POROMETRY AND BASELINE ANALYSIS: THE CASE FOR COMPATIBILITY*

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ABSTRACT

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This paper explores the suggestion by Idso and his colleagues that the response of stomata to saturation vapour pressure deficit may prove to be an artefact of porometry. Re-examination of their analysis reveals several potential sources of error leading to anomalously small ratios of aerodynamic to stomatal resistance both for leaves and for canopies. Arguments are advanced for adopting values of this ratio an order of magnitude larger than those used by Idso. The saturation deficit (D_0) estimated within the canopies explored by Idso is then less than 1 kPa even when the deficit in ambient air approaches 30 kPa. As Idso's own porometer measurements suggest that stomatal closure in water hyacinth did not occur until D_0 exceeded 1 kPa, his observations of stomatal resistance and radiative surface temperature appear to be fully compatible and his "apparent discrepancy" disappears.

INTRODUCTION

In micrometeorology, as in most branches of experimental science, fashions in research are often dictated by the evolution of instruments. In the 1970s, when portable porometers and radiation thermometers became sensitive and robust enough to use in the field, measurements with these devices soon become prominent in papers dealing with the heat and water balance of plant communities. Now, however, a group working in Arizona claims that because their own measurements with these two instruments appear incompatible, porometers as a class are unreliable. In particular, they suggest that the closure of stomata in dry air, as reported by many workers, is simply an artefact of porometry. The so-called "problems" and "perils" of porometry have been ex-

haustively discussed by Idso (1987), by Idso, Allen and Kimball (1987), by Idso, Clawson and Anderson (1986) later referred to as ICA, and by Idso, Allen and Choudhury (1988) referred to as IAC.

The purpose of this paper is to demonstrate that the conclusions reached by Idso and his colleagues are based on a physically implausible interpretation of their primary data. Indisputably, measurements with porometers are subject to several systematic errors, but most of these are avoidable or correctable. The interpretation which the Arizona group place on their measurements does not justify denigrating porometers as a class.

The argument advanced by ICA and IAC hinges on the interpretation of "non-water-stressed baselines" ("baselines" hereafter) used by Idso (1982) to relate the radiative temperature T of a canopy to the saturation vapour pressure deficit D of the air passing over it. In trials with three species freely supplied with water and grown in tubs, both indoors and outdoors, ICA found that the measured relation between T and D was indistinguishable from a theoretical prediction based on the assumption that stomata did not close as D increased to 30 kPa. This conclusion is wholly inconsistent with a wealth of laboratory and field evidence obtained from measurements with different types of equipment as described, for example, by Schulze and Hall (1982) and by El-Sharkaway et al. (1985). To explore the source of this inconsistency, it is necessary to restate the theory used by ICA as a basis for re-interpreting their measurements.

THEORY

Two complementary equations are needed. Their derivation (Monteith, 1981) and their validity are not at issue. The precise definition of terms used in these equations includes the term "reference point" (RP), a convenient point in space where temperature, vapour pressure and wind speed are assumed to represent the environment of leaves or foliage, unmodified by their presence. Essential symbols and their definitions follow.

H = available energy – net radiation flux received by unit plan area of a leaf or canopy (W m^{-2})

T_a = temperature of air at RP (°C)

T = aerodynamic surface temperature of leaf or canopy (defined by eq. 2)

r_a = aerodynamic resistance between a leaf and an RP (s m^{-1})

r_a' = corresponding resistance between a canopy and an RP

r_s = stomatal resistance of a leaf (s m^{-1})

r_s' = corresponding "surface" resistance of a canopy

$\varDelta$ = change of saturation vapour pressure deficit between T_a and T divided by $(T_a - T)$ (kPa K^{-1})

γ = psychrometer constant (kPa K^{-1})

γ^* $= \gamma(1+r_s/r_a)$ or $\gamma(1+r_s'/r_a')$

ρc $=$ volumetric specific heat of air at constant pressure set at an arbitrary value of $1.20 \text{ kJ m}^{-3} \text{ K}^{-1}$.

