, eliminating the need for measured wind data extending into the logarithmic regime. Also, various schemes are presented for determining the transition-layer depth z_* in terms of the particular physical characteristics of the canopy.

1. Introduction

Wind profiles above plant canopies have been observed to follow the modified logarithmic law, depending on the atmospheric stability. Just above and within a canopy, however, the observed profiles deviate systematically from the theoretical profiles (Garratt 1980). The choice of the values for the zero-plane displacement d and roughness length z_0 can significantly affect the analysis of the other meteorological parameters, especially flux-profile relations and stability functions. Molion and Moore (1983), DeBruin and Moore (1985), and Lo (1990) took into consideration the existence of a transition layer (between the forest canopy and the inertial boundary layer) in determining d and z_0 during their analysis of the Thetford Forest Experiment profile data.

The basic assumption made by DeBruin and Moore (1985) is that the condition of mass conservation can be imposed on the logarithmic wind profile; that is, 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. Providing one measurement of wind speed is available in the inertial sublayer well above the surface, the additional relationship (1) given by the mass-conservation principle, together with a measurement of the friction velocity u_*, allows estimation of d and z_0 without assumptions on the nature of the transition layer. However, as the authors pointed out, in many cii` nstances a measured value of u_* may not be available. Thom (1971) suggested a semi-empirical relation for the roughness parameter of vegetation of height h,

$$z_0 = \lambda(h - d), \qquad (2)$$

where λ is the specific density of the main roughness elements. DeBruin and Moore (1985) reported that the use of the semi-empirical formula (2) as an alternate for a measure u_* yielded satisfactory results. Lo (1990) proposed another method that uses wind velocities from two top levels, z_n and z_{n+1}, of the wind profile within the inertial boundary layer for neutral stability, replacing the need for a simultaneously measured u_*.

In tall vegetation and forest canopies most of the momentum is absorbed in the upper part of the canopy where leaves are concentrated. Farther down, as the leaf-area density decreases to zero, wind speed may increase with decreasing height above the ground, until surface friction reverses this trend close to the ground level. This suggests that a low-level wind maximum may appear in the lower part of certain forest canopies. Moreover, Hanna (1971) found that local pressure gradients within a forest canopy may be overwhelmed by the effect of synoptic pressure gradients. Thus, it is possible that only a small percentage of measured wind profiles would resemble the near-perfect wind profile used in DeBruin and Moore (1985) and Lo (1990).

A disadvantage of the mass-conservation method

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proposed by DeBruin and Moore (1985) and Lo (1990) is the need for measured wind data within the inertial sublayer. On the other hand, the selection of the value for z_f (where $z_f \leqslant z_*$) was found to be the most critical step in applying the method (Lo 1990).

Garratt (1980) suggested that a limit (z_*) above d exists below which the Monin–Obukhov functions $\Phi_{M,H}(z/L)$ does not hold. Garratt found that $z_*/z_0 \approx 35$ and 150 for wind at a dense and a less dense underlying forest canopy surface, respectively, while for temperature $z_*/z_0 \approx 100$. Tennekes (1982) also reports on a suggested relationship between the lower limit of the inertial sublayer (z_*) and z_0, which is given by

$$z_* \approx d + 20z_0. \tag{3}$$

As suggested by Lo (1990), it would be desirable to extend measured wind profiles to some higher levels in order to ascertain that the two top levels z_n and z_{n+1} are within the logarithmic profile regime. However, this is usually impossible because it requires elaborate and expensive experimental equipment. Therefore, in micrometerological studies it is common to rely on semi-empirical modifications of the wind profile within the transition layer.

2. Methodology and discussion

Modifications of the nondimensional vertical gradients $\Phi^0_{M,H}$ of wind and potential temperature in the transition layer can be described through a function (Garratt 1980):

$$\Phi^0_{M,H}\left(\frac{z}{L}, \frac{z}{z_*}\right) = \Phi_{M,H}\left(\frac{z}{L}\right)\Phi\left(\frac{z}{z_*}\right), \tag{4}$$

with

$$\Phi\left(\frac{z}{z_*}\right) \equiv \alpha \exp\left[\alpha_1\left(\frac{z}{z_*}\right)\right], \quad z < z_*, \tag{5}$$

where L is the Monin–Obukhov stability length and the parameter $\alpha \equiv \exp(-\alpha_1)$ has a value close to 0.5 (Garratt 1980); that is, the gradient Φ attains a minimum value of 0.5 as the surface is approached ($z/z_* \rightarrow 0$).

