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The concept of canopy resistance: historical survey and comparison of different approaches

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ABSTRACT

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An historical account concerning the evolution of the concept of canopy resistance over the last 40 years is presented, from the classical Penman–Monteith equation, which is based on a single-layer approach, up to the generalized combination equation derived by Lhomme using a multi-layer approach. The different procedures for calculating the bulk aerodynamic and surface resistances of a plant canopy are given. Using a numerical simulation, the bulk canopy resistances calculated with the multi-layer approach are analysed and compared with those of the classical single-layer approach, in order to determine under which conditions the classical Penman–Monteith equation can provide a good estimate of the evapotranspiration rate of a plant canopy.

INTRODUCTION

The concept of diffusive resistance in the atmosphere comes from the integration of a diffusion equation over a segment where flux is conservative and the driving force has a specific value at its limits (Philip, 1966; Monteith, 1981). The result of the integration is an equation often treated as an analogue of Ohm's law in electricity, where flux or intensity is proportional to a potential difference and inversely proportional to a resistance. This type of equation is also applicable to water vapour diffusing through the stomata of individual leaves of plants, and tools such as the porometer exist for measuring this resistance. The problem which arose at the beginning of the 1960s was the development of a reliable method to include the transfer processes in the stomata and in the air within the canopy in a simple model, in order to bridge the gap of knowledge between the single leaf and the plant canopy. The method which remains roughly valid so far is that of Monteith (1963), who defined a canopy stomatal resistance using a one-dimensional, one-parameter

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model based on an extension of Penman's original formula. This approach is known as the single-leaf or big-leaf model.

The objective of this paper is to review the evolution of the concept and the formulation of canopy resistance over the last 40 years, from the publication of the original Penman formula (1948) up to the generalized combination equation based on a multi-layer approach derived by Lhomme (1988b). A numerical comparison between the different approaches is also undertaken in order to determine, by comparison with the multi-layer approach, the most accurate formulations of the bulk resistances of the single-layer approach.

THE SINGLE-LAYER APPROACH

Evaporation from natural surfaces is commonly estimated with the classical Penman equation. The original formula (Penman, 1948) gives the evaporation rate λE of a completely wet surface. It is derived by eliminating the surface temperature between the convective flux equations of sensible and latent heat, and the energy balance equation. This elimination is made possible by linearizing the saturated vapour pressure curve by the slope, s, of the curve determined at the temperature of the air. The equation has the form

$$\lambda \boldsymbol{E}=\frac{s(\boldsymbol{R}_{\mathrm{n}}-\boldsymbol{G})+\rho c_{\mathrm{p}}D_{\mathrm{a}}/\boldsymbol{r}_{\mathrm{a}}}{s+\gamma} \tag{1}$$

where $\boldsymbol{R}_{\mathrm{n}}$ is the net radiation, $\boldsymbol{G}$ is the soil heat flux, D_{a} is the vapour pressure deficit of the air, γ is the psychrometric constant, c_{p} is the specific heat of air at constant pressure, ρ is the mean air density and $\boldsymbol{r}_{\mathrm{a}}$ is the aerodynamic resistance calculated on a conservative path between the surface and a reference height.

The original Penman formula can readily be modified to describe the rate of evaporation from a dry surface when a specified surface resistance to vapour transfer, $\boldsymbol{r}_{\mathrm{S}}$, exists between the level where evaporation takes place and the interface with the atmosphere, source or sink of sensible heat (Penman, 1953; Monteith, 1973). Provided both levels are effectively at the same temperature, the new equation can be written

$$\lambda \boldsymbol{E}=\frac{s(\boldsymbol{R}_{\mathrm{n}}-\boldsymbol{G})+\rho c_{\mathrm{p}}D_{\mathrm{a}}/\boldsymbol{r}_{\mathrm{a}}}{s+\gamma(1+\boldsymbol{r}_{\mathrm{S}}/\boldsymbol{r}_{\mathrm{a}})} \tag{2}$$

A familiar example of this case is a single leaf with the epidermis acting as a source or sink of heat and the substomatal cavities acting as a source of vapour. Another example is a thin mulch or dry layer covering a wet soil.