Using these quantities, the loss of latent heat from a canopy is given by

$$\lambda E = \frac{\Delta H + (\rho c/r_a')D}{\Delta + \gamma^*} \tag{1}$$

and the aerodynamic surface temperature of the canopy is

$$T = T_a + \frac{(r_a' H \gamma^*/\rho c) - D}{\Delta + \gamma^*} \tag{2}$$

(the same equations are valid for a leaf, omitting primes from the resistances).

ICA assumed implicitly that the (theoretical) aerodynamic surface temperature T is identical to the (measured) radiative surface temperature. The relatively small systematic errors likely to be introduced by this assumption (Huband and Monteith, 1986; Choudhury et al., 1986) are ignored in the analysis which follows and measurements which ICA made with a radiometer are assumed to be free of error.

Equation 2 implies that $T - T_a$ should increase nearly linearly with H when D is constant and decrease nearly linearly with D when H is constant. The qualification "nearly" is needed because the increase of Δ with temperature introduces an element of non-linearity into baselines which extend over a wide temperature range – as ICA showed.

Another important feature of eq. 2 is that because γ^* is a function of r_s'/r_a', the equation can be recast as a quadratic in r_a', implying that there are conditions in which the same value of T is achieved at two discrete values of r_a'.

Following Choudhury and Monteith (1986), the same theoretical basis can be used to define the representative saturation deficit of air within a canopy as

$$D_0 = r_s' \gamma \lambda E/\rho c \tag{3}$$

This equation summarizes the complex microclimate of a canopy in a single term and it is fully compatible with eqs. 1 and 2 which are based on the same "big leaf" canopy model. Equation 3 has major physiological implications because it defines uniquely the way in which stomatal or surface resistances must respond to the state of the environment as defined by D_0 when the behaviour of λE is determined by the supply of water to a leaf or canopy. By manipulating terms, it can be shown that

$$D_0 = \frac{\gamma D (r_s'/r_a') + \gamma \Delta H r_s'/(\rho c)}{\Delta + \gamma^*} \tag{4}$$

and that D_0 will be greater or less than D depending on whether E is less than

or greater than the "equilibrium" evaporation rate as defined by McNaughton and Jarvis (1983), viz. $\Delta H/[\lambda(\Delta+\gamma)]$.

FIRST INSPECTION OF THE EVIDENCE

Accepting, for the time being, the values of r_a' and r_s' in the range adopted by ICA (Table 1) along with their representative value of $H = 450$ W m^{-2}, it is instructive to examine λE as a function of D and r_a' (eq. 1) and D_0/D as a function of r_s'/r_a' (eq. 4).

For a representative canopy resistance of 35 s m^{-1}, λE rises steeply with increasing D when r_a' is 20 s m^{-1} or less, and achieves values between 2000 and 3000 W m^{-2} at 30 kPa, the maximum saturation deficit which ICA used in their analysis (Fig. 1). Corresponding evaporation rates range from 3 to 4.5 mm h^{-1}, an order of magnitude larger than those usually encountered in the field where D rarely exceeds 5 kPa.

It seems extremely unlikely that plants of any species could continue to transpire so fast without attempting to close their stomata. What evolutionary advantage would there be in a vascular system large enough for plants to pass water at this rate? (The same argument could be applied to humans in relation to sweating which has an upper limit of about 400–500 W m^{-2}.) However, ICA's baselines suggest that closure, if it occurred, had an imperceptible effect on leaf temperature and, by inference, on the rate of transpiration. Suspicion must therefore fall, not on the values of r_s' chosen by ICA, but on their values of r_a'. Did they inadvertently select the smaller root of eq. 2 (Fig. 2) when the larger root was appropriate? Figure 2 shows that, for $D = 10$ kPa, the same canopy temperature would be achieved with r_a' set at 15 or at 80 s m^{-1}, but from Fig. 1, the transpiration rate would be much smaller with the larger resistance which is therefore the more plausible one.

