ESTIMATING SENSIBLE HEAT FLUX FROM RADIOMETRIC TEMPERATURE OVER CROP CANOPY

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Abstract. The model devised by Lhomme *et al.* (1988) allows one to calculate the sensible heat flux over a homogeneous crop canopy from radiometric surface temperature by adding a so-called canopy aerodynamic resistance to the classical aerodynamic resistance calculated above the canopy. This model is reformulated in order to simplify the mathematical procedure needed to calculate this additional resistance. Analytical expressions of micrometeorological profiles within the canopy are introduced. Assuming a constant leaf area density, an analytical expression of canopy aerodynamic resistance is inferred, which is a function of wind velocity, inclination angle of the radiometer and crop characteristics such as crop height, leaf area index, inclination index of the foliage and leaf width. Sensitivity of this resistance to the different parameters is investigated. The most significant are wind velocity and LAI. Finally, the predictions of the model are tested against two sets of measurements obtained for two different crops, potato and maize.

1. Introduction

Remotely sensed surface temperature, obtained with ground-based or airborne infrared radiometers, has been widely used over crop canopies to determine the sensible heat flux and to calculate the evaporation rate as a residual term of the energy balance equation. Most of these studies rely on the assumption that the measured infrared temperature is identical to the computed aerodynamic surface temperature, classically defined as the temperature of the apparent source or sink of heat and estimated from extrapolation of temperature and windspeed profiles down to this level. However, there are problems associated with this assumption because experimental data show large discrepancies between the two temperatures (Huband and Monteith, 1986; Kustas *et al.*, 1989; Kalma and Jupp, 1990). Differences between the radiative and aerodynamic temperatures are typically of the order of 2–6 °C (Baldocchi *et al.*, 1991).

Lhomme *et al.* (1988) published an analytical model that provides a means of using the infrared surface temperature T_R to calculate the sensible heat flux H over homogeneous crop canopies from the classical flux equation

$$H = \rho c_p (T_R - T_a)/r_a \, , \tag{1}$$

where ρ is the mean air density, c_p is the specific heat of air at constant pressure, T_a is the air temperature at a reference height z_r and r_a is a resistance to sensible

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heat transfer from the canopy to the air. They showed that this resistance r_a must be considered as the sum of two resistances

$$r_a = (r_a)_a + (r_a)_c\,, \tag{2}$$

where $(r_a)_a$ is the classical aerodynamic resistance of the air stream calculated between the height h of the crop canopy and the reference height z_r, and $(r_a)_c$ is an additional resistance hereafter called the canopy aerodynamic resistance, which accounts for heat transfer within the canopy between the exchange surfaces (soil surface and leaves) and the top of the canopy. This canopy aerodynamic resistance is defined by a mathematical expression (Equation (3) of the next section), which is not easy to calculate because it requires knowledge of micrometeorological profiles within the canopy and involves the calculation of several integrals.

The present paper aims at simplifying the calculation of this additional resistance in order to make the original model more operational. A sensitivity analysis of the dependence of this resistance on the controlling parameters is presented, and experimental data obtained for potato and maize crops are used to test this simplified model.

2. Model Development

2.1. THEORETICAL EXPRESSION FOR $(r_a)_c$ AND $(r_a)_a$

The additional resistance appearing in Equation (2), $(r_a)_c$, is defined by the following expression (Lhomme *et al.*, 1988)

$$(r_a)_c = (P + Q)/R\,, \tag{3}$$

with

$$P = \int_{0+}^{h} s(z)a(z)r_A(z)\,\mathrm{d}z\,, \tag{3a}$$

$$Q = s(0)r_A(0)\,, \tag{3b}$$

$$R = \int_{0+}^{h} s(z)a(z)\,\mathrm{d}z + s(0)\,, \tag{3c}$$

where h is the canopy height, $a(z)$ is the leaf area density, and $s(z)$ is a function which represents the fraction of surface viewed by the radiometer at any horizontal level z within the canopy. Provided that the viewing angle of the radiometer is small, this function can be approximated by the function classically used to express the sunlit horizontal area within the canopy. $r_A(z)$ is defined by the following expression

$$r_A(z) = (\mathrm{d}A^*/\mathrm{d}z)[r_b(z)/2a(z)] + \int_z^h [A^*(z)/K(z)]\,\mathrm{d}z\,. \tag{4}$$

$A^*(z)$ is the normalized available energy defined by

$$A^*(z) = [R_n(z) - G]/[R_n(h) - G]\,, \tag{5}$$

where $R_n(z)$ is the net radiation at level z within the canopy and G is the soil heat flux. $r_b(z)$ is the boundary-layer resistance of the leaves at level z and $K(z)$ is the eddy diffusivity at the same level. $r_A(0)$ in Equation (3b) is the value of $r_A(z)$ at the soil surface ($z = 0$). It is given by Equation (4) in which $\mathrm{d}A^*/\mathrm{d}z$ is replaced by $A^*(0)$ and $r_b(z)/2a(z)$ by the boundary-layer resistance of the soil surface (Lhomme *et al.*, 1988, Equation (A.15)).

