NOTES AND CORRESPONDENCE

The Roughness Length for Heat of Sparse Vegetation

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ABSTRACT

A dual-source model that solves the energy balance over vegetation and soil separately can be inverted to obtain the roughness length for heat z_{0h} of a single-source model. Model parameters for the dual-source model were taken from previous analysis of data from a sparse canopy in semiarid terrain. In these circumstances, the value of z_{0h} is shown to be dependent on the humidity deficit, the available energy, the vegetation fraction, and the surface resistance of the soil and the vegetation.

1. Introduction

The roughness length for heat z_{0h} is used to define the relationship between the vertical temperature gradient above a surface and the surface sensible heat flux:

$$T_s - T(z) = \frac{H}{ku_*\rho c_p}\left[\ln\left(\frac{z-d}{z_{0h}}\right) - \psi\right], \quad (1)$$

where T_s is the surface temperature, $T(z)$ is the temperature at height z, H is the sensible heat flux, ρ is the density of air, c_p is the specific heat capacity of air, u_* is the friction velocity, k is von Kármán's constant, d is the displacement height, and ψ is the stability correction.

For a homogeneous surface, z_{0h} has been found to be proportional to the roughness length for momentum z_{0m} (Garratt and Hicks 1973):

$$\ln\left(\frac{z_{0m}}{z_{0h}}\right) \approx 2.$$

For sparse canopies the situation is more complex. Beljaars and Holtslag (1991) reported that an increase in momentum flux due to bluff body effects of sparse vegetation is not accompanied by a similar increase in sensible heat flux. Without considering the effect of changes in u_* on ψ, if the temperature gradient and the sensible heat flux above sparse vegetation were the same as for homogeneous vegetation, the increase in u_* will force a decrease in z_{0h} through Eq. (1). This simple result was confirmed by Wood and Mason (1991). In addition, in sparse canopies the sources and sinks of sensible and latent heat are not necessarily the same. This difference destroys the otherwise unique relationship that exists for a homogeneous surface between the above canopy gradients of temperature and humidity and the sensible and latent heat fluxes. Garratt et al. (1993) qualitatively described this phenomenon and then asked the provocative question, Can this be modeled? This note is in response to that question.

The phenomenon is explicitly modeled by so-called dual-source models. Given available energy, air temperature, and humidity deficit, these models generate area-average heat fluxes and surface temperatures for a surface consisting of two distinct components, for example, bare soil and vegetation. Equation (1) can then be used to find an effective value for z_{0h}. For the purposes of the following examples, the model developed by Dolman (1993) was used.

This note addresses the effect of the difference of the sources and sinks of sensible and latent heat on z_{0h} and does not address the question of momentum absorption. This, when necessary, is considered to be constant to isolate the thermodynamic effect.

2. Model results for z_{0h} of a sparse canopy

The difference between scalar and momentum transfer is parameterized in this model through the use of boundary layer resistances that represent the interfacial sublayer close to the surface. Figure 1 shows the

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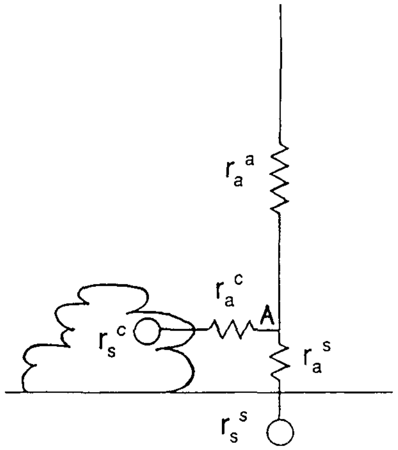

FIG. 1. Two-source SVAT scheme used to simulate sensible heat flux and surface temperature.

layout of the resistances of the model. The aerodynamics of the model were simplified for this exercise. The aerodynamic resistance r_a^a between the reference height and the point A in Fig. 1 was set at 20 s m^{-1}, the aerodynamic resistance plus the boundary layer resistance r_a^s between the soil and point A was set at 10 s m^{-1}, while the boundary layer resistance r_a^c between the bush and point A was set at 2 s m^{-1}. These values are similar to the resistances found by optimizing the model against data from the Sahelian tiger bush (Blyth and Harding 1994). The dual-source model works by extrapolating the humidity deficit from the reference height to point A, from which point the Penman–Monteith equation is used to solve the energy balance over each surface. If the fractional coverage of the vegetation is set at 50%, the surface resistances of the soil and vegetation are set at 1500 and 60 s m^{-1}, respectively, the friction velocity is 0.4 m s^{-1}, the available energy of both the soil and the vegetation is 500 W m^{-2}, the humidity deficit is 0.015 kg kg^{-1}, and the air temperature is 25°C, then the sensible heat flux predicted by the dual-source model is 116 W m^{-2} and the average temperature difference between the surface and the air is 4.4°C. By substituting these values into Eq. (1), the value obtained for z_{0h} is 0.01 m. Since the height of the bushes is 4 m, it would normally be assumed that $z_0 = 0.4$ m, although the measured value was somewhat higher than this (Dolman et al. 1993). Thus, this diagnosed value of z_{0h} is considerably lower than the equivalent homogeneous value.

Figure 2 shows how z_{0h} varies with two environmental properties: available energy and humidity deficit. At low values of available energy and at high values of humidity deficit, the sensible heat flux of the bushes can become negative. The coincidence of the low sensible heat flux with the low aerodynamic resistance of the vegetation means that average sensible heat fluxes can be low while the average vertical temperature gradient remains high; this results in low values of z_{0h} (Blyth et al. 1993).