This case has been extended to a stand of vegetation by Monteith (1963, 1965), assuming that the canopy exchanges sensible and latent heat with the atmosphere from a theoretical surface located at the same level as the effective sink of momentum, i.e. level $d+z_0$ above the ground, where d is the zero plane displacement and z_0 the roughness length. This model is often called the 'big-leaf' model because this fictitious surface is considered to possess the physiological properties of a leaf. The temperature of this leaf is obtained by extrapolating the logarithmic profiles of air temperature and wind velocity down to level $d+z_0$. The air within the substomatal cavities is assumed to be saturated at the same temperature. Aerodynamic resistance, r_a, is calculated between this level $d+z_0$, where fluxes are supposed to originate, and the reference height. It is given by

$$r_a = u_a/u_*^2 \quad (3)$$

where u_a is the wind speed at the reference height and u_* is the friction velocity. This resistance is assumed to be the same for sensible and latent heat. The surface resistance, r_S, first called 'stomatal resistance' by Monteith, is expected to be a plant factor depending only (when soil evaporation is negligible) on the stomatal resistance of the individual leaves forming the canopy and on the total foliage area.

There has been some controversy regarding the true meaning of r_S and the applicability of eqn. (2) to a real canopy. Tanner (1963) wrote: "What Monteith defines as the stomatal resistance is not clear. I am impressed with the fact that such a simple set of measurements taken in the turbulent layer above the crop provides estimates of stomatal resistance with the proper range of values". Philip (1966) continued to protest: "r_S is an artefact of a somewhat unrealistic analysis, and its physiological significance is questionable".

The applicability of Penman's second equation (eqn. (2)) to a real canopy raises two kinds of question.

(1) Where to put the equivalent surface and its corollary question: how to calculate the bulk aerodynamic resistance r_a?

(2) How to relate the bulk stomatal resistance of the canopy to the stomatal resistance of individual leaves?

The original idea of Monteith to place the equivalent surface at the level of the effective sink of momentum is questionable and without theoretical foundation. Later, Thom (1972) showed that the transfer of mass and heat encounters greater aerodynamic resistance and, therefore, the effective source of sensible and latent heat must be located at a lower level than the effective sink of momentum: $d+z_0'$ with $z_0' < z_0$ (e.g. Garrat and Hicks, 1973; Stewart and Thom, 1973). The appropriate value of the bulk aerodynamic resistance is not u_a/u_*^2 but

$$r_a' = u_a/u_*^2 + B^{-1}/u_* \quad (4)$$

where B^{-1}/u_* represents the excess resistance. B^{-1} is the dimensionless bulk parameter used by Chamberlain (1968) and Thom (1972), which can be expressed as

$$B^{-1}=\ln(z_0/z_0')/k \quad (4')$$

where k is von Karman's constant (0.41). The value of B^{-1} is about 4 for most arable crops (Thom, 1972; Monteith, 1981).

The other problem is linked with the calculation of bulk stomatal resistance, r_S, from elementary stomatal resistances of leaves as measured with a porometer. When evaporation from soil is negligible, r_S is interpreted by Monteith (1973) as the effective stomatal resistance of all the leaves acting as resistances in parallel, and is calculated for an amphistomatal canopy as

$$r_S=\bar{r}_s/2L \quad (5)$$

where $\bar{r}_s$ is the mean leaf stomatal resistance and L the leaf area index. However, nothing is said about the practical calculation of $\bar{r}_s$. A more correct procedure would be to divide the canopy into several parallel layers, to calculate for each layer a stomatal resistance $r_{S,i}$ as $\bar{r}_{s,i}/2\delta L_i$, where $\bar{r}_{s,i}$ is the mean leaf resistance of a layer i with a partial leaf area index of δL_i, and to interpret the stomatal resistance of the canopy as the effective resistance of the $r_{S,i}$ acting in parallel (Shuttleworth, 1976; Monteith, 1985; Lindroth and Halldin, 1986)

$$r_S'=1/\sum_i(1/r_{S,i}) \quad (6)$$

To calculate a correct value of $\bar{r}_{s,i}$, it is necessary to use a detailed sampling scheme that weights porometer measurements according to leaf position in sun and shade regimes. No theoretical justification has ever been proposed for eqn. (6). The main argument is always the experimental evidence. However, many authors have used this type of formulation to calculate what they call "the integrated canopy stomatal resistance" (Baldocchi et al., 1987). Nevertheless, in a recent paper Paw U and Meyers (1989), using a higher-order canopy turbulence model, show clearly that the parallel resistance weighted by leaf area index is problematic, even when the soil is dry, and can generate serious errors when used to estimate the bulk canopy resistance.