In neutral conditions, assuming that the roughness lengths for momentum and sensible heat are the same, the aerodynamic resistance above the canopy $(r_a)_a$ is classically expressed as

$$(r_a)_{a0} = \ln[(z_r - d)/(h - d)]\,\ln[(z_r - d)/z_0]/k^2u\,, \tag{6}$$

where u is the wind velocity at the reference height z_r, k is von Karman's constant (0.4), d is the zero plane displacement and z_0 is the roughness length, which can be obtained from the canopy height by making use of the empirical relationships given by Monteith and Unsworth (1990) for a dense canopy

$$d = 0.65h \qquad \text{and} \qquad z_0 = 0.10h\,. \tag{7}$$

In non-neutral conditions, the ratio between the stability-corrected aerodynamic resistance and $(r_a)_{a0}$ is generally expressed as a function of the bulk Richardson number

$$(r_a)_a/(r_a)_{a0} = f(\mathrm{Ri}_B)\,, \tag{8}$$

Ri_B being defined by

$$\mathrm{Ri}_B = -g(z_r - d)(T_s - T_a)/(T_a u^2)\,, \tag{9}$$

where g is the gravitational acceleration and T_s is the surface temperature taken to be equal to T_R. Under stable conditions ($\mathrm{Ri}_B > 0$), an exact analytical equation has been worked out for function f (Choudhury *et al.*, 1986). In unstable conditions ($\mathrm{Ri}_B < 0$), only approximate solutions can be obtained, which have been reviewed by Viney (1991). However, it should be noted that the expressions for f in Equation (8) have generally been derived for resistances calculated between the levels $d + z_0$ and z_r and not between h and z_r, as is the case in this model. Nevertheless, we can legitimately assume that the same correction applies.

2.2. PRACTICAL CALCULATION OF $(r_a)_c$

It is possible to calculate $(r_a)_c$ provided each of the functions appearing in expressions (3) is analytically defined. The functions retained to calculate $(r_a)_c$ are given below.

Following Ross (1975), the function commonly used to calculate the horizontal sunlit area within the canopy, and utilized here to calculate the area viewed by the radiometer at any level z within the canopy, is expressed as an exponential function of the cumulative leaf area index $L(z)$

$$s(z) = \exp[-\alpha_\beta L(z)] \quad \text{with} \quad \alpha_\beta = G(\beta)/\sin\beta\,, \tag{10}$$

where β is the inclination angle of the radiometer to the horizontal and $G(\beta)$ is the G function, giving the projection of the unit foliage area in the direction of the radiometer. The G function can be calculated, for $\beta > 15^0$, by means of the following approximate expression (Ross, 1975; Goudriaan, 1977)

$$G(\beta) = G_1 + 0.877(1 - 2G_1)\sin\beta\,, \tag{11}$$

with

$$G_1 = 0.5 - 0.633X_L - 0.33X_L^2\,, \tag{12}$$

where X_L is the inclination index of the foliage ($X_L = +1$ for foliage having only horizontal leaves and $X_L = -1$ for foliage having only vertical leaves). This semi-empirical relation is valid for $-0.4 < X_L < 0.6$; values of X_L for different crops are given by Ross (1975).

A Beer's law relationship is assumed to describe the extinction of net radiation within the canopy

$$R_n(z) = R_n(h)\exp[-\alpha_r L(z)]\,. \tag{13}$$

The extinction coefficient α_r depends upon the canopy structure, but for most agricultural crops α_r is not very different from 0.6. The soil heat flux is taken as a given proportion of the net radiation reaching the ground $G = \mu R_n(0)$ with $\mu = 0.2$.

The leaf boundary-layer resistance is calculated as (Jones, 1983)

$$r_b(z) = [w/u(z)]^{1/2}/\alpha_0\,, \tag{14}$$

where w is leaf width, $u(z)$ is wind velocity at level z and α_0 is a constant coefficient ($= 0.005$ in SI units for one side of the leaf). The soil boundary-layer resistance is taken to be equal to $r_b(0)$, the value of $r_b(z)$ for $z = 0$.

Wind velocity and eddy diffusivity are assumed to decrease exponentially through the canopy (Choudhury and Monteith, 1988; Shuttleworth and Gurney, 1990)

$$u(z) = u(h)\exp[-\alpha_w(1 - z/h)]\,, \tag{15}$$

$$K(z) = K(h) \exp[-\alpha_w(1 - z/h)] . \tag{16}$$

A typical value of α_w for agricultural crops is 2.5. Using traditional theory, $K(h)$ can be expressed as a function of $u(h)$:

$$K(h) = K_0 u(h), \quad \text{with} \quad K_0 = k^2(h - d)/\ln[(h - d)/z_0] . \tag{17}$$

The wind velocity at canopy level $u(h)$ can be calculated from the wind velocity (u) measured at a reference height z_r by means of the following relationship based upon the classical logarithmic profile

$$u(h) = \{\ln[(h - d)/z_0]/\ln[(z_r - d)/z_0]\}u , \tag{18}$$

where d and z_0 are given by Equations (7).