For the neutral transition layer, we justify for the vertical wind shear (Garratt 1980)

$$\frac{\partial u}{\partial z} = \left(\frac{u_*}{kz}\right)\Phi\left(\frac{z}{z_*}\right), \quad z < z_*, \tag{6}$$

where k is von Kármán's constant. Integrating Eq. (6) from z to z_* gives the wind profile $u_T(z)$ within the transition layer:

$$u(z_*) - u_T(z) = \frac{u_*}{k}\int_z^{z_*} \frac{1}{z}\,\Phi\left(\frac{z}{z_*}\right)dz. \tag{7}$$

Then we write Eq. (7) as

$$u_T(z) = u_L(z) + u_G(z), \tag{8}$$

where

$$u_G(z) = \frac{u_*}{k}\left[\ln\left(\frac{z_*}{z}\right) - \int_z^{z_*} \frac{1}{z}\,\Phi\left(\frac{z}{z_*}\right)dz\right]$$

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

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

To integrate the preceding equations, we expand the exponential function $\Phi(z/z_*)$ by considering only the first three terms (Garratt 1980, 815–816).

Extending the measured velocity profile $u_m(z)$ to higher levels ($z_f \leqslant z \leqslant z_*$), from the principle of mass conservation [Eq. (1)] and from Eq. (8), yields

$$\int_{d+z_0}^{z_*} u_L(z)dz = \int_0^{z_f} u_m(z)dz + \int_{z_f}^{z_*} u_T(z)dz, \tag{9}$$

$$\int_{d+z_0}^{z_f} u_L(z)dz + \int_{z_f}^{z_*} u_L(z)dz = \int_0^{z_f} u_m(z)dz + \int_{z_f}^{z_*} u_L(z)dz + \int_{z_f}^{z_*} u_G(z)dz, \tag{10}$$

and from Eqs. (7), (8), (9), and (10) yields

$$\frac{\int_{d+z_0}^{z_f} u_L(z)dz - \int_{z_f}^{z_*} u_G(z)dz}{u_T(z_f)} = A_f, \tag{11}$$

where

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

$$\int_{z_f}^{z_*} u_G(z)dz = (z_* - d)\left(\frac{u_*}{k}\right)(I_1 + I_2 + I_3 + I_4),$$

$$I_1 = -(\alpha - 1)[q(\ln q - 1) + 1],$$

$$I_2 = -\left(\alpha\frac{\alpha_1}{2}\right)(q-1)^2,$$

$$I_3 = -\left(\alpha\frac{\alpha_1^2}{12}\right)(q^3 - 3q + 2),$$

$$I_4 = -\left(\alpha\frac{\alpha_1^3}{72}\right)(q^4 - 4q + 3),$$

$$A_f = \int_0^{z_f} \frac{u_m(z)}{U}\,dz,$$

where $x = (z_f - d)/z_0$, $q = (z_f - d)/(z_* - d)$, $U = u_m(z_f)$ is the measured wind velocity at the level z_f, and $\{u_m(z)/U\}$ is the normalized mean wind speed (DeBruin and Moore 1985; Lo 1990). The quantity