Much of the evidence for stomatal closure in dry air was obtained at values of D_0 exceeding 1 kPa. Figure 3 shows that provided r_a/r_s lies in the range 2–4,

TABLE 1

Values of resistance (s m^{-1}) and of net radiation (W m^{-2}) used by Idso et al. (1986) and derived by re-examining their data and assumptions

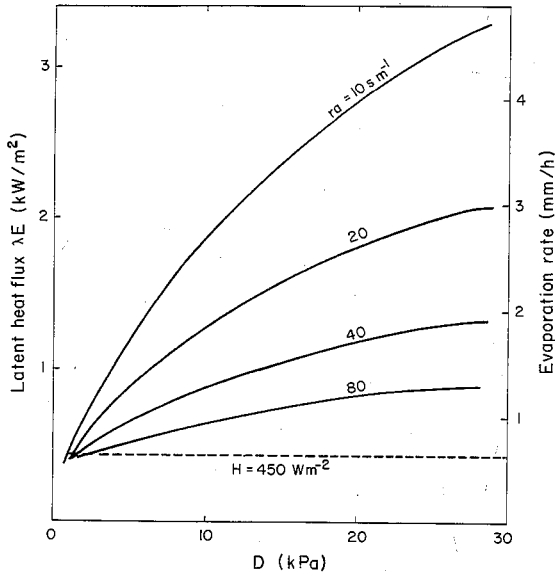|	ICA values			New values		
	r_a	r_s	r_a/r_s	r_a	r_s	r_a/r_s
Water hyacinth	24	35	0.7	70	15	4.7
Alfalfa	8	15	0.5	70	15	4.7
Cotton	15	25	0.6	70	12	5.8
Net radiation		450			$250+10(T_a-T)$	

Fig. 1. Increase in rate of latent heat loss, λE, with increase of vapour pressure deficit measured at a reference point for $r_s = 35$ s m^{-1} and four levels of r_a. H is set at 450 W m^{-2}.
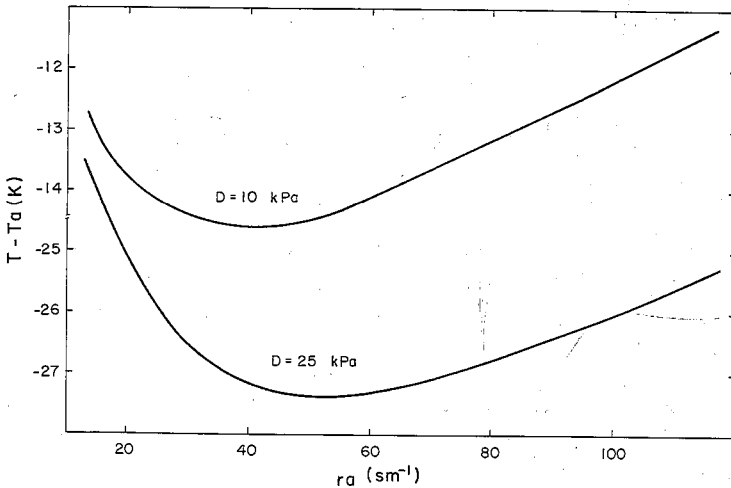

Fig. 2. Difference between radiative surface temperature and air temperature at reference point $(T - T_a)$ as function of aerodynamic resistance r_a for $D = 10$ and 25 kPa and for $r_s = 35$ s m^{-1}.