Much has been said about the combination equation and its applicability to a real canopy from a theoretical standpoint (Shuttleworth, 1976; Finnigan and Raupach, 1987) and also from an experimental point of view (Lindroth and Halldin, 1986). However, it is certain that "the physical meaning of the canopy resistance is not easy to comprehend" (Brutsaert, 1982) and that the classical Penman–Monteith equation is not sufficient to correctly describe the complexity of the vegetation–atmosphere interaction.

THE MULTI-LAYER APPROACH

The approach described above is often referred to as the single-layer approach because the stand of vegetation is treated as a single equivalent surface absorbing radiative energy, and transferring sensible and latent heat to the atmosphere, as opposed to the multi-layer approach where the stand is treated as a continuous or discrete set of horizontal planes, each one absorbing net radiation and transferring sensible and latent heat. The multi-layer model constitutes a sound analogue of energy exchange within tall crops.

The basic equations of multi-layer models form a closed set of equations which can be solved to calculate the total convective fluxes at the top of the canopy, and the profiles of temperature and humidity within the canopy. The discrete or stratified approach conceives the canopy as being divided into a finite number of layers, each one with a given thickness, and yields linear equations which are solved by means of matrix methods (Waggoner and Reifsnyder, 1968; Waggoner et al., 1969; Furnival et al., 1975). In the continuous approach (Philip, 1964; Cowan, 1968; Goudriaan and Waggoner, 1972; Furnival et al., 1975; Perrier, 1976), the canopy is conceived as an infinite number of strata. All of the variables are continuous functions of height z. The authors derive differential equations which generally do not have analytical solutions and are solved by numerical methods after a previous discretization.

It is worthwhile pointing out that the theoretical formalism used in all the models cited above rests on K-theory (K, eddy diffusivity). At present in the micrometeorological community, it is generally accepted that flux estimates, within the canopy, based on K-theory must be accepted with a degree of scepticism. Turbulent transfer is dominated by intermittent events that can cause countergradient transfer. K-theory models seem to be valid only if the length scale of the turbulence is fine grained with respect to the length scale of the concentration gradient. However, it is fairly hard, in a general way, to quantify the errors this assumption brings into the models.

Even if the multi-layer models describe the transfers within the canopy fairly well, they do not directly provide explicit expressions for total fluxes above the canopy as in the single-layer approach. Attempts have been made to derive such expressions. Using a simple two-layer model to describe the energy partition of sparse crops, Shuttleworth and Wallace (1985) derived explicit equations of the Penman type. Shuttleworth (1976) succeeded in deriving a general combination equation from a continuous multi-layer model, but the relevant resistances contain temperature and humidity profiles within the canopy, which are unknown a priori, so that this equation cannot be used as a practical tool in any predictive sense. Chen (1984), using a discrete approach, derived explicit expressions of total fluxes, the resistances being retained in their ordinary sense. However, to establish the bridge between single- and multi-layer models he must define the flux of a fictitious variable called 'saturation deficit'. Starting from a discrete approach, Lhomme (1988a) derived general expressions for sensible and latent heat fluxes by means of a mathematical algorithm which does not require the introduction of a fictitious flux. The general expressions obtained can be considered as an extension of Penman's original formulae to a multi-layer system. They are valid for both single- and multi-layer models, the familiar Penman formulae appearing as a particular case of these more general equations. However, these extended Penman formulae do not have the same form as the familiar Penman–Monteith equation. Hence, from these equations it is impossible to infer bulk resistances, combinations of elementary resistances, which would play the same role in the multi-layer system as the aerodynamic and surface resistance in the single-layer approach. At this stage, it is important to point out that the 'integrated' formula (eqn. (6)), used to calculate the canopy resistance, is not a true multi-layer approach in so far as eqns. (2) and (6) are not mathematically derived from the basic equations of the multi-layer approach.

