A Note on Alternatively Direct Measurement of the Transfer Resistance over Vegetation

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ABSTRACT

The boundary layer transfer resistance is an important parameter in micrometeorology. The most common approach to determining it uses a wind function that is extremely sensitive to the specified roughness length and can suffer large uncertainties, especially for partially vegetated surfaces. In order to avoid using some sensitive parameters not easily determined, a simple apparatus was designed for direct measurement of the resistance. This note reports the preliminary results of a test using the apparatus in a sparse wheat field.

1. Introduction

The energy and mass fluxes in the atmospheric boundary are important to the understanding of processes in micrometeorology, hydrology, and agriculture, etc. At present, many methods can be used to estimate or measure the fluxes. One of them, flux models based on the surface transfer resistance, is widely applied in many fields. Typically, for instance, the resistance to momentum transfer is defined as

$$r_{\mathrm{am}} = \int_{d+z_0}^{z} \frac{1}{K}\, dz, \tag{1}$$

where d is the zero-plane displacement height, z_0 is momentum roughness length, z is a reference height, and K is momentum eddy diffusivity. Using the surface-layer similarity relationship, the above equation can be expressed as

$$r_{\mathrm{am}} = \left[\ln\frac{z-d}{z_0} - \Psi\left(\frac{z-d}{L}\right)\right]^2 \Bigg/ \kappa^2 u, \tag{2}$$

where Ψ is the integral form of the stability function (Paulson 1970), L is Monin–Obukhov length, κ (=0.4) is the von Kármán constant, and u is wind speed at height z.

The transfer resistance to water vapor, r_{aw}, differs from Eq. (2) because of two mechanisms: First, the efficiency of eddy transport of water vapor in ambient air is different from that of momentum. Second, water vapor roughness length is smaller than momentum roughness length, due to the fact that the exchange of water vapor between the air and plant elements depends on molecular diffusion only, whereas the dominant process of momentum sink is form drag. To account for the second mechanism, Thom (1972) and others have introduced an excess resistance, r_b, so that

$$r_{\mathrm{aw}} = r_{\mathrm{am}} + r_b. \tag{3}$$

For a water-saturated evaporating surface, r_b is much less than r_{am} and can be neglected. To evaluate r_{am} using Eq. (2), information on air stability, which is not a routine measurement, is required. Also, Eq. (2) is extremely sensitive to the specified roughness length. For general vegetation, surface roughness length is often taken as

$$z_0 = 0.1h, \tag{4}$$

where h is the mean height of the roughness elements. This simple relationship may be in gross error for a partially vegetated surface. For example, Raupach (1994) showed that the ratio, z_0/h, can vary by a factor of 10 over sparsely vegetated surfaces.

Monteith (1981) presented a method for determining evapotranspiration over a water-saturated surface only using surface temperature and humidity at one height, and the transfer resistance to water vapor, r_{aw}, can be calculated by the following equation:

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$$r_{aw} = \frac{\rho c_p}{\upsilon} \frac{e_s(t_0) - e_a}{\lambda E}, \quad (5)$$

where ρc_p is the heat capacity of air at constant pressure, $e_s(t_0)$ is the saturation vapor pressure at t_0, which is the evaporating surface temperature, λ is the latent heat of vaporization, E is the evaporation rate, and υ is the psychrometric constant. This method lead us to the idea that if we can design a simple apparatus to measure all items of the right-hand side of Eq. (5), r_{aw} can be determined.

In this note, the designed apparatus is described and the results of the field test are verified with other methods. Our main purpose is to explore a simple and feasible method of directly measuring or estimating transfer resistance and to avoid using sensitive parameters such as z_0, stability function, etc.

2. Apparatus, method, and principle for direct measurement of the transfer resistance

The apparatus consisted of four components: 1) A fully water-saturated evaporating surface made of cotton cloth and in full contact with a piece of sponge immersed in a metal pan of 15-cm diameter and 5-cm depth. The sponge was saturated with water. Covered under the cloth were four precision platinum resistance thermometers (PT100) that measured the average temperature of the surface, t_0. 2) A psychrometer consisting of a web-bulb and a dry-bulb PT100 resistance thermometer. It measured the actual water vapor pressure of the air, e_a, at reference height z. 3) A datalogger that recorded the temperature signals. 4) A precision balance (BAL-001, Shanghai, China), with 0.01-g accuracy, to measure the weight change of the evaporation pan and hence the evaporation rate E, typically over a 15–30-min interval. Using the measurements above, R_a, used specially to denote the results acquired by this apparatus, can be computed by Eq. (5).