To calculate the integrals in Equations (3) and (4), it is necessary to give an analytical expression to $a(z)$. We shall use a constant profile of leaf area density defined by $a(z) = L_0/h$, where L_0 is the total leaf area index (LAI). Therefore, $L(z)$ is defined by $L(z) = L_0(1 - z/h)$ and the calculation of R, P and Q can be carried out.

R (Equation (3c)) is given by

$$R = [1 - (1 - \alpha_\beta) \exp(-\alpha_\beta L_0)]/\alpha_\beta . \tag{19}$$

Putting $y = 1 - z/h$, $r_A(z)$ can be expressed as

$$\begin{aligned} r_A(z) = \Omega\{&B \exp(\alpha_w y) + C \exp[(\alpha_w - \alpha_r L_0)y] \\ &+ D \exp[(\alpha_w/2 - \alpha_r L_0)y] - B - C\} , \end{aligned} \tag{20}$$

with

$$\Omega = 1/[1 - \mu \exp(-\alpha_r L_0)] , \tag{20a}$$

$$B = -h\mu \exp(-\alpha_r L_0)/[K_0 \alpha_w u(h)] , \tag{20b}$$

$$C = h/[K_0(\alpha_w - \alpha_r L_0)u(h)] , \tag{20c}$$

$$D = \alpha_r w^{1/2}/[2\alpha_0 u(h)^{1/2}] . \tag{20d}$$

The calculation of Q (Equation (3b)) gives

$$\begin{aligned} Q = \Omega'[&B \exp(\alpha_w) + C \exp(\alpha_w - \alpha_r L_0) + \\ &+ D' \exp(\alpha_w/2 - \alpha_r L_0) - B - C] , \end{aligned} \tag{21}$$

with

$$\Omega' = \exp(-\alpha_\beta L_0)\Omega , \tag{21a}$$

$$D' = 2[(1 - \mu)/\alpha_r]D . \tag{21b}$$

As to P (Equation (3a)), it is written as

$$P = L_0\Omega\{(B/b)(\exp(b) - 1) + (C/c)(\exp(c) - 1) + (D/d)(\exp(d) - 1) + [(B + C)/(\alpha_\beta L_0)](\exp(-\alpha_\beta L_0) - 1)\}\,, \tag{22}$$

with

$$b = \alpha_w - \alpha_\beta L_0\,, \tag{22a}$$

$$c = \alpha_w - (\alpha_r + \alpha_\beta)L_0\,, \tag{22b}$$

$$d = \alpha_w/2 - (\alpha_r + \alpha_\beta)L_0\,. \tag{22c}$$

Each term appearing in the expression of $(r_a)_c$ can be written as an analytical function of easily obtainable parameters.

3. Model Predictions

3.1. Model sensitivity

Practically, the canopy aerodynamic resistance $(r_a)_c$ depends upon six parameters: the view angle of the radiometer (β), the wind velocity (u) at a reference height (z_r) and four crop characteristics, crop height (h), leaf area index (L_0), leaf width (w), and inclination index of the foliage (X_L). We have assessed the sensitivity of $(r_a)_c$ to these different parameters using a standard agricultural canopy, the characteristics of which are close to those of a potato crop ($h = 0.7$ m, $L_0 = 3$, $w = 0.1$ m, $X_L = 0.4$). The results are shown in Figure 1 and Tables 1 through 5.

In Figure 1 the canopy aerodynamic conductance $(g_a)_c$ (inverse of resistance) and the aerodynamic conductance above the canopy $(g_a)_a$ calculated in neutral conditions between levels $h = 0.7$ m and $z_r = 3$ m, have been plotted against the wind velocity at the reference height z_r. The canopy aerodynamic conductance depends on wind velocity but not as strongly as $(g_a)_a$. Table 1 shows the influence of the inclination angle of the radiometer β upon the canopy aerodynamic resistance as defined by Equations (3). $(r_a)_c$ increases slightly with β. This increase is greater for low values of β than for high values. For instance, when β increases from 20 to 40°, $(r_a)_c$ increases by about 4%, but when β increases from 70 to 90°, $(r_a)_c$ does not increase significantly.