D_0 is less than 1.7 kPa over the range of D explored by ICA. However, ICA's values of r_a/r_s ranged from 0.5 to 0.7 implying that D_0 was usually between 2 and 4 kPa and measurable closure of stomata would therefore be expected. This strengthens the suspicion that ICA underestimated r_a and/or overestimated
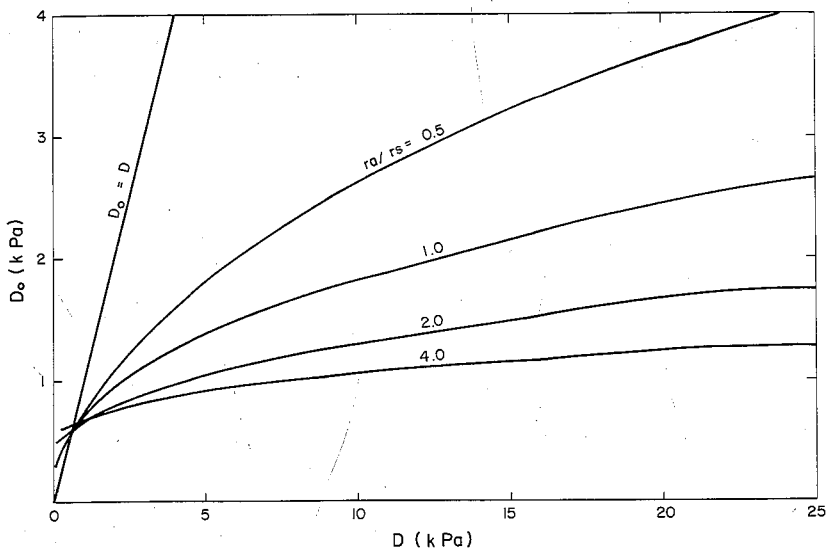
Fig. 3. Dependence of surface or canopy value of vapour pressure deficit D_0 on deficit at a reference point D as a function of r_a/r_s with $r_s = 35$ s m^{-1}.

r_s. As doubt has been cast on the resistances adopted by ICA, they will now be scrutinized in the sequence of the original paper.

REVIEW OF RESISTANCES

Stands of water hyacinth, alfalfa and cotton were grown in containers exposed both out of doors and in a "sealed and unventilated greenhouse ... which on extremely hot summer days experienced internal air temperatures in excess of 75°C and air VPD (i.e. D) values of almost 40 kPa". The water hyacinth grew in tubs of water. Alfalfa and cotton were watered several times a day. IAC state that the reference point in the open was 1 m above the canopy but the corresponding position in the glasshouse was not specified either by IAC or by ICA.

Water hyacinth

A Licor 1600 steady-state porometer and 6000 Photosynthesis System were used to determine stomatal resistance, r_s. ICA's conclusion was that baselines incorporating some of their measurements of r_s are a valid description of how a canopy responds to D whereas the complete set of porometer measurements is faulty. (The flaw in this argument will not be pursued.) Although a plot of r_s against net radiation showed a substantial amount of scatter, ICA chose a single representative mean value of $r_s = 35$ s m^{-1} for values of net radiation

ranging from 100 to 800 W m^{-2} and for air temperatures between 20 and 70°C. The scatter at 450 W m^{-2} was from 26 to 56 s m^{-1}, approximately.

ICA did not distinguish between the stomatal resistance of single leaves and of a whole canopy but there are at least three reasons why the latter should be smaller.

(1) The resistance of a canopy can be regarded as the resistance of foliage components wired in parallel. For complete ground cover and when stomatal conductance is proportional to incident solar radiation, $r_s' \simeq Kr_s$ where K is an extinction coefficient for light (Choudhury and Monteith, 1988). The value of K for ICA's canopies was probably between 0.5 and 0.7 implying an overestimate of r_s' by a factor between 1.4 and 2.0.

(2) The resistance of a canopy is conventionally calculated from the flux of water vapour per unit plan area and per unit of vapour pressure difference, a procedure which assumes that the canopy is extensive enough for edge effects to be negligible. The water hyacinth plants extended 0.3 m above the surface of a tank with a diameter of 2 m and a significant amount of water vapour must have been lost laterally from such a system. Assuming that the rate of transpiration per unit of vertical surface was half the rate per unit horizontal surface, r_s' would be overestimated by a factor of 1.3.