The evaporation pan was placed in the middle of a 500 m $\times$ 1500 m leveled wheat field, with the evaporating surface positioned at the zero-plane displacement height. Theoretically, the evaporating surface should be positioned at the height of $d + z_{0\upsilon}$, where $z_{0\upsilon}$ is the roughness length of water vapor transfer. However, during the experiments, because $z_{0\upsilon}$ is very small, the height mentioned above is regarded as approximately equal to $(d + z_{0\upsilon})$. At the time of the experiment, the average crop height, h, was 0.22 m (ranging from 0.18 to 0.26 m), and mean leaf area index was 0.9 (ranging from 0.6 to 1.2). Because the crop was planted in rows, over 80% of the soil was not covered by vegetation. Supporting measurements, taken at a reference height $z = 2$ m, included: 1) Wind speed with a cup anemometer (model VF-1, Meteorological Instruments Co., Changchun, China); 2) vegetation surface infrared temperature (BS-32T, 7–20 μm, OPTEX Co. Ltd., Japan); and 3) friction velocity (u_*), the Monin–Obukhov length (L), and fluxes of water vapor and carbon dioxide with an eddy covariance system which consisted of a sonic anemometer/thermometer (model DA600, KAIJO, Japan) and an H_2O/CO_2 analyzer (model Licor 7500, Licor, Inc., Lincoln, Nebraska).

Because of its small size, the presence of the evaporation pan should have had little effect on the boundary layer's turbulent transport. It is understood that r_{am} is a property of the flow, and hence it should have exerted an equal influence on both water evaporated from the wheat field and that from the evaporation pan. On the other hand, the excess resistance depends mostly on the property of the evaporating surface. Since the surface of the evaporation pan was very smooth and was saturated with water, its excess resistance should resemble that of a water body and be negligibly small (Garratt 1990). In other words, the resistance measured by the above apparatus, R_a, is equivalent to r_{am} except for the stability correction and does not include the excess resistance of the wheat field. This point should be kept in mind when interpreting the data below.

The idea of placing a small emission source of a scalar of some sort in an otherwise uniform flow field for the study of turbulent transport has been investigated by other researchers. In a study of the denitrification process, Warland and Thurtell (2000) estimated N_2O flux ratios from several microplots by limiting the plot size sufficiently small so that the same eddy diffusion mechanism prevailed over all the plots. Paw U and Daughtry (1984) solved for the diffusive resistances of a pair of energy balance equations (one for a dry leaf and another for a leaf coated with water), based on the assumption that the water coating did not change the diffusion characteristics through the leaf boundary layer. Apparently, leaves coated with water were often used for the estimation of leaf diffusion resistance (see the literature reviewed by Paw U and Daughtry 1984).

3. Results and discussion

a. The relationship between R_a and wind speed

Transfer resistance is very much dependent on wind speed. Equation (2) has shown a clear relationship between the resistance to momentum, r_{am}, and wind speed. For a proper interpretation of the experimental result, an estimate of the roughness length is required. The roughness value given by Eq. (4) is 2.2 cm. A much more robust estimate, Q, is obtained by minimizing the following least squares error over the whole observation period:

$$Q = \sum (u - \hat{u})^2, \quad (6)$$

where u is the wind speed observed at $z = 2.0$ m, and $\hat{u}$ is the wind speed predicted by

$$\hat{u} = \frac{u_*}{\kappa}\left[\ln\frac{z - d}{z_0} - \Psi\left(\frac{z - d}{L}\right)\right]. \quad (7)$$

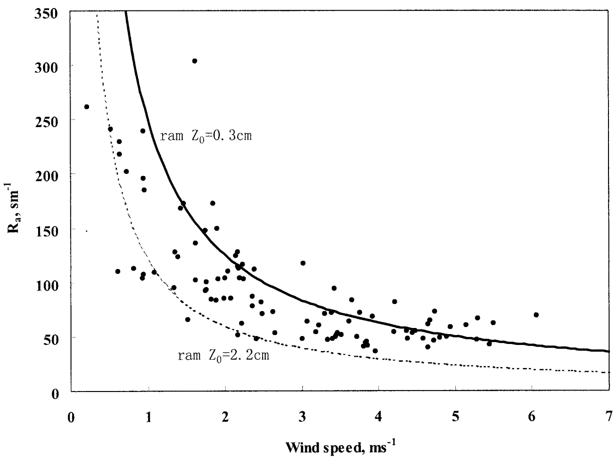

FIG. 1. Transfer resistance as a function of wind speed at the reference height (z = 2.0 m): dots, R_a [Eq. (5)]; solid line, calculated by Eq. (2) under neutral conditions with z_0 = 0.3 cm; dashed line, same as above but with z_0 = 2.2 cm.