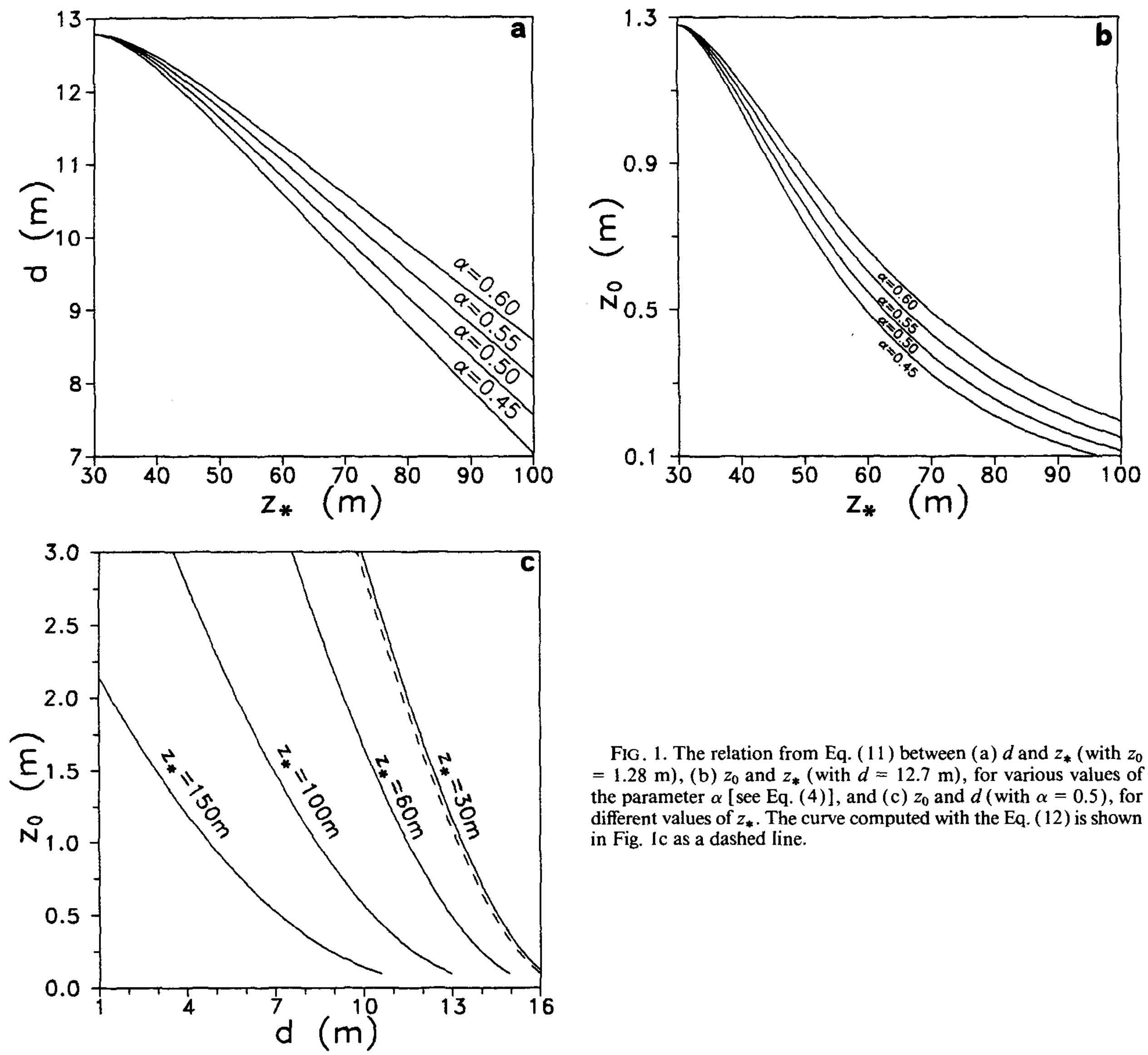

FIG. 1. The relation from Eq. (11) between (a) d and z_* (with z_0 = 1.28 m), (b) z_0 and z_* (with d = 12.7 m), for various values of the parameter α [see Eq. (4)], and (c) z_0 and d (with α = 0.5), for different values of z_*. The curve computed with the Eq. (12) is shown in Fig. 1c as a dashed line.

A_f can be determined by integrating the measured wind profile using the Thetford Forest Experiment data (with z_f = 29.93 m) published by DeBruin and Moore (1985) and Lo (1990).

The principle of mass conservation [Eq. (1)] leads to a relationship between the aerodynamic characteristics of the canopy [Eq. (11)], which allows estimates of z_0, d, and z_* without assumptions on the structure of the canopy. Based on Eq. (11), Figs. 1a and 1b show the relation between d and z_* (with z_0 = 1.28 m) and between z_0 and z_* (with d = 12.7 m), respectively, for various values of the parameter α. Then for different values of z_*, based on Eq. (11), the plot in Fig. 1c was constructed expressing the relation between d and z_0 (with α = 0.5). Figure 1 shows clearly that d and z_0 are strongly dependent on z_*. On the other hand, one can show that it is important to include the transitional-layer profile function $u_G(z)$ for estimates of d and z_0, when the measurements are obtained in the transition sublayer. If the logarithmic wind profile $u_L(z)$ is used rather than $u_T(z)$; that is, $u_G(z) \approx 0$, from Eq. (8) and (11) yields

$$\frac{\int_{d+z_0}^{z_f} u_L(z)dz}{u_L(z_f)} = A_f. \tag{12}$$

The curve computed with the Eq. (12) is shown in Fig. 1c as a dashed line. Thus, according to Fig. 1, the transition sublayer wind can significantly affect the analysis of the parameters d and z_0. The important point to be mentioned here is that users of such methods (Molion and Moore 1983; DeBruin and Moore 1985; Lo 1990) should be careful in their z_f selection (where $z_f \leqslant z_*$),