Using the same type of multi-layer approach, Lhomme (1988b) also derived a general combination equation, similar in form to that produced by the single-layer approach. In this equation, bulk aerodynamic and stomatal resistances are expressed in terms of multi-layer elementary resistances. This generalized combination equation is written

$$\lambda E = \frac{s(R_n - G) + \rho c_p (D_a + s\delta Te)/r_{c,a}}{s + \gamma(1 + r_{c,s}/r_{c,a})} \tag{7}$$

This is not, strictly speaking, of the Penman–Monteith type. $\delta Te = Te_V - Te_H$ represents the difference between two 'equivalent temperatures' which are weighted means of leaf and soil temperatures. The weighting systems involve the elementary resistances of the multi-layer approach. Te_H is not equal to Te_V because the weighting system is different. Te_H only takes account of elementary aerodynamic and boundary-layer resistances within the canopy, while Te_V also accounts for leaf and soil resistances. The derivation of this equation clearly shows that the canopy cannot be considered, from a theoretical standpoint, as a system exchanging sensible and latent heat from the same level. The sources or sinks of sensible and latent heat are different and have different temperatures, Te_H and Te_V. In their recent paper already cited, Paw U and Meyer (1989) draw the same conclusions. They demonstrate, by using higher-order closure principles, that the concept of a single effective source–sink height (an essential condition for the derivation of the Penman–Monteith equation) is not easily applied to plant canopies because of the erratic behaviour of the zero plane displacements for water vapour and heat. In the same paper (Lhomme, 1988b), it was also proven that δTe can be neglected, and consequently the Penman–Monteith equation holds, every time the soil surface resistance is of the same order of magnitude or greater than the stomatal resistance of the lowest layers of vegetation. This means that evaporation from a dry canopy with the presence of significant below-canopy evaporation cannot be adequately described by a simple combination equation.

In eqn. (7), $r_{c,a}$ represents the bulk aerodynamic resistance. It is the sum of two resistances

$$r_{c,a}=r_{a,0}+r_{c,H} \tag{8}$$

$r_{a,0}$ is the familiar aerodynamic resistance of the air-stream above the canopy, calculated between the canopy height and the reference height (where the saturation deficit D_a is measured). In near-neutral conditions, $r_{a,0}$ is given by

$$r_{a,0}=\frac{1}{ku_*}\ln\left(\frac{z_r-d}{h_c-d}\right) \tag{9}$$

where z_r is the reference height and h_c is the canopy height. $r_{c,H}$ is the bulk resistance opposed by the canopy to sensible heat transfer. It represents a combination of diffusive resistances and leaf boundary-layer resistances within the canopy. $r_{c,S}$ is the bulk stomatal or surface resistance, defined as the difference between the bulk resistance opposed by the canopy to water vapour transfer ($r_{c,V}$) and the bulk aerodynamic resistance ($r_{c,H}$) opposed by the canopy to sensible heat transfer

$$r_{c,S}=r_{c,V}-r_{c,H} \tag{10}$$

The mathematical definition of $r_{c,V}$ involves all the elementary resistances (air and surface), while $r_{c,H}$ only involves air resistances. The mathematical algorithm used to calculate these bulk resistances is described by Lhomme (1988b). As pointed out by Finnigan and Raupach (1987), it is now clear that the bulk surface resistance of the combination equation includes, in fact, information on air resistances within the canopy and on soil evaporation.

The assumptions used for deriving eqn. (7) are basically the same as those used in the models cited as references. The similarity between the boundary-layer resistances and the diffusive resistances for heat and water vapour is a rather good approximation which has been discussed extensively (Monteith, 1973). The linearization of the saturated vapour pressure curve is performed over the interval defined by the difference between the canopy equivalent temperature, Te_V, and the air temperature. The slope, s, of the saturated vapour pressure curve is calculated at the temperature of the air at the reference height, which is the only temperature introduced as input into the model. Chen (1984) showed that within a 10°C temperature interval, the error caused by the linearization is rather small in such a model. The detailed analysis by Paw U and Gao (1988) of the implications of a non-linearization of the saturation vapour pressure curve in the energy budget equations does not seem to question this statement.