Tables 2 through 5 show the influence of crop characteristics on the canopy aerodynamic resistance. $(r_a)_c$ is a decreasing function of LAI. This decrease is fairly important, particularly for low values of LAI. When LAI increases from 1 to 2, $(r_a)_c$ decreases by 54%, whereas when LAI increases from 4 to 5, $(r_a)_c$ only decreases by 14%. For the same leaf area index $(r_a)_c$ decreases with the height of the canopy. The canopy aerodynamic resistance is also a decreasing function of the inclination index of the foliage X_L. But the dependence is not as strong as with LAI or crop height. The fact that leaf boundary-layer resistance is an increas-

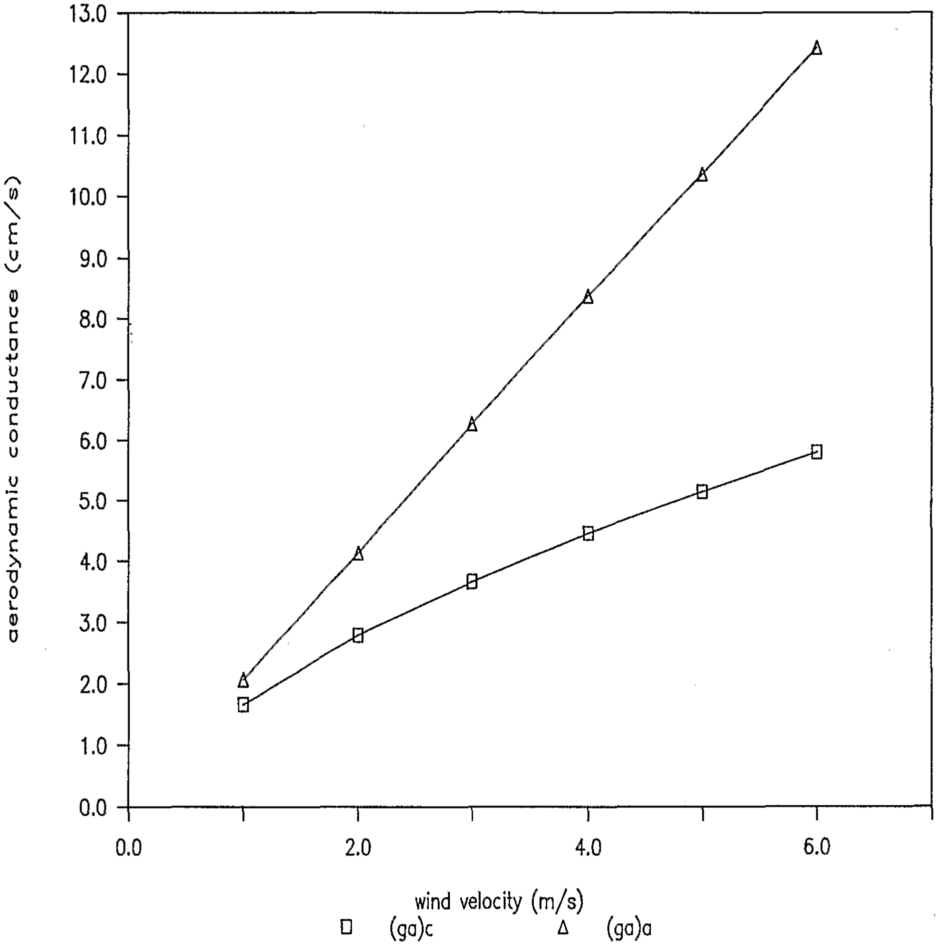

Fig. 1. Variation in the canopy aerodynamic conductance $(g_a)_c = 1/(r_a)_c$ and in the aerodynamic conductance above the canopy $(g_a)_a = 1/(r_a)_a$ (calculated in neutral conditions) as a function of the wind velocity at a reference height of 3 m. The characteristics of the canopy are: $h = 0.7$ m, $L_0 = 3$, $w = 0.1$ m, $X_L = 0.4$, and the view angle of the radiometer is 90°.

ing function of leaf width (Equation (14)) explains why $(r_a)_c$ also increases fairly rapidly with leaf width (Table 3).

3.2. EXPERIMENTAL VALIDATION

The original model had been tested with a set of data obtained for a potato crop in July and August 1986 at the experimental station of Grignon in the Paris area (Lhomme *et al.*, 1988). This new simplified model is tested with the same set of data (30 days of measurements) and with other data collected at the same experimental station for a maize crop at the end of July and the beginning of August 1990. The experiment took place during ten days without rain, the pre-dawn plant