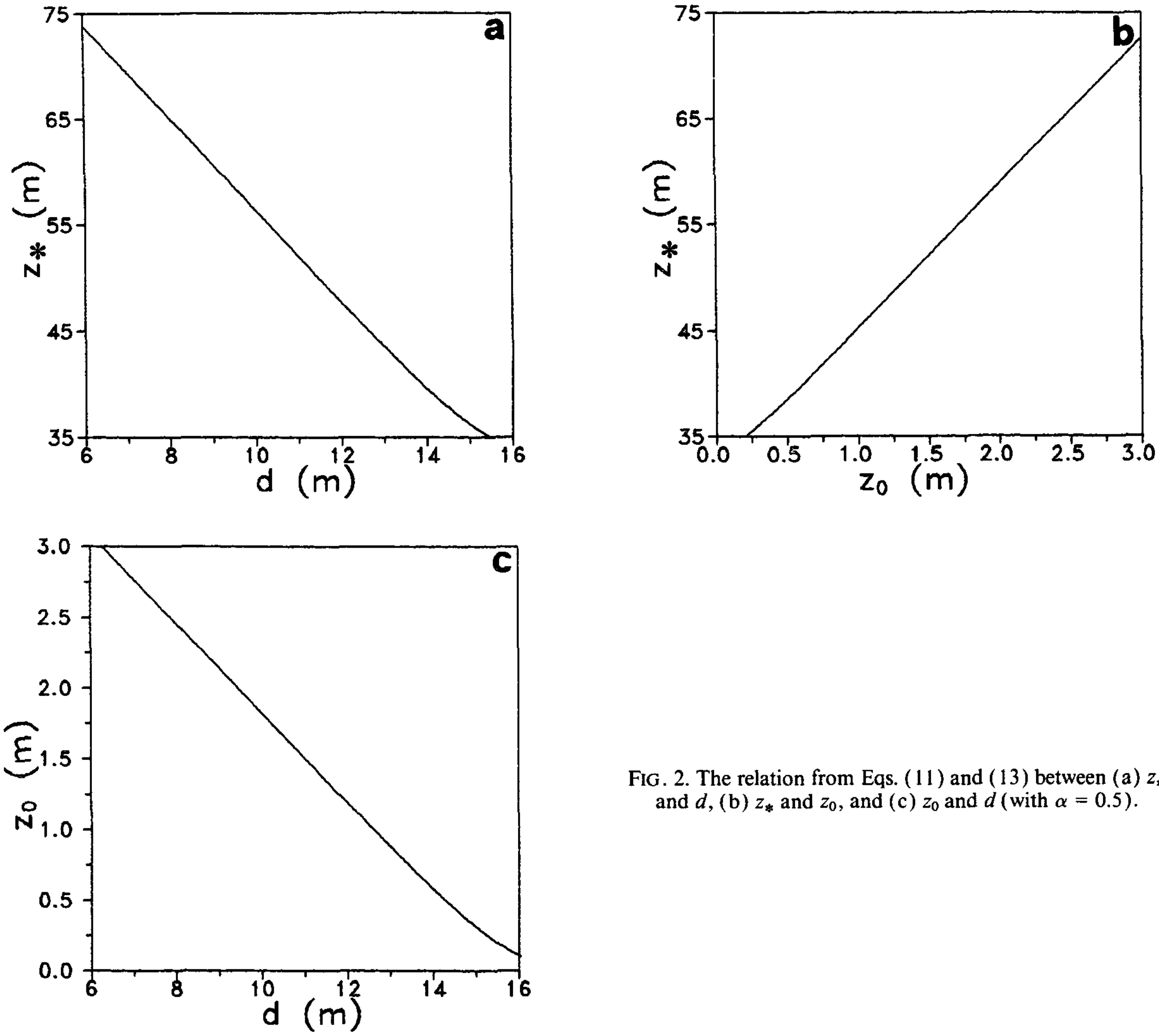

FIG. 2. The relation from Eqs. (11) and (13) between (a) z_* and d, (b) z_* and z_0, and (c) z_0 and d (with $\alpha = 0.5$).

because their results may be quite sensitive to the value of z_* (using different values of z_* is an essential cause for differing results). It is for these reasons that the ability to determine realistic values for z_* to characterize the presence of a forest canopy is important.

