RESISTANCE OF A PARTIALLY WET CANOPY: WHOSE EQUATION FAILS?

(Research Note)

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(Received 19 November, 1976)

Abstract. Shuttleworth's analysis of evaporation from partly wet canopies is appropriate only for the unrealistic case of dispersed, minute water droplets. When a more realistic model is used, the predicted range of canopy resistances is consistent with experimental estimates for a pine forest.

1. Concept of Intrinsic Resistance

Evaporation cannot occur from a free water surface when the air in immediate contact with the water is saturated at the temperature of its surface. When the air is not saturated, the saturation deficit needed to sustain unit flux of water vapour is proportional to a resistance (R_I) which depends on the molecular properties of the air-water interface. This resistance is omitted from standard micrometeorological analyses on the grounds that it is negligible and Shuttleworth (1975) confirmed the validity of this assumption by using kinetic theory to show that R_I was probably about 0.05 s m^{-1} for water vapour – three to four orders of magnitude less than the aerodynamic boundary-layer resistances characteristic of leaves. He then deduced from an equation which he stated, but did not derive, that the resistance of a canopy to the diffusion of water vapour should be negligible even when the foliage was only slightly wet. This deduction is contrary both to intuition about the loss of water from plants and to human experience. For example, sweat breaking out on the face does not produce evaporative cooling over the whole body! A short supplementary paper by Shuttleworth (1976) contains experimental evidence that when the canopy of a pine forest was partly wet, the value of r_s, derived by manipulating the Penman–Monteith formula, ranged from 0 to 100 s m^{-1}. Because this result was inconsistent with his own equation, Shuttleworth deduced that the Penman–Monteith equation was not valid for a partly wet canopy. The purpose of this note is to argue the contrary proposition – that Shuttleworth's equation is inappropriate for partly wet canopies because its validity is limited to the unrealistic case where water is uniformly distributed in very small droplets.

2. Restricted Validity of Shuttleworth's Equation

It is convenient to consider a layer of canopy containing unit leaf area index of n identical leaves (or needles in the stand considered by Shuttleworth) each with an

Boundary-Layer Meteorology **12** (1977) 379–383. *All Rights Reserved*

area of $1/n$, a stomatal resistance of r_{sto}, and a boundary-layer resistance of r_v depending on wind speed. A fraction W of each needle is wetted by rain or dew.

Shuttleworth dealt with the special case in which the flux of water vapour from each needle could be treated as a current through two parallel resistances $r_{\mathrm{sto}}/(1-W)$ representing the dry fraction of the epidermis; and r_I/W representing the wet fraction (Figure 1a).

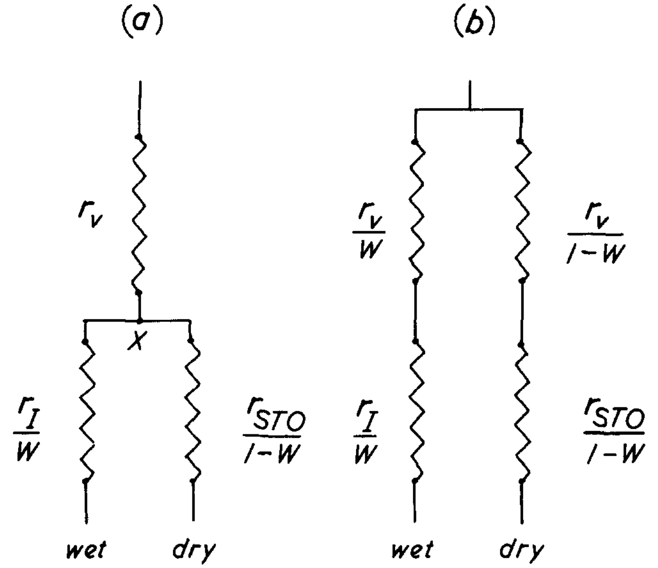

Fig. 1. Electrical analogues for water-vapour flux from partly wet canopy – (a) according to Shuttleworth (1976) and Equation (1); (b) according to Equation (4).

The combined surface resistance of n needles is then

$$r_s = n^{-1}\left[\frac{1-W}{r_{\mathrm{sto}}} + \frac{W}{r_I}\right]^{-1} \tag{1}$$

equivalent to Shuttleworth's equation; and when the aerodynamic resistance is included, the total resistance of the system is

$$r_t = r_s + n^{-1} r_v \,. \tag{2}$$

(This equation omits a shelter factor (Thom, 1971) which is not relevant to the discussion.) From the literature reviewed by Jarvis *et al.* (1976), characteristic and convenient values for a pine forest may be chosen as $r_{\mathrm{sto}} = 10^3\ \mathrm{s\,m^{-1}}$ and $r_v = 10\ \mathrm{s\,m^{-1}}$. Figure 2 shows how the resistance of a single needle (nr_s) depends on W when these values are put in Equation (1). For all values of W exceeding 0.01, the effective resistance of a single needle is less than $r_I/0.01 = 5\ \mathrm{s\,m^{-1}}$ which is trivial compared with the resistance of $10^3\ \mathrm{s\,m^{-1}}$ for $W = 0$. In other words, Equation (1)

