MASS TRANSFER FROM DISCRETE WATER DROPS ON LEAVES IN A CEREAL CANOPY

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Abstract. The boundary-layer resistance, r_d, for water vapour transfer from single drops on a wheat leaf was derived from field measurements of the evaporation rate, drop temperature and air humidity. Parameters are estimated in an equation to calculate r_d from drop diameter and wind speed. The relationship between resistance and wind speed is compared with that from other sources, and possible systematic errors in temperature measurements are examined using a model of the drop energy balance.

1. Introduction

The leaves of many plant species do not wet readily, so rain water often collects on vegetation in the form of discrete drops. Drop shape is determined by the contact angle between water and the leaf surface and this varies greatly, depending on the plant species, variety and the leaf age and condition.

The persistence of surface water on vegetation is relevant to a number of disciplines such as meteorology, hydrology, agronomy and pathology. Drop size and shape affect the amount of water which can be held on leaves and the rate at which it evaporates. There have been several attempts to calculate evaporation from drops on leaves in recent years (e.g., Leclerc *et al.*, 1985; Butler, 1986; Barr and Gillespie, 1987) and their success largely depends on the use of appropriate values for mass transfer coefficients from discrete drops on an otherwise dry leaf surface. Leclerc *et al.* (1986) measured transfer coefficients for drops in the laboratory using electrochemical simulations. They concluded that differences between their measurements for drops on realistic leaves and a relationship derived for spheres in a free stream (Ranz and Marshall Jr., 1952) were small. The applicability of their findings to natural air flow in crops needs confirming.

Here, coefficients for transfer of water vapour from drops are derived from measurements in a wheat field. The relationship between wind speed and the boundary-layer resistance for a single drop is compared with that found by Leclerc *et al.* (1986) and that for spheres in a free stream.

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2. Theory

Evaporation from water drops depends on the drop temperature, the exposed drop surface area, the vapour pressure of air, and the boundary resistance for water vapour transfer, r_d. It can be described by the equation:

$$\lambda E = \frac{\rho c_p (e_s(T_d) - e_a)}{\gamma r_d} \tag{1}$$

where E is the evaporation rate (per unit exposed drop surface area), $e_s(T_d)$ is the saturated vapour pressure at drop temperature, ρ is the density of dry air, c_p is the specific heat of air at constant pressure, γ is the psychrometric constant (taken as 0.066 kPa K^{-1}) and λ is the latent heat of evaporation. Using measured values for the temperature of the drop, the vapour pressure of the air and the evaporation rate, Equation (1) is solved for r_d.

To obtain the evaporation rate, it is necessary to know the exposed surface area of the drop. The shape of drops on young green wheat leaves can be well approximated by a truncated oblate spheroid (Butler, 1985). However, since drop shape depends on the contact angle between water and the leaf surface, and this varies with leaf age and condition, other shapes may be appropriate. Leclerc *et al.* (1985) suggested representing drops either as hemispheres or as short vertical cylinders. Barr and Gillespie (1987) used an oblate hemispheroid. Here each drop was observed and the most appropriate geometric shape was used; a truncated oblate spheroid, an oblate hemispheroid, or a combination of a hemisphere and a cylinder.

3. Methods

Measurements were made at Long Ashton Research Station, U.K., in a mature wheat field in 1985, 1986 and 1987. The work was carried out in July of each year when crop senescence was advanced, so a young green leaf from a potted wheat plant was used for the experiments. This was supported horizontally at the height of the flag leaves of the surrounding plants, and adjacent stems were restricted with string from touching the supported leaf in strong wind. The weather was mostly warm and dry (air temperatures greater than 20° C) so evaporation rates were rapid, and times for data collection were selected to achieve a suitable range of wind speeds (between 0.3 and 2.4 m s^{-1}).

A set of five copper/constantan thermocouples wired in series was used to measure the temperature difference between the leaf and the air. The measuring junctions were attached to the underside of the supported leaf in different locations to represent the mean leaf temperature, and the reference junctions were grouped together and mounted in a ventilated radiation shield at the same height. To reduce errors caused by conduction of heat to or from the measuring junctions, the wires (0.1 mm diameter) were coated with a thin layer of adhesive to hold them in contact with the leaf for several centimeters from each measuring junction.