The description of the wind profile through the concept of a transition layer requires determination of the quantity z_*. Now it seems reasonable to assume that the transition-layer depth z_*, at least in neutral conditions, will be uniquely determined by d and z_0 through a relationship

$$z_* = z_*(d, z_0), \qquad (13)$$

where $z_*(d, z_0)$ are analytical semi-empirical functions quoted in the literature (e.g., Garratt 1980; Tennekes 1982). Based on Eqs. (3) and (11), Figs. 2a, 2b, and 2c show the relation between z_* and d, z_* and z_0, and z_0 and d, respectively (with $\alpha = 0.5$). Moreover, attempts have been made to associate z_0 and d with some physical characteristics of the atmosphere–vegetation interaction. A simple approach is to assume that z_0 may be uniquely determined by λ, h, and d through a relationship

$$z_0 = z_0(\lambda, h, d), \qquad (14)$$

where $z_0(\lambda, h, d)$ are analytical semi-empirical functions quoted in the literature. Thom (1971) suggested the semi-empirical equation (2), in which the parameter λ ought to be insensitive to vegetation height. Oke (1978) also reports on a simple empirical formula between roughness and vegetation height for tall, dense vegetation, which is given by

$$z_0 \approx \mu h, \qquad (15)$$

where μ is an empirical coefficient that depends upon the particular physical characteristics of the canopy. Also, a simple approach is to assume that d may be uniquely determined by h through a relationship

$$d \approx \nu h, \qquad (16)$$

where ν is an empirical coefficient that depends upon the particular physical characteristics of the canopy.