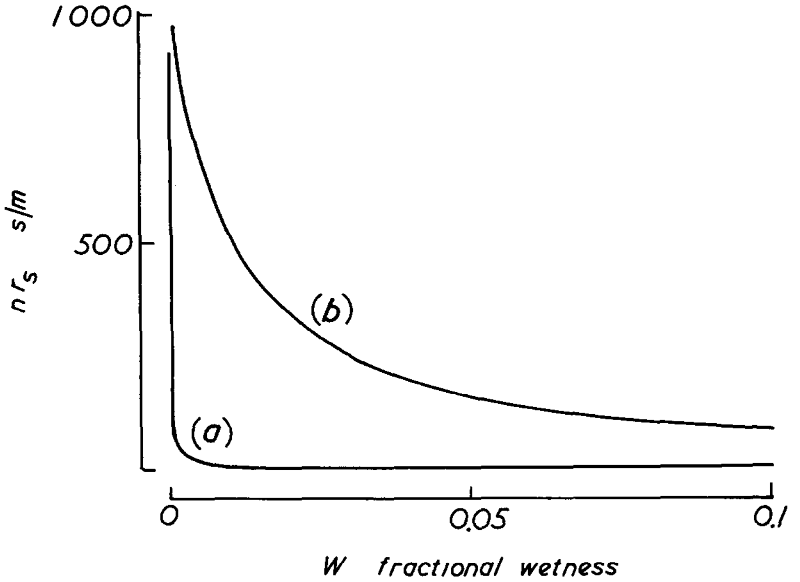

Fig. 2. Dependence of resistance nr_s on surface wetness W assuming: $r_l = 0.05$ s m^{-1}; $r_{sto} = 10^3$ s m^{-1}; $r_v = 10$ s m^{-1} – (a) according to Shuttleworth (1975) and Equation (1); (b) according to Equation (4).

predicts that, when only 1% of the foliage in a canopy is wet, the rate of evaporation is virtually the same as when all surfaces are covered with water.

This implausible result is a direct consequence of treating $r_{sto}/(1 - W)$ and r_l/W as parallel resistances, a procedure which is valid only when both resistances meet at an equipotential point (X in Figure 1a), which is inside the aerodynamic boundary layer of the needle (represented by r_v in Figure 1a). For this condition to be satisfied, the boundary layer must be occupied by equipotential shells surrounding the needle, more or less parallel to the epidermis. For example, in the simplest case of a dry needle ($W = 0$), transpiration takes place mainly through stomata and to a much smaller extent through the almost impermeable cuticle. Although stomatal pores usually occupy only about 1% of a leaf surface, the rate of water loss can approach the loss from a free water surface because there is a large number of pores per unit area. More specifically, when the distance between the pores is of the order of 100 μm, the equipotential shells associated with the end of each pore intersect well within the boundary layer and a two-dimensional field plotter has been used to demonstrate this behaviour (Monteith, 1975). For such a distribution of water-vapour sources, it is justifiable to treat the stomatal resistance r_{sto} and the boundary-layer resistance r_v as distinct components connected in series. This simple procedure would not be valid, however, if stomata were much larger and more widely spaced.

Returning to the case of a wetted leaf, it follows that Equation (1) is valid when large numbers of very small droplets are distributed more or less uniformly over the epidermal surface. This is the least likely of all the ways in which liquid water might be distributed among pine needles, or in any other type of foliage. To be more exact, the mean separation of the droplets would need to be an order of magnitude less than the mean boundary-layer thickness which is given by $r_v D$, where D is the molecular diffusion coefficient for water vapour. Putting $r_v = 10\,\mathrm{s\,m^{-1}}$ and $D = 2.5 \times 10^{-5}\,\mathrm{m^2\,s^{-1}}$ gives $r_v D = 250\,\mu\mathrm{m}$ implying a droplet separation of the order of 25 μm. The implausible conclusion from Shuttleworth's equation is therefore a consequence of the unrealistic distribution of water for which it is valid.

3. Alternative Equation for Partly Wet Canopy

In contrast to the extreme dispersion of water needed to make Equation (1) valid, a partly wet canopy might consist of a fraction W of completely wetted needles. This distribution is consistent with Shuttleworth's experimental criterion for partial wetness: some, but not all his electrical sensors indicated the presence of water. The effective resistance of unit leaf layer is found by combining the wet and dry components in parallel and subtracting r_v to give

$$r_s = n^{-1}\left\{\left[\frac{W}{r_I + r_v} + \frac{1-W}{r_{\mathrm{sto}} + r_v}\right]^{-1} - r_v\right\} \tag{3}$$

which satisfies the condition $r_s = n^{-1} r_{\mathrm{sto}}$ when $W = 0$ (see Figure 1b). Because r_I is much smaller than r_v, Equation (3) can be reduced to the simpler form

$$r_s \simeq n^{-1}(1 - W)[(W/r_v) + (1/r_{\mathrm{sto}})]^{-1} \tag{4}$$

which is independent of r_I. Figure 2 shows that when standard values of r_v, r_{sto} and r_I are inserted in Equation (4), nr_s may assume a much wider range of values than was predicted by Equation (1). This wider range is consistent with the experimental evidence that the canopy resistance of a pine forest (approximately nr_s divided by the leaf area index) assumes values up to $100\,\mathrm{s\,m^{-1}}$ when the foliage is partly wet (Shuttleworth, 1976).

The relation between r_s and W cannot be unique: for a given value of W, water may be distributed in many different ways from which two limiting cases have been selected. Lack of uniqueness may limit the predictive value of the Penman–Monteith equation but it does not demonstrate its 'failure'. Indeed, because the equation is derived by combining expressions for the conservation of energy and of mass, it cannot fail when used retrospectively to derive a value of r_s for a uniform canopy. This contention is supported by 10 years of experimental evidence for crops, orchards and forests (Gash and Stewart, 1975; Black *et al.*, 1970; Szeicz *et al.*, 1973; Monteith *et al.*, 1965; etc.).

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