On the upper leaf surface, a thermocouple was arranged to measure the difference in temperature between two locations. It was made from 0.025 mm diameter chromium nickel/constantan wire with 0.08 mm copper leads and was held in contact with the leaf by coating the wires with adhesive. Adhesive was not used at the nickel chromium/constantan junction where the water drop was placed.

All the thermocouples were calibrated to better than ± 0.1 K in vacuum flasks of stirred water by comparison with a mercury-in-glass thermometer.

Air temperature and humidity were measured with a ventilated wet and dry bulb psychrometer with double radiation shields and platinum resistance sensors. These had been calibrated in a vacuum flask by comparison with the same mercury-in-glass thermometer to better than ± 0.1 K. The psychrometer was mounted at the same height as the supported leaf at a distance of approximately 40 cm. Wind speed was measured adjacent to the leaf. In 1985 and 1986 a hot-wire anemometer (PSI, AVM 502) was used with the output damped to give a response time of several seconds. The calibration agreed with a miniature cup anemometer to ± 5%. In 1987, a low-velocity flow analyser system was used (Dantec, 54N50) with the manufacturer's calibration. On some occasions, incoming solar radiation and net radiation over the crop were measured with a solarimeter (Kipp and Zonen) and Funk net radiometer (Middleton Ltd), respectively. Outputs from all the sensors were connected to a data logger, programmed to record average values every 2 min from scans at 10 sec intervals.

At the start of each set of measurements, a drop from a microsyringe was placed on the leaf over the chromium nickel/constantan thermocouple junction. Each drop was photographed from the side every 2 min to record its shape and dimensions. After a period of exposure, normally between 15 and 30 min, it was possible to remove the drop with the microsyringe and the final volume was recorded in this way. The initial drop volume varied between 10 and 50 mm^3.

4. Results and Discussion

The mean evaporation rate, E, for each drop was obtained from its change in volume and the exposed surface area. This was the average area, estimated from drop shape and dimensions at the start and end of each measurement period. Drop temperature and vapour pressure of the air were averaged over the same period and used with E in Equation (1) to obtain r_d. Conforming with Leclerc *et al.* (1986), r_d was related to the drop diameter, d, and the mean wind speed, u, by:

$$r_d = \frac{d}{(b \, \mathrm{Re}^m \, \mathrm{Sc}^{0.33} \, D)} \tag{2}$$

where D is the diffusivity of water vapour in air, Sc is the Schmidt number (taken as 0.63 for air, Monteith, 1973) and $\mathrm{Re} = ud/\nu$ is the Reynolds number, where ν is the kinematic viscosity of air. Equation (2) gives a linear relationship between

TABLE I

Parameter values in Equation (2) derived from this study and from electro-chemical simulations (Leclerc *et al.* 1986)

b	m	Source
0.66	0.40	This study
0.76	0.47	Leclerc *et al.* (1986)

log(Re) and log($d/(r^d\,\mathrm{Sc}^{1/3}\,D)$) and regression analysis was used to evaluate b and m (Table I).

The relationship between log (r_d) and log (u) (Figure 1) ignores the effect of drop diameter on r_d, but this was of secondary importance for the diameters examined. These ranged from 2.7 to 5.4 mm, and would lead to a change in log(r_d) of ±12% from the value for the mean diameter of 3.9 mm. Relationships for a drop diameter of 4 mm are shown in Figure 1 for the parameter values in Table I and for a sphere in a free stream (Ranz and Marshall Jr., 1952). In the discussion which follows, the relationships from this study and Leclerc *et al.* (1986) will be referred to as relationship A and relationship B, respectively.