ANALYSIS OF BULK CANOPY RESISTANCES

A numerical simulation was carried out to study the behaviour of bulk canopy resistances ($\boldsymbol{r}_{c,a}$ and $\boldsymbol{r}_{c,S}$) derived from the multi-layer approach, and to compare them with the canopy resistances ($\boldsymbol{r}_a$ and $\boldsymbol{r}_S$) of the familiar Penman–Monteith equation. Besides the air characteristics at a reference height above the canopy, several structural, physiological and micrometeorological profiles are needed as input to the model.

Model inputs

The profiles of wind velocity $u(z)$, turbulent diffusivity $K(z)$ within the canopy and leaf boundary-layer resistance $r_b(z)$ used in the simulation are taken from Perrier (1967, 1976)

$$u(z)=u(h_c)\exp[-B_0L(z)] \tag{11}$$

$$K(z)=[A_0/a(z)^2]\mathrm{d}u(z)/\mathrm{d}z \tag{12}$$

$$r_b(z)=\alpha[w/u(z)]^\beta \tag{13}$$

where $a(z)$ is the leaf area density, $L(z)$ is the downward cumulative leaf area index and w is the leaf width. h_c specifies the canopy height. A_0 and B_0 are equal to 0.4 and 0.6, respectively. α is equal to 300 and β to 0.5.

Solar radiation, $\boldsymbol{R}_s$, and net radiation, $\boldsymbol{R}_n$, are assumed to decrease as exponential functions of cumulative leaf area index $L(z)$

$$\boldsymbol{R}_s(z)=\boldsymbol{R}_s(h_c)\exp[-\alpha_0L(z)] \tag{14}$$

$$\boldsymbol{R}_n(z)=\boldsymbol{R}_n(h_c)\exp[-\alpha_0L(z)] \tag{15}$$

The attenuation coefficient, α_0, is assumed to be the same for both profiles and is taken as 0.6. In addition, net radiation above the canopy is calculated as 60% of global radiation and soil heat flux as half the net radiation at the soil surface.

The mean stomatal resistance profile, $r_s(z)$, was modelled by assuming it was inversely proportional to solar radiation $\boldsymbol{R}_s(z)$. If $r_{s,n}$ specifies the minimum value of r_s and $r_{s,x}$ the maximum value, which correspond, respectively, to solar radiation values $\boldsymbol{R}_{s,x}$ and $\boldsymbol{R}_{s,n}$, we can write

$$\frac{1}{r_s(z)}-\frac{1}{r_{s,x}}=\left(\frac{1}{r_{s,n}}-\frac{1}{r_{s,x}}\right)\left[\frac{\boldsymbol{R}_s(z)-\boldsymbol{R}_{s,n}}{\boldsymbol{R}_{s,x}-\boldsymbol{R}_{s,n}}\right] \tag{16}$$

In the present simulation, the following values have been used: $r_{s,x}=1000$ s m^{-1}; $r_{s,n}=100$ s m^{-1}; $\boldsymbol{R}_{s,x}=300$ W m^{-2}; $\boldsymbol{R}_{s,n}=50$ W m^{-2}. The soil surface resistance is assumed to be 1000 s m^{-1}.

We have simulated the microclimate of a standard canopy whose characteristics are the following: canopy height, 1.5 m; leaf width, 0.03 m; number of layers inside the vegetation, 6; layer thickness, 0.25 m; leaf area profile; 0.75, 1, 1, 0.75, 0.5, 0.5 from the top of the canopy to the soil surface. The climatic characteristics at a reference height of 3 m are: air temperature, 25 °C; relative humidity, 70%; wind velocity, 3 m s^{-1}; solar radiation, 800 W m^{-2}. Using the mathematical procedure described by Lhomme (1988b), the total fluxes and the microclimatic profiles corresponding to this case were calculated. Net radiation (R_n) is equal to 480 W m^{-2} and is partitioned into soil heat flux (G) 16 W m^{-2}, sensible heat flux (H) 20 W m^{-2} and latent heat flux (λE) 444 W m^{-2}. This case is close to neutral conditions.