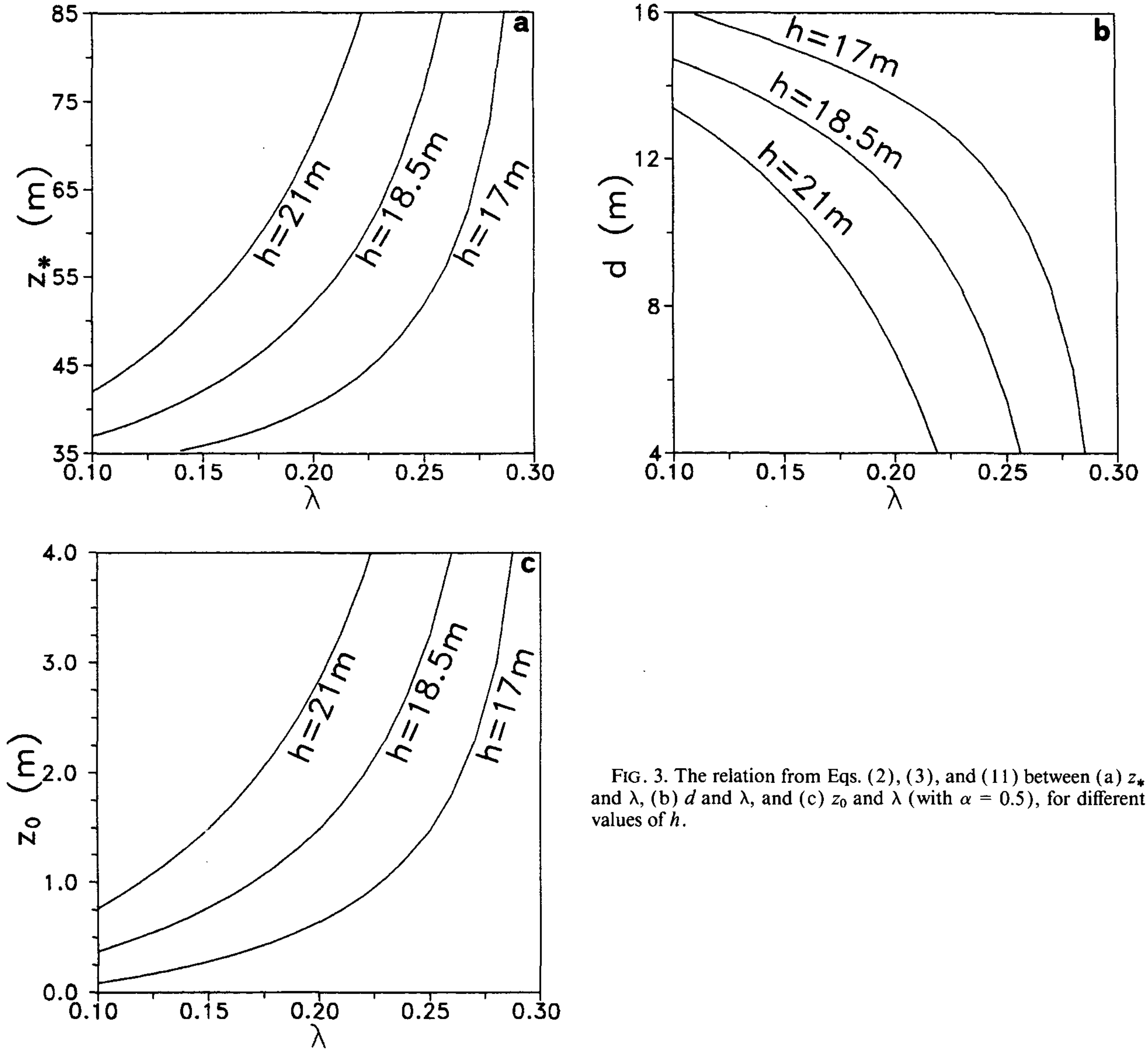

FIG. 3. The relation from Eqs. (2), (3), and (11) between (a) z_* and λ, (b) d and λ, and (c) z_0 and λ (with α = 0.5), for different values of h.

Based on Eqs. (11) and (13), the semi-empirical relationships (2), (15), and (16) can then be used to establish various schemes for determining the transition-layer depth z_*, in terms of the particular physical characteristics of the canopy. One such a scheme is presented in Fig. 3. Based on Eqs. (2), (3), and (11), Figs. 3a, 3b, and 3c show the relation between z_* and λ, d and λ, and z_0 and λ, respectively, for various values of the height h of the vegetation (with $\alpha = 0.5$). Although the precise functional dependence of $z_*(d, z_0)$ and $z_0(\lambda, h, d)$ have been difficult to determine even for well-specified rough surfaces and flow characterization, Fig. 3 also shows the importance of the transitional sublayer profile function $u_G(z)$ and the structure of the canopy in estimating the parameters d, z_0, and z_*.

Garratt (1980) suggested that the transition layer depth z_*, at least in neutral conditions and for $z_* < |L|$, will be uniquely determined by the surface length scale z_s. This length scale is imposed upon the flow through the action of turbulent wakes generated by flow around the roughness elements. Garratt found that δ (spacing between trees) is the relevant surface length scale z_s, whereas Raupach et al. (1980) suggested that z_* is related to the lateral horizontal length scale of trees (l_h). However, we find that the density of the roughness elements within the canopy plays an important role in determining the thickness of the transition sublayer. Figure 3 allows the tentative suggestion that the transition-sublayer depth z_* can be uniquely determined by the parameters λ and h (for any given A_f).

Because of the crucial importance of the bottom boundary for the mesoscale atmospheric systems, it is essential that it be represented as accurately as possible. Since much of the world is vegetated, it would be inappropriate to neglect this important component of the ground characteristics in a mesoscale model (Pielke 1984). It is felt that z_0, d, and z_* are very important parameters that can have a significant impact on the analysis of meteorological and flux transfer parameters when modeling boundary-layer flows over tall vegetation and forest canopies. Consequently, by the incorporation of a further relationship among z_0, d, and z_* [such as Eq. (9)] into the set of equations used in a mesoscale atmospheric model, it may be possible to represent properly the effects of the underlying canopy on the atmospheric boundary layer.

In conclusion, the present method is based on the same mass-conservation principle as that of DeBruin and Moore (1985) and Lo (1990). An important difference, however, is that the proposed methodology uses semi-empirical modifications of the wind profile in the transition layer, eliminating the need for measured wind data extending into the logarithmic regime. Moreover, the suggested methodology represents a preliminary step in a more basic parameterization of the flow over tall vegetation and forest canopies. However, more studies are probably needed to determine the lower limit of the inertial sublayer and to investigate the transition-layer wind profile before the suggested procedure may be used in an operational mode.

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