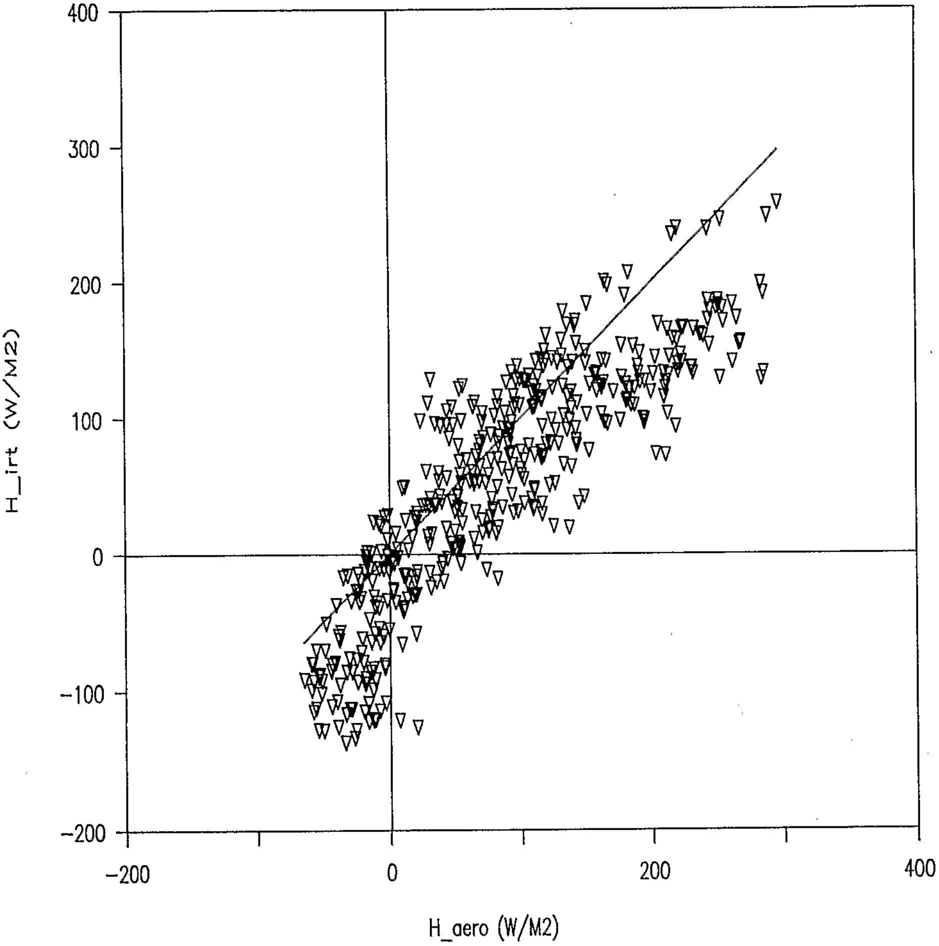

Fig. 2. Comparison of model estimates of hourly values of sensible heat flux (H_{irt}) over a potato crop with the values obtained by the aerodynamic method (H_{aero}) from air temperature and wind speed gradients.

water potential falling from −0.6 MPa on the first day of the experiment to −1.2 MPa on the last day. Because of their contrasting structures, these two canopies should provide a good test of the model. At the start of the experiment the potato crop (Solanum tuberosum) had a height of 0.6 m and a leaf area index of 2.8, whereas the maize crop had a height of 1.8 m and a LAI of 2.6. The mean leaf width was 0.15 m for maize and 0.10 m, for potato, and the inclination index of the foliage was taken as 0.4 for both crops (Ross, 1975).

Radiometric temperature was measured over the potato crop by an AGA infrared radiometer (type TPT80) with a 2° field of view. Over the maize crop, an Everest infrared thermometer (type 4000A) with a 4° field of view was used. Both were equipped with a band-pass filter which limited the optical response to 8–