Here u_* and L were measured by the eddy correlation system. During the experiments, most of the stability, $(z - d)/L$, ranged from 0 to -1. The zero-plane displacement height that appears in the stability function is taken as $0.7h$, or 0.15 m. (The choice of d is not important for the least squares procedure because the stability function, Ψ, is only weakly sensitive to d.) The least squares procedure gives the best estimate for $\ln[(z - d)/z_0]$ of 6.42, or a roughness length of 0.3 cm if d is assigned a value of 0.15 m. This is much smaller than the value given by Eq. (4) but is more appropriate for the partially vegetated surface.

Figure 1 plots the transfer resistance, R_a, as a function of wind speed, along with the transfer resistance to momentum, r_{am}, determined by Eq. (2) for neutral air ($\Psi = 0$) for two surface roughness values, z_0 = 0.3 and 2.2 cm. The data show that R_a and r_{am} are both inversely proportional to u, with some of the scatter arising from the variations in air stability. The transfer resistance r_{am} given by Eq. (2) with z_0 = 0.3 cm is 46% higher than that with z_0 = 2.2 cm, highlighting the fact that, without a robust estimate of z_0, Eq. (2) would be subject to large uncertainties. The reader should also be aware that air was mostly unstable during the experiment, and hence a correction for air stability would make the r_{am} values lower than those shown in Fig. 1.

b. The verification of R_a

Based on the flux-gradient theory for the atmospheric boundary layer, fluxes for momentum, and sensible and latent heat can be expressed as (Chen and Schwerdtfeger 1989)

$$\tau = \rho K_m \frac{\partial \overline{u}}{\partial z}, \tag{8}$$

$$H = -\rho c_p K_h \frac{\partial \theta}{\partial z}, \tag{9}$$

$$\lambda E = -\lambda \rho K_w \frac{\partial \overline{q}}{\partial z}, \tag{10}$$

where τ, H, and λE are the shear stress, and the sensible and latent heat flux densities, respectively; ρ is the mean air density; $\overline{u}$, $\overline{\theta}$, and $\overline{q}$ are the mean wind speed, potential temperature, and specific humidity; and K_m, K_h, and K_w the eddy diffusivities for momentum, heat, and water vapor, respectively.

The eddy diffusivities K_s are assumed to be related to wind shear and thermal stratification via the stability function Ψ_s. Thus,

$$K_s = \kappa u_*(z - d)/\Psi_s, \tag{11}$$

where the subscript s denotes m, h, or w. Therefore, the transfer resistance r_s should be proportional to Ψ_s.

In horizontally uniform conditions, Ψ_s have been studied extensively and are expected to be universal functions of stability (Obukhov 1971). It has been generally accepted (Dyer 1974), although not undisputed, that in neutral conditions

$$\Psi_m = \Psi_h = \Psi_w = 1, \tag{12}$$

in unstable conditions

$$\Psi_m^2 = \Psi_h = \Psi_w = [1 - 16(z - d)/L]^{-1/2}, \tag{13}$$

and in stable conditions

$$\Psi_m = \Psi_h = \Psi_w = 1 + 5.2(z - d)/L. \tag{14}$$

Therefore, combining Eq. (1), the transfer resistances r_{am}, r_{ah}, and r_{aw} are related to each other:

$$r_{aw} = r_{ah} = \frac{\Psi_w}{\Psi_m} r_{am}. \tag{15}$$

Thus, theoretically, Eq. (15) can be used to verify R_a, determined by Eq. (5) using our method.

To compare R_a and r_{am}, the directly measured r_{am} is used rather than the r_{am} calculated by Eq. (2); that is (Monteith 1975),

$$r_{am} = \Psi_m(u/u_*^2), \tag{16}$$

which can be directly measured by sonic anemometer using the eddy correlation method.