(3) Evaporation must have occurred directly from water and from wet soil beneath the canopies as well as by transpiration. This component of evaporation may have contributed 5–10% of the total flux of vapour.

All three of these processes imply that the appropriate value of the canopy resistance for the test canopies should have been less than the resistance of single leaves, possibly by a (combined) factor of between 2 and 3.

A value of r_a' (unspecified RP) was obtained inside the glasshouse by measuring $T - T_a$ for dead foliage as a function of net radiation. Again, substantial scatter is evident, ascribed by IAC to convection currents: at $H = 450$ W m^{-2}, $T - T_a$ ranged from 6 to 13 K. ICA chose a mean value of 24 s m^{-1} and applied it over a temperature differential of $T - T_a$ from 0 to -35 K. They conceded that the aerodynamic resistance for heat transfer could be "somewhat different" for canopies hotter than or colder than the ambient air but decided that such differences could be ignored because a value of $r_a = 24$ s m^{-1} gave a theoretical baseline from eq. 2 consistent with measurements with a radiation thermometer. This procedure is not consistent with the treatment of free convection by engineers and micrometeorologists. However, no formula exists for calculating the correct value of r_a' for a tub of plants with foliage 0–35 K cooler than the ambient air in an air-tight glasshouse. The appropriate value must therefore be found empirically. ICA assumed, without comment, that a value of $r = 24$ s m^{-1} was also valid in the open, irrespective of windspeed.

Alfalfa

Stomatal conductance was not measured and a value of $r_s = 15$ s m^{-1} was

taken from unpublished work by Clawson. This value is well outside the range for herbaceous species reported in the literature (Jones, 1983). However, it may well be appropriate for the canopy resistance of alfalfa in the conditions established by ICA. The value of r'_a obtained from the sensible heat loss from dead foliage was 8 s m^{-1} and the same value was subsequently used for transpiring leaves. It is improbable that a tub of transpiring plants in a sealed and unventilated greenhouse presented an aerodynamic resistance in the range normally associated with a windswept forest (McNaughton and Jarvis, 1983).

Cotton

Explaining how resistances were chosen for cotton, ICA wrote: "we merely guessed at what we thought would be reasonable starting values for these parameters and then made a series of readjustments to derive a baseline which provides the best fit to our greenhouse data and the outside data set of Idso et al. (1982). The values we finally settled on at the conclusion of this exercise were $r'_a = 15$ s m^{-1} and $r'_s = 25$ s m^{-1}." The value of r_a is unacceptably small for reasons already given.

To summarize, the resistances used by ICA were: (1) to some extent based on measurements with a porometer whose performance they proceeded to question; (2) derived from measurements of sensible heat transfer in unstable conditions within a glasshouse but applied to stable conditions both within the glasshouse and in the open without regard to the magnitude of temperature gradients responsible for free convection or of wind responsible for forced convection; (3) based on the implicit assumption that leaf and canopy resistances were identical; (4) not wholly independent but to some extent chosen to fit the observed relation between $T - T_a$ and D.

It cannot be denied that ICA's baselines fit their measurements of radiative surface temperature extremely well over a very wide range of D, but the gross assumptions behind their choice of resistance values, coupled with the anomalously large transpiration rates implied by Fig. 1, justify this attempt to reinterpret their data.

RESOLVING THE "DISCREPANCY"

How can ICA's measurements be reconciled with the evidence that the stomata of many species respond to changes in the vapour pressure deficit of ambient air? To establish a convenient quantitative relation for such a response, suppose it is governed by a maximum rate of transpiration, independent of weather and related to the size and growth rate of the root system and/ or to hydraulic resistances within plants (Monteith, 1988). (In this context, it is not necessary to specify details of the feedback mechanism responsible for such control or to consider the possibility that a feedforward mechanism may reduce the transpiration rate when the vapour pressure deficit exceeds some

limiting value (Farquhar, 1978).) The equivalent maximum flux of latent heat will be written $\lambda E\,(\mathrm{max})$.