It is difficult to assess the size of errors associated with the data points in

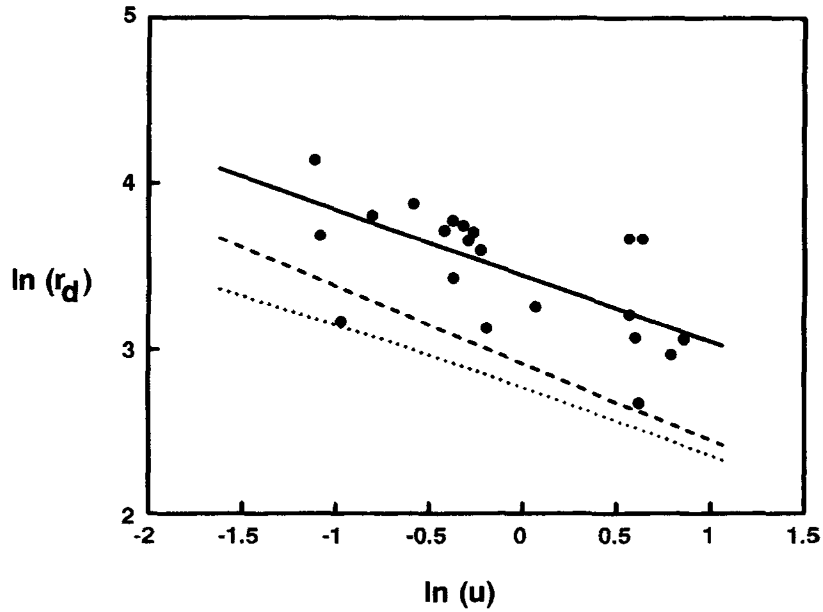

Fig. 1. The relationship between log(u) and log(r_d) for water drops on wheat leaves. The range of drop diameters was 2.7 to 5.4 mm. The lines are relationships for a drop of 4 mm diameter with parameters in Equation (2) from this study (______); from Leclerc *et al.* (1986), (---------); and for a sphere in a free stream $r_d = d/\{(2 + 0.60\ \mathrm{Re}^{0.5}\ \mathrm{Sc}^{0.33})D\}$ (. . . . .).

Figure 1 since they depend largely on prevailing environmental conditions. Some measurements were made on hot days when the water drop was about 10 K cooler than the leaf. The vapour pressure difference in Equation (1) was about 1 kPa, so an error in drop temperature of 1 K would result in a 15% error in the estimate of r_d. At other times, a smaller error in drop temperature would result in a larger error in r_d. Measurements of initial drop volume were subject to small errors (less than ±1%), but final drop volumes were more difficult to determine and could have been wrong by as much as ±5%. The effect of such uncertainties could lead to errors of about 20% in the estimate of r_d. In addition, there was some uncertainty in estimates of exposed surface area from the drop shape and dimensions. The photographs magnified the drop about 6 times, so the diameter could be measured to ± 0.01 mm and the appropriate geometric shape was checked by calculating initial and final drop volumes from the dimensions. Agreement was usually within ±2.5%, giving confidence to surface area estimates.

These possible sources of error account for much of the scatter in Figure 1, and although relationship A (for natural air flow) is similar to relationship B (for the flow of liquid in electrochemical simulations), it is likely that there is a real difference between them. Leclerc *et al.* (1986) found little difference between values of transfer coefficients derived from their measurements and from the relationship for spheres in a free stream, in the range of Sherwood numbers they examined. However, with Sherwood numbers appropriate for water drops in canopies, the relationship for spheres in a free stream gives smaller values of r_d than either of the other relationships, particularly at low wind speeds.

The difference between relationships A and B in Figure 1 could result from systematic errors in temperature measurements so this possibility will be examined. It is likely that the thermocouples on the lower leaf surface underestimated the leaf-to-air temperature difference. The measuring junctions were attached to the leaf with adhesive, giving good thermal contact, so the size of the error is likely to be about 10% (Thorpe and Butler, 1977). The finer thermocouple wires on the upper leaf surface would provide values closer to the true leaf temperature. When the leaf was warmer than the air, the net outcome would be an underestimate of the drop temperature, which would make the value of r_d from Equation (1) too small. Correcting for this would slightly increase the difference between relationships A and B.

Another possible systematic error could result from temperature gradients within the drop. If substantial amounts of energy from radiation and conduction were supplied to the base of the drop, there would be a significant temperature difference between the evaporating surface and water inside the drop where the temperature was measured. This would lead to an overestimate of r_d and requires further examination.