Behaviour of the bulk canopy resistances derived from the multi-layer approach

The bulk canopy resistances defined by eqns. (8) and (10) were determined. $r_{a,0}$ is calculated by means of eqn. (9) which is valid in near-neutral conditions with $d=0.75h_c$ and $z_0=0.13h_c$. $r_{c,H}$ and $r_{c,V}$ are calculated using the algorithm detailed by Lhomme (1988b), with the input profiles mentioned above. Figure 1 shows the variation in these resistances as a function of wind velocity at the reference height. $r_{c,H}$ and $r_{c,V}$, as $r_{a,0}$, are decreasing functions of wind velocity, whereas $r_{c,S}$, defined as $r_{c,V}-r_{c,H}$, is almost independent of wind velocity (the small variations cannot be seen on the graph). If soil evaporation is negligible, $r_{c,S}$ can really be considered as a physiological

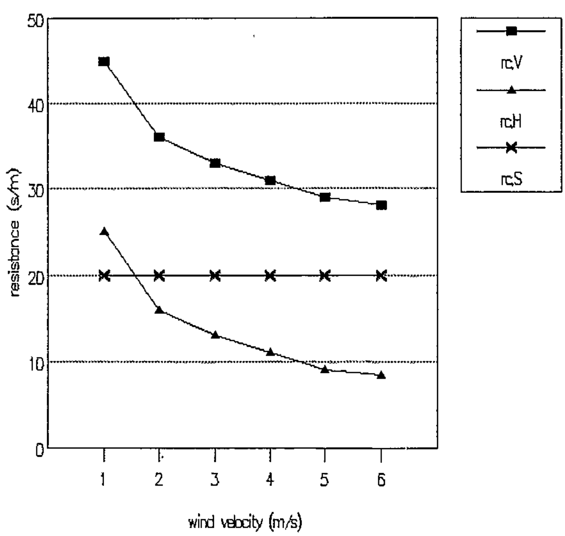

Fig. 1. Variations in bulk canopy resistances of the multi-layer approach (eqns. (8), (9) and (10)) as a function of wind velocity at the reference height.

TABLE 1

Variations in bulk surface resistance (s m^{-1}) as a function of solar radiation R_s (W m^{-2})

R_s	400	500	600	700	800	900
$r_{c,S}$	34.9	27.5	24.1	21.5	19.7	18.9
r_S	38.9	30.8	27.6	24.8	22.8	21.7
r'_S	35.8	28.0	24.6	21.8	19.8	18.9

$r_{c,S}$ = bulk surface resistance defined by eqn. (10) (Lhomme).
r_S = bulk surface resistance defined by eqn. (5) (Monteith).
r'_S = bulk surface resistance defined by eqn. (6) (Shuttleworth).

parameter directly linked with the stomatal resistance of the leaves. Table 1 shows the variation in $r_{c,S}$ as a function of global radiation.

Comparison of the bulk canopy resistances derived from the multi-layer and single-layer approaches

The bulk canopy resistances $r_{c,a}$ and $r_{c,S}$, as calculated by the algorithm mentioned above based on the multi-layer approach, were compared with the bulk resistances derived from the single-layer approach of Penman–Monteith. In Table 1, the variation in multi-layer surface resistance ($r_{c,S}$) as a function of global radiation is compared with the same variation in r_S defined by eqn. (5) and in r'_S defined by eqn. (6), the mean leaf stomatal resistance ($\bar{r}_s$) in eqn. (5) being calculated as

$$1/\bar{r}_s = (1/h_c)\int_0^{h_c}[1/r_s(z)]\,dz \qquad (17)$$

r'_S appears to be a very good approximation to the multi-layer surface resistance $r_{c,S}$ and better than r_S. In Fig. 2, the variation in multi-layer aerodynamic resistance ($r_{c,a}$) as a function of wind velocity is compared with the same variation in r_a as defined by Monteith (eqn. (3)) and in r'_a as defined by Thom (eqns. (4) and (4′)). From these curves, it is clear that r'_a is a fairly good approximation to $r_{c,a}$ and is much better than r_a.

Finally, we have compared three different approaches to estimate the latent heat flux from the classical combination equation (eqn. (2)): (1) bulk aerodynamic and surface resistances (r_a and r_S) are calculated by eqns. (3) and (5) (original combination equation); (2) r_a and r_S are calculated by eqns. (4) and (6) (modified combination equation); (3) r_a and r_S are calculated by eqns. (8) and (10) (generalized combination equation).