Figure 2 shows a comparison of R_a with the r_{am} given by Eq. (16). It can be seen that most points are scattered near the 1:1 line. Of course, big differences still exist in some cases. The linear regression relationship between them, for this sample of 88 cases, is

$$R_a = 0.86 r_{am} + 9.5, \tag{17}$$

with a correlation coefficient r = 0.83.

In order to further validate the stability dependence

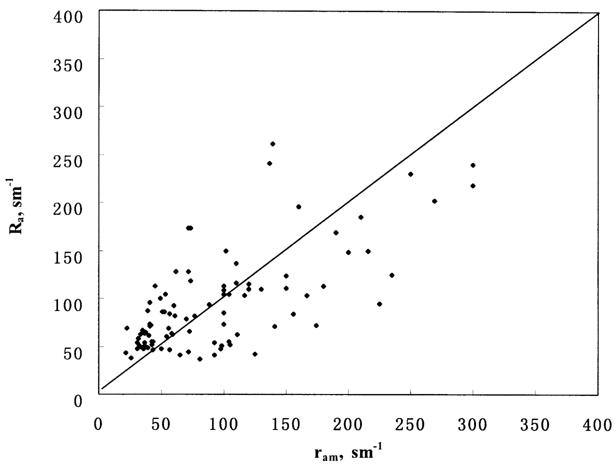

FIG. 2. Comparison of the transfer resistance measured by the evaporation pan (R_a) with the transfer resistances r_{am} from Eq. (16). Also shown is the 1:1 line.

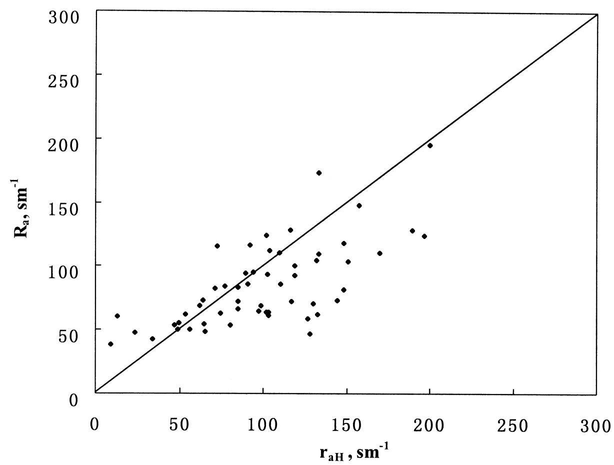

FIG. 3. Comparison of the measured transfer resistance (R_a) with the transfer resistance r_{ah} from Eq. (18). Also shown is the 1:1 line.

of R_a, the transfer resistance to heat transfer, r_{ah}, is calculated by (Nichols 1992)

$$r_{ah} = \rho C_p(T_s - T_a)/H, \tag{18}$$

where T_s is the canopy surface temperature, directly measured by an infrared thermometer, T_a is air temperature at 2 m, and sensible heat flux H is measured by the eddy correlation system. Figure 3 shows the comparison of r_{ah} given by Eq. (18) and R_a measured by our method during the observations. The linear regression relationship between R_a and r_{ah}, based on 63 cases, is

$$R_a = 0.76r_{ah} + 12.5, \tag{19}$$

with a correlation coefficient $r = 0.75$.

Overall, the relationships of resistance values is $R_a \approx r_{am} < r_{ah}$, and there is reasonable agreement between Figs. 2 and 3. This supports our contention that R_a is equivalent to r_{am} rather than r_{aw}. Big differences occurred when wind speeds were low or when sensible heat fluxes were very small, which may be caused by measurements errors.

4. Summary

In this note, a relatively simple and feasible method for evaluating atmospheric boundary layer resistances is introduced. Via field tests and verification with an eddy correlation technique, reasonably good agreements are acquired. The main advantage of this method is that it avoids using sensitive parameters such as z_0, z/L, etc., which require more sophisticated techniques. Our method can also be used in other situations. For example, it can be used to measure the transfer resistance to gaseous transport near the floor of a forest. Such information is valuable for modeling studies of forest evaporation and pollution deposition (Black and Kelliher 1989; Dolman and Wallace 1991; Baldocchi 1990). Of course, the method has some limitations and disadvantages. For instance, at night and under overcast skies, because of a low evaporation rate, it might result in big errors in the R_a calculation. In addition, it cannot be measured automatically and instantaneously. Even so, the authors think that it may be useful for estimating transfer resistance in some special conditions. Surely, more improvements and experiments in different conditions are necessary in the future, too.

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