To be more precise, suppose that: (1) when λE is smaller than $\lambda E\,(\mathrm{max})$, the stomatal (or canopy) resistance has a constant minimum value $r_s(\mathrm{min})$ (or $r'_s(\mathrm{min})$) and D_0 is less than a critical value D_{0c}; (2) when D_0 is larger than D_{0c}, then $\lambda E = \lambda E\,(\mathrm{max})$ and $r_s = \rho c D_0/\gamma\lambda E\,(\mathrm{max})$.

The apparent response of r_s to D (not D_0) found by IAC using a Licor photosynthesis system (Fig. 4) was re-analysed, accepting the value of $r_a = 30$ s m^{-1} used by IAC (although the manufacturers give $r_a = 15$ s m^{-1} for the porometer cup) and their value of $r_s(\mathrm{min}) = 35$ s m^{-1}. The relation between D and T_a was established by appealing to ICA's Fig. 3 which shows that the vapour pressure of air both within the glasshouses and outdoors was approximately 2 kPa. Using this value, the dependence of Δ on T and T_a and the dependence of r_s on D_0 were established by iteration of eqs. 2 and 3. Figure 5 (lower section) shows that the measurements of $T - T_a$ were consistent with
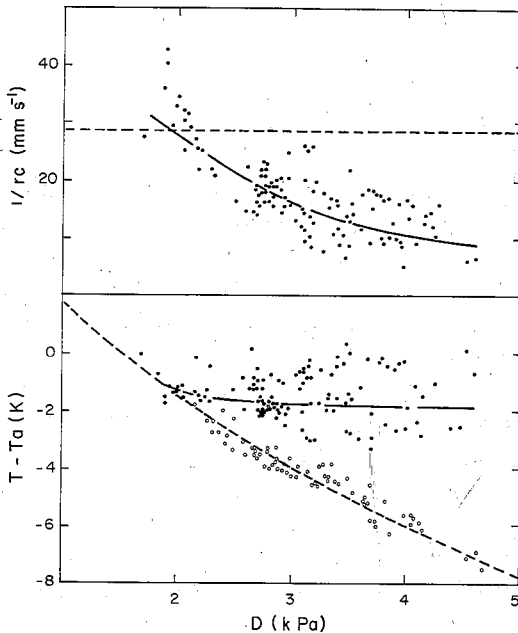

