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

$$r_m = \int_{z_0}^{z} \frac{1}{K} d\eta,$$  \hspace{1cm} (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

$$r_m = \left[ \ln \frac{z - d}{z_0} - \Psi \left( \frac{z - d}{L} \right) \right]^{1/\kappa^2 u},$$  \hspace{1cm} (2)

where \(\Psi\) is the integral form of the stability function (Paulson 1970), \(L\) is Monin–Obukhov length, \(\kappa\) (=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

$$r_w = r_m + r_b.$$  \hspace{1cm} (3)

For a water-saturated evaporating surface, \(r_b\) is much less than \(r_m\) and can be neglected. To evaluate \(r_m\) 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

$$z_0 = 0.1 h,$$  \hspace{1cm} (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:
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, \( t_c \). 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, \( R_a \), is equivalent to \( r_m \) 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\(_2\)O 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, \( r_m \), 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:

\[
Q = \sum (u - \hat{u})^2, \tag{6}
\]

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

\[
\hat{u} = \frac{u_d}{\kappa} \ln \frac{z - d}{z_0} - \Psi \left( \frac{z - d}{L} \right). \tag{7}
\]
Here $u_a$ 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 0.7$h$, or 0.15 m. (The choice of $d$ is not important for the least squares procedure because the stability function, $\Psi$, 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)

$$\tau = \rho K_m \frac{\partial \bar{\pi}}{\partial z},$$  \hspace{1cm} (8)

$$H = -\rho c_p K_h \frac{\partial \bar{\theta}}{\partial z},$$  \hspace{1cm} (9)

$$\lambda E = -\lambda \rho K_w \frac{\partial \bar{Q}}{\partial z},$$  \hspace{1cm} (10)

where $\tau$, $H$, and $\lambda E$ are the shear stress, and the sensible and latent heat flux densities, respectively; $\rho$ is the mean air density; $\pi$, $\bar{\theta}$, and $\bar{Q}$ 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 $\Psi_s$. Thus,

$$K_s = k u_s (z - d) \Psi_s,$$  \hspace{1cm} (11)

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

In horizontally uniform conditions, $\Psi_s$ 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

$$\Psi_m = \Psi_h = \Psi_w = 1,$$  \hspace{1cm} (12)

in unstable conditions

$$\Psi^2_m = \Psi_h = \Psi_w = [1 - 16(z - d)/L]^{-1/2},$$  \hspace{1cm} (13)

and in stable conditions

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

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

$$r_{aw} = r_{ah} = \frac{\Psi_w}{\Psi_m} r_{am}.$$  \hspace{1cm} (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),

$$r_{am} = \Psi_m (u/u_a^2),$$  \hspace{1cm} (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

$$R_a = 0.86 r_{am} + 9.5,$$  \hspace{1cm} (17)

with a correlation coefficient $r = 0.83$.

In order to further validate the stability dependence
of $R_a$, the transfer resistance to heat transfer, $r_{ah}$, is calculated by (Nichols 1992)

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

(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

$$R_a = 0.76 r_{ah} + 12.5,$$

(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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