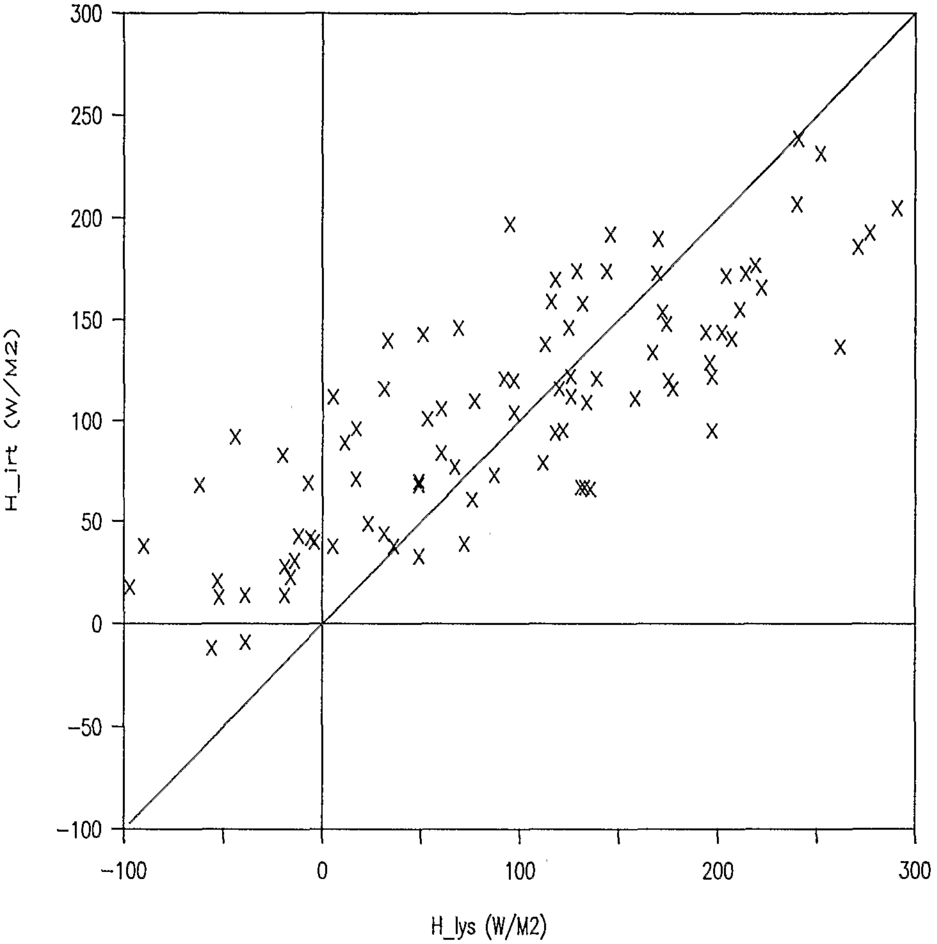

Fig. 3. Comparison of model estimates of hourly values of sensible heat flux (H_{irt}) over a maize crop with the values determined from the energy balance equation (H_{lys}), evaporation being measured by a weighing lysimeter. These values were obtained between 7 h and 18 h on ten consecutive days.

14 μm. We have to point out that the choice of a small field of view is made necessary by the fact that the function $s(z)$ representing the fraction of surface viewed by the radiometer within the canopy is approximated by the one classically used to express the sunlit horizontal area within the canopy (Equation (10)). The radiometers, previously calibrated with a reference black body, were set on a mast 6 m above the soil surface pointing southwards with an angle of inclination to the horizontal of 20°. The air temperature and wind speed used in the calculation were measured at 3 m above the soil surface over the potato crop, and at 4.3 m over the maize crop. Sensible heat flux was calculated from radiometric temperature, using Equations (1) and (2), $(r_a)_c$ being calculated by Equations (3) with the expressions of P, Q and R given respectively by Equations (22), (21) and (19). The values of the crop characteristics used in the calculation are those given above.