Fig. 4. Upper portion: stomatal conductance of water hyacinth leaves measured by ICA with a Licor porometer or Photosynthesis System. Full line was fitted to observations by ICA and dashed line is the value they chose for maximum conductance equivalent to $r_s = 35$ s m^{-1}. Lower portion: open circles are measured differences between surface radiative temperature and air temperature as function of vapour pressure deficit at reference point for water hyacinth in the open. Corresponding dashed line is theoretical relation from eq. 2 with $r_s = 35$ s m^{-1}, $r_a = 24$ s m^{-1} and $H = 450$ W m^{-2}. Closed circles are measurements of $(T - T_a)$ for leaves in a leaf chamber. Full lines calculated from dependence of r_s on D in upper part of figure and using $r_a = 30$ s m^{-1}.
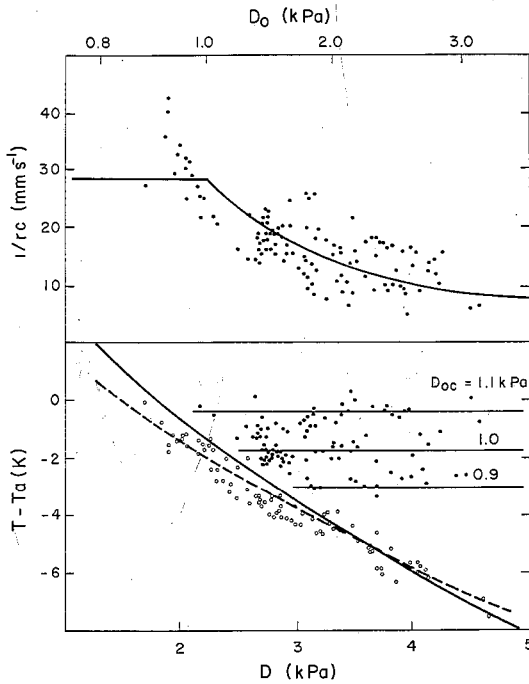
Fig. 5. Upper portion: measurements as in Fig. 4. Full lines based on assumption that $r_s = 35$ s m^{-1} and that above a limit of $D_{0c} = 1$ kPa, chosen from evidence in lower part of figure, r_s is inversely proportional to D_0 so that λE is constant (see text). Lower portion: dependence of $(T - T_a)$ on D for three cases: (a) leaves in leaf chamber with $r_a = 30$ s m^{-1} and three values of D_{0c} as shown; (b) canopy in the open with $r'_a = 60$ s m^{-1}, $D_{0c} = 1$ kPa, and $H = 450$ W m^{-2} (full curve); (c) as (b) but with $r'_a = 70$ s m^{-1} and $H = 250 + 10$ $(T - T_a)$ W m^{-2} (dashed curve).

values of D_{0c} between 0.9 and 1.1 kPa and an intermediate value of 1.0 kPa was chosen for further analysis.

Moving now to the behaviour of stomata on leaves exposed outdoors, Fig. 4 (lower section) shows that ICA's values of r_s(min) and r_a are incompatible with stomatal closure as specified by the critical value $D_0 = 1$ kPa. However, the validity of these resistances has already been questioned. Can other values, consistent with preceding assessments, produce a baseline compatible with Idso's measurements of radiative temperature? The answer is "yes". ·

First, r'_a was set at 60 s m^{-1} consistent with the larger root of eq. 2 at about $D = 10$ kPa (Fig. 2). This procedure did not greatly alter the position of the baseline directly but it had a significant indirect impact because increasing r'_a/r'_s decreases the value of D_0 associated with a given value of D (eq. 4 and Fig. 3). Foliage temperature was still overestimated however; it was found to be insensitive to the value of r'_a but sensitive to r_s(min). Reasons for decreas-
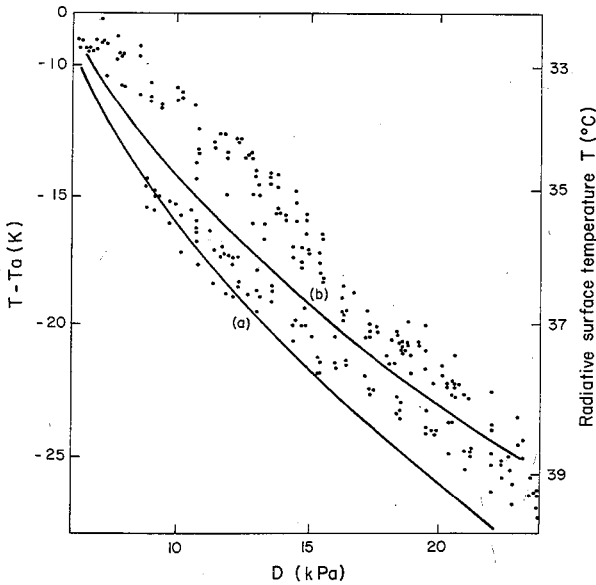
Fig. 6. (a) Dependence of $(T-T_a)$ on D for $r_a' = 70$ s m^{-1}, r_s'(min)$= 35$ s m^{-1}, $D_{0c} = 1$ kPa, $H = 450$ W m^{-2}. (b) As (a) but with $H = 250 + 10(T-T_a)$ W m^{-2}. Points are measurements by IAC. Scale for radiative surface temperature is based on assumption that absolute vapour pressure was 2 kPa and is therefore an approximation.