It is illuminating to calculate how much the drop temperature would need to change to explain the difference between relationships A and B. For this, a number of sets of measurements were selected to cover a wide range of evaporation rates.

TABLE II

Measured drop temperatures (T_d) and drop temperatures which satisfy Equation (2) with r_d from Leclerc's relationship ($T_d(L)$). The values cover a large range of evaporation rates. Air temperature (T_a) and the proportional change in the drop-to-air temperature difference (f) are given

T_d	$T_d(L)$	r_d	T_a	f
22.8	20.5	14.0	28.6	1.40
18.1	16.9	23.1	21.7	1.36
22.5	20.2	15.3	28.4	1.40
17.8	16.5	14.5	21.7	1.34
18.2	17.3	15.9	21.4	1.29

The wind speed and drop diameter of the selected set were used to give values of r_d from Equation (2), using the coefficients from Table I. Equation (1) was then solved for drop temperature using the measured evaporation rate and air vapour pressure. The result (Table II) indicates that the average air-to-drop temperature difference would have to increase by 36% (about 2.3 K on occasions) over measured values to obtain agreement with relationship B. To confirm the validity of measured drop temperatures, a computer model of the drop energy balance was used.

4.1. Drop Energy Balance

Solar radiation (Q_s) was assumed to be intercepted by the drop over its projected area and transmitted to the leaf beneath the drop. 50% of this energy was assumed to be absorbed and transferred to the drop (Butler, 1985).

Long-wave radiation exchange was assumed to occur between the sky and the drop over its projected area. The effective sky temperature (T_s) was estimated from the net radiation over the crop (Q_n), leaf temperature (T_l) and the short-wave balance (assuming a reflection coefficient of 0.2 for the crop).

$$Q_n = 0.8\,Q_s + \sigma(T_s^4 - T_l^4) \tag{3}$$

where σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).

The net radiation absorbed by the drop (Q_{nd}) is given by the sum of the short-wave and long-wave components:

$$Q_{nd} = (0.5Q_s + \sigma(T_s^4 - T_d^4))A_p/A_s \tag{4}$$

where A_p is the projected drop area and A_s is the exposed surface area. Long-wave radiation exchange between the crop and the base and sides of the drop is not included because the effective temperature of the surroundings is not known. Ignoring this component of the energy balance has a small effect on the calculated evaporation rate (about 5%) and does not change the conclusions which follow.

The drop energy balance equates the sum of net absorbed radiation and heat conducted from the leaf (C_d), with the sum of sensible and latent heat exchange between the drop and the air (all per unit exposed surface area).

$$Q_{nd} + C_d = H + \lambda E \tag{5}$$

where H is the sensible heat exchange. When written in its full form, Equation (5) can be solved for T_d (see Butler (1985) for the derivation),

$$T_d = \frac{A_s \rho\, c_p(T_a(\Delta + \gamma) - \delta e) + \gamma r_d(\eta\, \pi\, d_b T_l + A_s Q_{nd})}{A_s \rho c_p(\Delta + \gamma)\gamma r_d \eta \pi d_b}, \tag{6}$$

where $\eta = 0.11\ \mathrm{W\,m^{-1}\,s^{-1}}$ is an effective conduction coefficient, Δ is the slope of the curve relating saturated vapour pressure to temperature, γ is the psychrometric constant, δe is the vapour pressure deficit of the air and d_b is the base diameter of the drop.

The value of Δ is given by:

$$\Delta = (e_s(T_d) - e_s(T_a))/(T_d - T_a). \tag{7}$$

Since drop temperature is required to obtain Q_{nd} and Δ, an iterative procedure was used to satisfy Equations (4), (6) and (7).

