SIMPLIFIED EXPRESSIONS FOR VEGETATION ROUGHNESS LENGTH AND ZERO-PLANE DISPLACEMENT AS FUNCTIONS OF CANOPY HEIGHT AND AREA INDEX

(Research Note)

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Abstract. Using a previous treatment of drag and drag partition on rough surfaces, simple analytic expressions are derived for the roughness length ($z_0$) and zero-plane displacement ($d$) of vegetated surfaces, as functions of canopy height ($h$) and area index ($A$). The resulting expressions provide a good fit to numerous field and wind tunnel data, and are suitable for applications such as surface parameterisations in atmospheric models.

1. Introduction

There is a continuing need for simple descriptions of vegetation roughness, for instance, to parameterise surface momentum exchanges in mesoscale and global climate models. In particular, it is useful to relate the surface roughness length ($z_0$) and zero-plane displacement ($d$) to readily observable properties of vegetated surfaces, such as the canopy height ($h$) and the roughness density or frontal area index ($A$). This note advances and tests analytic expressions for $z_0$ and $d$ as functions of $h$ and $A$, based on a recent analytic treatment of drag and drag partition on rough surfaces (Raupach, 1992; henceforth R92). Both R92 and this note are both restricted to surfaces without strong horizontal anisotropy, thus excluding “two-dimensional” roughness such as repeated parallel windbreaks or laboratory bar roughness.

2. Previous Analysis

Drag coefficient: R92 used dimensional analysis, together with physical hypotheses about the scales controlling roughness element wakes and the way that element wakes interact, to predict the bulk drag coefficient $u^2_{\infty}/U_h^2$ of a rough surface at the roughness element height $h$. Here $u_{\infty}$ is the friction velocity and $U_h$ the mean velocity at height $h$ (with the height origin being the ground or substrate surface). The independent variable in the analysis, specifying the amount of roughness present, is the frontal area index or roughness density, $A$ (the frontal area of
roughness elements, from the mean wind direction, per unit ground area). From R92, the implicit equation predicting $\gamma = U_h/u_\ast$ is

$$\gamma = U_h/u_\ast = (C_S + C_R \lambda)^{-1/2} \exp(c\lambda \gamma/2) \quad (1)$$

where $C_S$ is the drag coefficient of the substrate surface at height $h$ in the absence of roughness elements, $C_R$ is the drag coefficient of an isolated roughness element mounted on the surface, and $c \approx 0.5$ is an empirical coefficient determined by the rate at which an element wake spreads in the cross-stream directions. Equation (1) predicts, firstly, that at low $\lambda$ values ($\leq 0.1$, in practice), $u_\ast/U_h = \gamma^{-1}$ is well approximated by the explicit limit

$$u_\ast/U_h = \gamma^{-1} \rightarrow (C_S + C_R \lambda)^{1/2} \quad \text{as } \lambda \rightarrow 0. \quad (2)$$

Secondly, Equation (1) predicts that $u_\ast/U_h = \gamma^{-1}$ increases with $\lambda$ up to a value $\lambda_{\text{max}}$ (around 0.3), beyond which it decreases. The value $\lambda_{\text{max}}$ can be interpreted as the onset of "over-sheltering", the point at which adding further roughness elements to the surface does not affect the bulk drag because additional elements merely shelter one another. However, for $\lambda \gg \lambda_{\text{max}}$, the assumptions leading to Equation (1) are untenable. To replace them, R92 used the observation that when $\lambda > \lambda_{\text{max}}$, $u_\ast/U_h$ is nearly constant (at about 0.3) for a wide range of natural and artificial surfaces (Jarvis et al., 1976; Raupach et al., 1991). Therefore, Equation (1) is extrapolated beyond $\lambda_{\text{max}}$ with

$$u_\ast/U_h = \gamma(\lambda) \quad \text{for } \lambda \leq \lambda_{\text{max}}$$

$$u_\ast/U_h = \gamma(\lambda_{\text{max}}) \quad \text{for } \lambda > \lambda_{\text{max}} \quad (3)$$

where $\gamma(\lambda)$ is the solution of Equation (1).

Roughness length: $z_0$ is related to $U_h/u_\ast$ (and thence to $\lambda$, from Equation (3)) by

$$z_0/h = (1 - d/h) \exp(-\kappa U_h/u_\ast - \Psi_h) \quad (4)$$

where $\kappa \approx 0.4$ is the von Karman constant and $\Psi_h$ is the roughness-sublayer influence function, describing the departure of the velocity profile just above the roughness from the inertial-sublayer logarithmic law. If the eddy diffusivity for momentum is constant in the roughness sublayer and the upper height limit $z_w$ of the roughness sublayer scales as $(z_w - d) = c_w(h - d)$ (where $c_w$ is an O(1) constant), then

$$\Psi_h = \ln(c_w) - 1 + c_w^{-1} \quad (5)$$

There is a sign error in Equations (29) and (31) of R92, which should read:

$$\Psi\left(\frac{z - d}{z_w - d}\right) = \ln\left(\frac{z_w - d}{z - d}\right) + \frac{z - z_w}{z - d} \quad (29)$$

$$\Psi_h = \ln(c_w) - 1 + c_w^{-1} \quad (31)$$