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Determination of momentum and mass exchange mechanisms in and above tall vegetation and forest canopies using a multidimensional minimization algorithm

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Summary. — A numerical model based on a multidimensional minimization algorithm was developed to estimate the aerodynamic characteristics of forest and tall vegetation canopies. The suggested methodology should be especially useful for many applications in the field of biotic and abiotic systems, air pollution modeling, and agricultural and forest micrometeorology.

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1. – Introduction

It is well known that transfer mechanisms and turbulence characteristics within and immediately above a canopy are significantly different from those of the atmospheric boundary layer over an open field [1-3]. It is obvious then, that 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. As suggested by Lo [4], it would be desirable to extend measured wind profiles to some higher levels in order to ascertain that the top level is within the logarithmic profile regime. However, this is usually impossible because it requires elaborate and expensive experimental equipment. Therefore, in micrometeorological studies it is usual to rely on semi-empirical modifications of the wind profile within the transition layer [5, 6].

2. – Methodology and discussion

The present study proposes that a realistic model should consist of a microscale flow field within the vegetative canopy coupled with the transition-layer flow field above the canopy. The basic assumption [2-6] 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 [6, 7]:

$$(1) \qquad F(z_0, d, z_*, h, \alpha, u_*/u_h) \equiv \int_{d+z_0}^{z_*} u_L(z)\mathrm{d}z - \int_0^h u_C(z)\mathrm{d}z - \int_h^{z_*} u_T(z)\mathrm{d}z = 0\,,$$

where $u_T(z)$ is a semi-empirical modification of the wind speed profile in the transition layer [6,7], z_* is the transition layer depth, $u_C(z)$ is a theoretical canopy wind profile [5-7], u_* is the friction velocity, h is the mean height of roughness elements, $u_h = u_C(h)$ is the mean horizontal wind speed at the top of the canopy, and α is the canopy wind profile extinction coefficient. The suggested semi-empirical modification of the wind speed profile in the transition layer is the unique polynomial approximation $u_T(z)$ having second-order osculation, 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 [6, 7].

The calculation of the parameters d, z_0, and z_* is carried out by fitting the measured wind data of the Thetford Forest Experiment [4] with the theoretical multidimensional function $F(z_0, d, z_*, h, \alpha, u_*/u_h)$ subject to some constraint conditions adopted in Zoumakis [6, 7], using a computer minimization algorithm [8,9]. By adopting the canopy exponential wind profile [6, 7], with $h = 18.5\,\mathrm{m}$, from the suggested regression technique finally yields: $\alpha = 2.53$, $u_*/u_h = 0.29$, $z_0 = 1.19\,\mathrm{m}$, $d = 11.32\,\mathrm{m}$, and $z_* = 32\,\mathrm{m}$ [1,2,6,7]. The preliminary results compare well with the experimental data [1,2,4], and theoretical deductions of Zoumakis [5-7].

Now there is a basis for developing a methodology for estimating the aerodynamic characteristics of forest and tall vegetation canopies, which are related to the momentum and mass exchange mechanisms between the atmosphere and the plant canopies. The suggested methodology should be especially useful for many applications in agriculture, forestry, hydrology, meteorology and air pollution modeling.

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