The reference value of the latent heat flux is calculated by means of the generalized Penman equation given by Lhomme (1988a). It is supposed to give the 'exact' value of the evapotranspiration rate on a K-theory basis. Examining the results shown in Table 2, it is clear that the multi-layer method

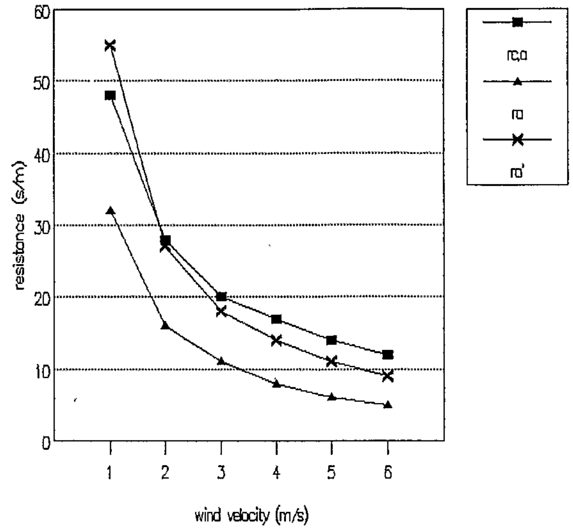

Fig. 2. Variations in bulk aerodynamic resistance as a function of wind velocity at the reference height; comparison of different approaches. $r_{c,a}$ = bulk aerodynamic resistance of the multi-layer approach (eqn. (8)); r_a = bulk aerodynamic resistance defined by Monteith (eqn. (3)); r'_a = bulk aerodynamic resistance defined by Thom (eqn. (4)).

TABLE 2

Evapotranspiration rate estimates based on the combination equation. Comparison of different methods as a function of wind velocity at a reference height u_a (m s^{-1}) and solar radiation R_s (W m^{-2})

u_a	1	2	3	4	5	6
λE_0	393	422	444	462	477	491
OCE	+3%	+7%	+9%	+11%	+12%	+12%
MCE	−1%	0%	+2%	+4%	+6%	+7%
GCE	<0.5%	<0.5%	<0.5%	<0.5%	<0.5%	<0.5%
R_s	400	500	600	700	800	900
λE_0	266	316	360	403	444	483
OCE	+12%	+12%	+11%	+10%	+9%	+8%
MCE	+2%	+3%	+2%	+2%	+2%	+2%
GCE	<0.5%	<0.5%	<0.5%	<0.5%	<0.5%	<0.5%

λE_0 = evapotranspiration rate used as reference (W m^{-2}).
OCE (original combination equation) = resistances calculated by eqns. (3) and (5).
MCE (modified combination equation) = resistances calculated by eqns. (4) and (6).
GCE (generalized combination equation) = resistances calculated by eqns. (8) and (10).

(generalized combination equation, GCE) gives very good estimates (relative error <0.5%) and that the classical combination equation, with the resistances estimated by the equation proposed by Thom (4) for r_a and by

Shuttleworth (6) for r_S, constitutes a fairly good method.

CONCLUSIONS

The historic outline presented in this paper relates the evolution of the concept of canopy resistance, starting with the 'big-leaf' model of Monteith up to the multi-layer approach. It is shown that the bulk surface resistance of the multi-layer approach (eqn. (10)), which is mathematically defined in terms of air, soil and stomatal elementary resistances, is practically independent of wind velocity and can be considered as a good physiological parameter when soil evaporation is negligible. It is also shown that the classical Penman–Monteith combination equation is a fairly good estimator of the evapotranspiration rate provided three conditions are satisfied: (1) soil evaporation must be negligible; (2) the aerodynamic resistance must be calculated taking into account the excess resistance linked with the transfer of mass or heat (eqn. (4)); and (3) the stomatal resistance must be interpreted as the effective resistance of a set of parallel resistors, each representing one layer in the canopy (eqn. (6)). These conclusions, which were experimentally derived in previous papers, receive theoretical support here.

In this paper, no reference is made to the modern theories on the turbulent structure of the transport in plant canopies (Finnigan and Raupach, 1987). These theories (higher-order closure models, Lagrangian approach) are fairly complicated and do not allow simple equations of total fluxes to be inferred. For larger-scale applications and global climate models, it is certainly more useful to have approximate equations based on K-theory, which can be easily handled, than more precise equations which cannot be used owing to their complexity.

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