The model was first used to examine how drop temperature, evaporation rate and sensible heat exchange change with r_d. For this purpose, solar radiation, net radiation over the crop, air temperature and vapour pressure were fixed at $Q_s = 500\ \mathrm{W\,m^{-2}}$, $Q_n = 300\ \mathrm{W\,m^{-2}}$, $T_a = 25\,°\mathrm{C}$ and $e_a = 1.7\ \mathrm{kPa}$. The result (Figure 2)

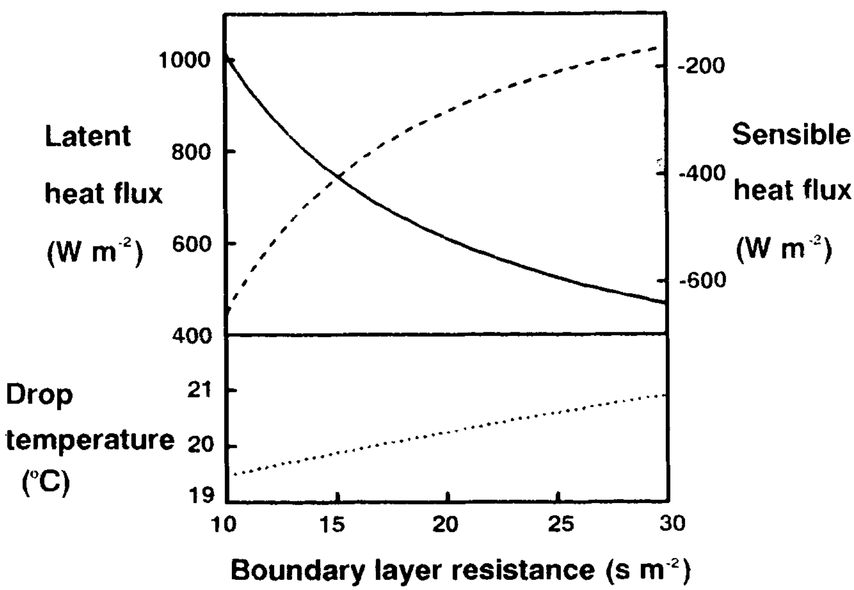

Fig. 2. The effect of boundary-layer resistance (r_d) on drop temperature, latent heat flux and sensible heat flux. Values were calculated from the model described in the text with $Q_s = 500\ W\mathrm{m^{-2}}$, $Q_n = 300\ \mathrm{W\,m^{-2}}$, $T_a = 25\,°\mathrm{C}$ and $e_a = 17\ \mathrm{kPa}$. Key: (______) latent heat flux; (------------) sensible heat flux; (. . . . .) drop temperature.

shows that r_d has a small effect on T_d, and a large effect on latent and sensible heat exchange.

Secondly, the model was used to calculate drop temperature and evaporation rate from the environmental conditions pertaining for the sets of measurements