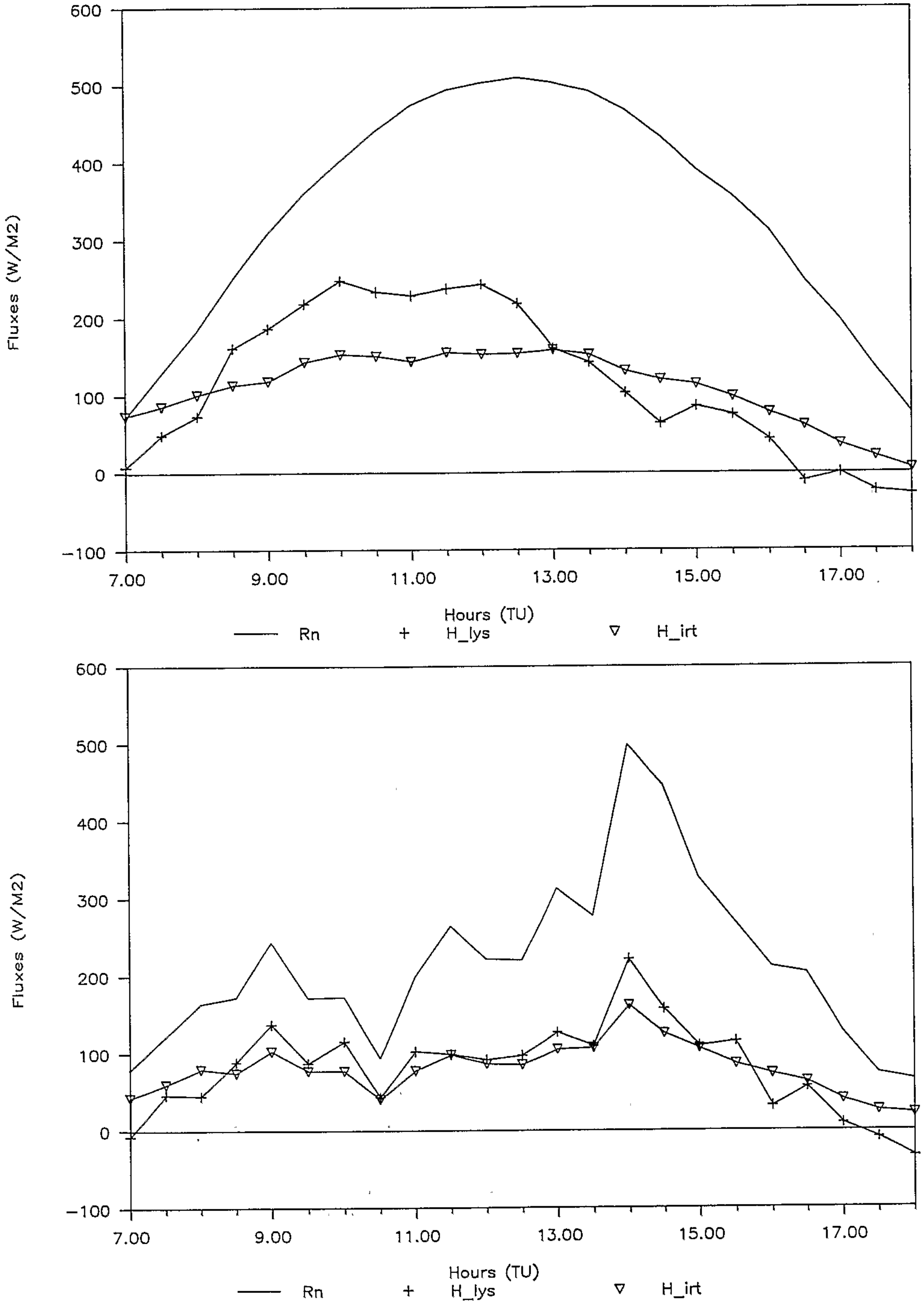

Fig. 4. Half-hourly values of sensible heat flux (H_{irt}) over the maize crop, as estimated by the model from the IRT measurements, are plotted against time for two typical days, and compared with values (H_{lys}) obtained from the lysimeter and the energy balance equation.

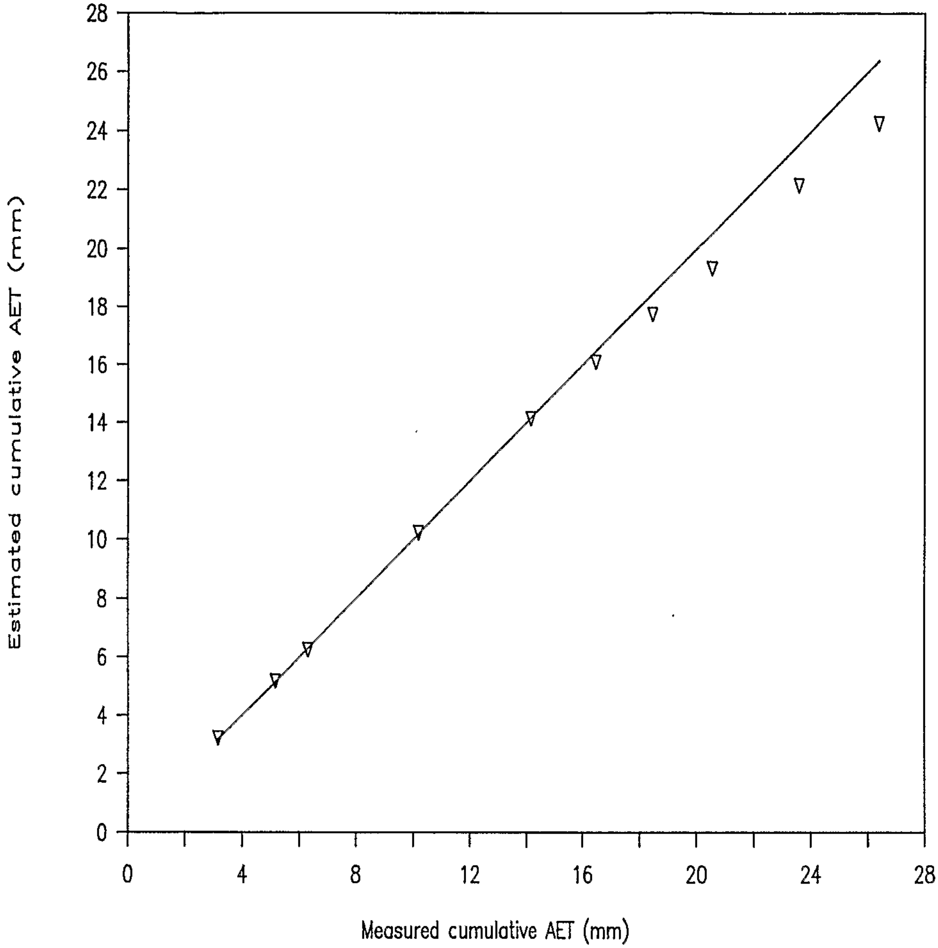

Fig. 5. Cumulative evapotranspiration during ten consecutive days, determined by the energy balance from the IRT measurements, as a function of cumulative evapotranspiration measured by a weighing lysimeter.