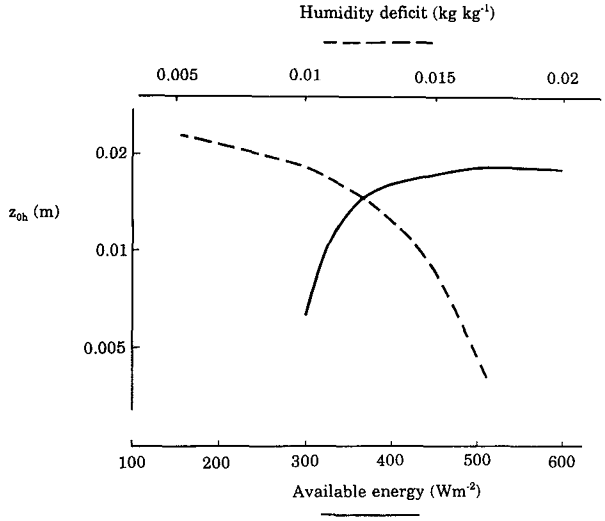

FIG. 2. Diagnostic value of z_{0h} from simulated sensible heat flux and surface temperature, varying with available energy and humidity deficit.

Figure 3 shows how z_{0h} varies with the percentage cover of vegetation. The values of the aerodynamic resistances used in the dual-source model were taken from observations with vegetative cover of about 50%. As the vegetation cover tends to 0% or 100%, they probably no longer apply, as, for instance, the observed aerodynamic resistance over bare soil includes turbulence generated by the vegetation. Therefore, the calculations are only made from 10% to 90% vegetation cover. With partial vegetative cover, the value of z_{0h} is biased toward the lower values of z_{0h} that correspond to the soil, and the lower the surface resistance of the vegetation, the lower the value of z_{0h}.

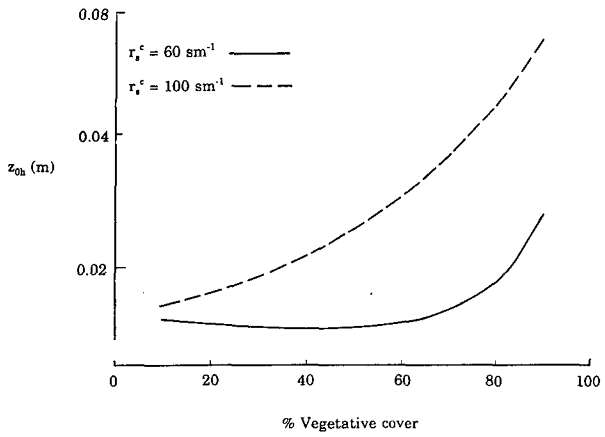

FIG. 3. Diagnostic value of z_{0h} varying with vegetation cover and with surface resistance of the vegetation.

3. Comparison with homogeneous case

To compare the new varying value of z_{0h} to its equivalent homogeneous value z'_{0h}, the momentum roughness length of the sparse canopy needs to be estimated. Momentum exchange of a sparse canopy is dominated by the vegetation. So, rather than attempting to parameterize the complex change of momentum roughness with vegetative cover, the momentum roughness length was assumed to be constant and equal to the momentum roughness length of the vegetation. This assumption clearly could not hold over zero vegetation cover, so the calculations are made at a minimum vegetation cover of 10%. The equivalent homogeneous value of roughness length for heat for this example z'_{0h} is then given by the following:

$$r_a^a + r_a^c = \frac{1}{ku_*}\left[\ln\left(\frac{z}{z'_{0h}}\right) - \psi\right].$$

This estimate of z'_{0h} is probably too large for low percentage cover and possibly too small for middle and high percentage cover, but it is adequate as a first-order approximation. Figure 4 shows how the ratio z'_{0h}/z_{0h} varies between 20 and 30 with percentage cover of vegetation of a sparse canopy. It is worth noting that the dual-source model used to generate these curves has nothing to teach us about homogeneous vegetation; hence the calculations are made between 10% and 90% vegetation cover. The lower curve is the result of assuming a vegetation substrate: the roughness length is not changed but the surface resistance is set at 100 s m^{-1}. In this case the ratio z'_{0h}/z_{0h} is about 5.

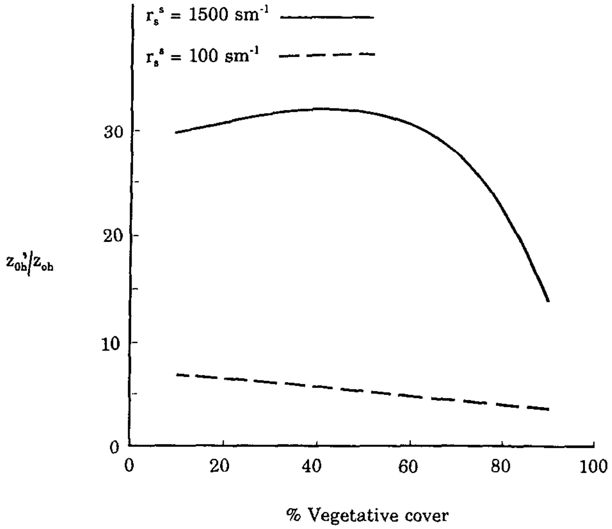

FIG. 4. The ratio of the value of z_{0h} that would be estimated from the height of the roughness obstacles to the diagnostic value varying with vegetation cover and with surface resistance of the soil.

4. Conclusions

The thermodynamic relationship between vegetation and soil in a sparse canopy can account for at least one order of magnitude difference between the roughness length for heat of a homogeneous surface and a sparse canopy. Any meteorological model using a fixed value of z_{0h} to represent the heat transfer properties of a sparse surface is introducing errors. A dual-source model is the ideal method of representing sparse terrain.

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