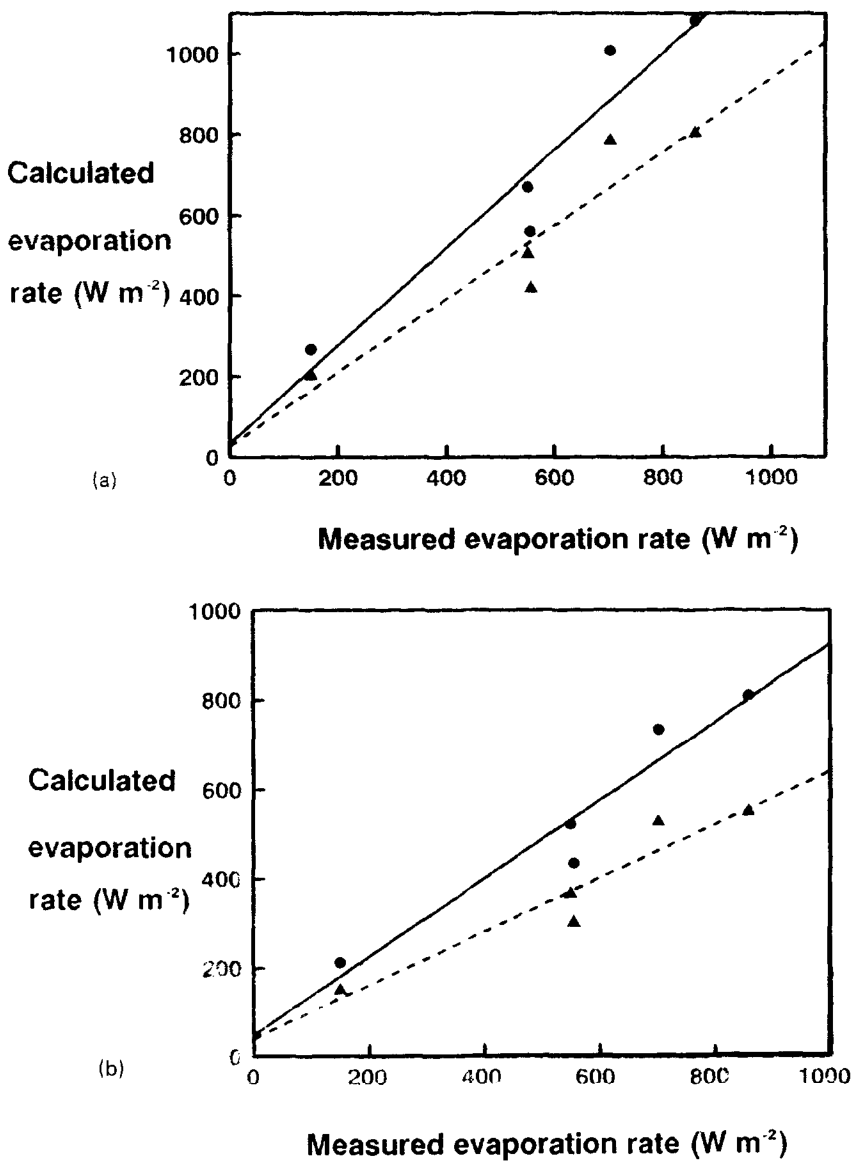

Fig. 3. A comparison between measured and calculated evaporation rates from drops. For the calculations, r_d was obtained from wind speed and drop diameter (Equation (1)) and drop temperature was given by Equation (6), (a) including heat conduction from the leaf ($\eta = 0.11\ \mathrm{W\,m^{-1}\,K^{-1}}$), and (b) ignoring heat conduction (η set to zero). Key: (--▲--) r_d from this study; (— ● —) r_d from Leclerc *et al.* (1986).

examined earlier (Table II). As before, values of r_d were obtained from wind speed and drop diameter, using relationships A and B. The measured and simulated evaporation rates show good agreement for relationship A, but the values for relationship B are about 20% greater (Figure 3a).

There are a number of reports of good agreement between simulated and observed drying times of drops using values of r_d similar to those for relationship B (e.g., Leclerc *et al.*, 1985; Gillespie and Duan, 1987; Barr and Gillespie, 1987). None of these simulations includes a term in the drop energy balance for conduction (C_d), so the model described here was run with conduction set to zero. The result (Figure 3b) showed good agreement between observed and measured evaporation rates for relationship B and values about 40% too low for relationship A. The result with relationship B when conduction of heat from the leaf is ignored, is virtually identical to the result with relationship A when the conduction term is included.

Since the same result can be obtained from both relationships, the question of which one is correct may be academic. The drop temperature measurements from this study suggest that the heat conduction term in Equation (5) is substantial. This being the case, significant temperature gradients within the drop are likely to exist, leading to an underestimate of the air-to-drop temperature difference. Rough calculations, taking the thermal conductivity for water as $0.6\ \mathrm{W\,m^{-1}\,K^{-1}}$ and a heat flux of $300\ \mathrm{W\,m^{-2}}$, indicate a temperature difference between the base and top of the drop of about 1.3 K. The measured drop temperature would represent a value between the base and the surface, and correcting for this would reduce the values of r_d in relationship A. On the other hand, the assumptions in the model for the radiation balance of the drop suggest small values of Q_{nd} (usually $< 70\ \mathrm{W\,m^{-2}}$). If there was also no significant conduction of heat from the leaf, the main source of energy for evaporation would be sensible heat supplied at the exposed surface, so temperature gradients in the drop would be very small (similar calculations indicate a maximum difference of about 0.3 K). This suggests that the term for effective conduction in Equation (5) (which may include a long-wave radiation component) is significant. The true situation is almost certainly somewhere between the two extremes considered here, and it is fortuitous that accurate simulations of evaporation rates can be obtained with either relationship.

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