ing r_s(min) by a factor of 2–3 were advanced in the last section. Reducing r_s(min) by a factor of 2.3 to give $r_s' = 15$ s m^{-1} with $r_a = 60$ s m^{-1} gave a baseline between $D = 1$ and 5 kPa close to IAC's observations and therefore to their baseline for which $r_s' = 35$ s m^{-1} and $r_a' = 24$ s m^{-1} (Fig. 5, lower section, full line). The new baseline shows no evidence of stomatal closure as D increases, not because the possibility is ignored but because D_0 never exceeds its critical value and E never reaches its maximum value.

Even better agreement with IAC's observations and baseline was obtained by making allowance for the correlation between air temperature and radiation which their measurements imply but which they ignored by choosing a fixed radiative flux of 450 W m^{-2}. When r_a' was set at 70 s m^{-1} and H was assumed to be 250 W m^{-2} at $T_a = 20°$C, increasing by 10 W m^{-2} K^{-1}, agreement with IAC's baseline was within ± 0.05 K for $D = 1$–5 kPa (Fig. 5, lower section, dashed line). This procedure altered the relation between $T - T_a$ and D for leaves in the porometer cup but did not affect the conclusion that 1.0 kPa was an appropriate value for D_{0c}.

When the analysis was extended to values of D up to 25 kPa, the range covered by ICA, the difference between the revised values of $T - T_a$ and those calculated by ICA was only $+0.1$ to -0.5 K, well within the scatter of measurements (Fig. 6, curve b). The predicted rate of transpiration did not reach

its maximum value of $\lambda E = 1300$ W m^{-2} until D reached 27 kPa. The same values of surface and aerodynamic resistance were found to be valid for cotton because, for a given value of D, the mean value of T measured by ICA differed very little between the canopies of water hyacinth and cotton. The alfalfa canopy was cooler than the other two by about 1.0–1.5 K over most of the range of D and this difference can be accommodated by reducing r_s from 15 to 12 s m^{-1}. The revised values of aerodynamic and stomatal resistance (Table 1) are therefore much more homogeneous than those chosen by ICA. Even these values should be regarded as approximations, however, because the dependence of r_a' on wind speeds and temperature gradients remains imponderable.

CONCLUSIONS

Re-examination of measurements made by ICA with a radiation thermometer and a porometer suggest that: (1) the former are of high quality; (2) there is no reason to question the validity of the latter. However, it appears that IAC and ICA failed to account for systematic differences between leaf and canopy resistances and that they were indiscriminate in their choice of aerodynamic resistances. To obtain a new set of resistances consistent with ICA's measurements of temperature, I increased the ratio of aerodynamic to canopy resistance by an order of magnitude and assumed that net radiation flux increased linearly with air temperature. These actions, to some extent arbitrary but based on physical reasoning, served to resolve the "apparent discrepancy" which has been exercising many workers since ICA and IAC began to question the validity of measurements with porometers.

Resolving the discrepancy does not remove the need for extreme care when porometers are used in the field, particularly to assess the response of stomata to saturation deficit. If this response reflects the existence of a limiting transpiration rate, as assumed here, then the shape of the response to D (as distinct from D_0) will depend on values of r_a, r_s and H. Stomatal resistance or conductance should therefore be presented as a function of the deficit at the leaf surface or within the canopy (D_0) rather than of D, a procedure made possible by appeal to eq. 4.

As an additional precaution, the deficit within the porometer should be kept as close as possible to the value in the external air and a value of stomatal resistance should be established before guard cells start to respond to their new environment, say within 10–15 s. An accurate measurement of leaf temperature is also essential to make an appropriate correction as described, for example, by Monteith et al. (1988).

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