TABLE I

Variation in coefficient α_β (Equation (10)) and in canopy aerodynamic resistance (s/cm) as a function of the view angle β (°) of the radiometer ($h = 0.7$ m, $L_0 = 3$, $w = 0.1$ m, $X_L = 0.4$, $u = 3$ m/s).

β	20	30	40	50	60	70	80	90
α_β	1.10	0.92	0.84	0.79	0.76	0.74	0.73	0.73
$(r_a)_c$	0.25	0.26	0.26	0.27	0.27	0.27	0.27	0.27

The aerodynamic resistance above the canopy $(r_a)_a$ was calculated by Equation (8) using the expressions for f given by Choudhury *et al.* (1986).

The sensible heat flux used as reference, with which the estimated sensible heat flux is compared, was calculated in two different ways. Over the potato canopy it

TABLE II

Variation in canopy aerodynamic resistance (s/cm) as a function of canopy leaf area index L_0 ($h = 0.7$ m, $w = 0.1$ m, $X_L = 0.4$, $u = 3$ m/s, $\beta = 90°$).

L_0	1	2	3	4	5
$(r_a)_c$	0.94	0.43	0.27	0.21	0.18

TABLE III

Variation in canopy aerodynamic resistance (s/cm) as a function of canopy height h (m) ($L_0 = 3$, $w = 0.1$ m, $X_L = 0.4$, $u = 3$ m/s, $\beta = 90°$).

h	0.3	0.5	0.7	1.0	1.5
$(r_a)_c$	0.32	0.29	0.27	0.25	0.22

TABLE IV

Variation in canopy aerodynamic resistance (s/cm) as a function of leaf width w (m) ($h = 0.7$ m, $L_0 = 3$, $X_L = 0.4$, $u = 3$ m/s, $\beta = 90°$).

w	0.01	0.05	0.10	0.15	0.20
$(r_a)_c$	0.15	0.22	0.27	0.31	0.35

TABLE V

Variation in coefficient α_β (Equation (10)) and in canopy aerodynamic resistance (s/cm) as a function of leaf inclination index X_L ($h = 0.7$ m, $L_0 = 3$, $w = 0.1$ m, $u = 3$ m/s, $\beta = 90°$).

X_L	−0.4	−0.2	0.0	0.2	0.4	0.6
α_β	0.35	0.41	0.50	0.61	0.73	0.88
$(r_a)_c$	0.31	0.30	0.29	0.28	0.27	0.26

was calculated using the aerodynamic method (Itier, 1980) from the temperature and wind speed gradients, measured above the canopy by shielded thermocouples and cup anemometers, and logged automatically as quarter-hour averages (Lhomme *et al.*, 1988). Over the maize crop the sensible heat flux used as reference was determined on a half-hourly basis as the residual term of the energy balance equation $R_n - G - \lambda E$. Evaporation was measured by a 2 m deep weighing lysimeter, the precision of which was about 0.2 mm. Net radiation was measured by a Swissteco (type S1) radiometer and soil heat flux was estimated as a given fraction (10%) of the net radiation above the canopy.

Figures 2 and 3 show the comparison between the model estimates of the sensible heat flux and the measured values respectively for the potato crop and the maize crop. For the potato crop the agreement is much better in unstable than stable conditions. There is a slight underestimate by the model with respect to the aerodynamic method. For the maize crop there is greater scatter, but it can be explained by the fact that the two methods of calculation of the sensible heat flux are far more independent than in the case of the potato crop. However, it seems the model has a tendency to systematically overestimate the low values of the sensible heat flux and underestimate the large values with respect to the lysimeter-derived ones. Figure 4 shows the diurnal evolution of the sensible heat flux over maize on a half-hourly basis, as predicted by the model from the radiometric temperature and as determined from the weighing lysimeter. Two typical days have been chosen as examples. One is sunny with almost no cloud, the other is cloudy with some sunny spells. The agreement is fairly good, especially for the cloudy day. Figure 5 shows the cumulative actual evapotranspiration from the maize crop during the ten-day period of measurement, as predicted by the energy balance equation, with H estimated by the model, and as measured by the weighing lysimeter. The agreement is good.

4. Conclusion

The model, originally devised by Lhomme *et al.* (1988), has been made more operational by simplifying the calculation of the additional resistance $(r_a)_c$ (Equations (3)), which appears in the expression of the sensible heat flux (Equation (1)). Assuming a constant leaf area density profile and using analytical expressions for the profiles of net radiation, wind velocity, eddy diffusivity, leaf boundary-layer resistance and horizontal sunlit area, analytical expressions have been inferred for the three terms P, Q and R in Equation (3) (Equations (19), (21) and (22)). They are formulated in terms of wind velocity, inclination angle of the radiometer, crop height, leaf area index, leaf width and inclination index of the foliage. This new and explicit expression of the additional resistance $(r_a)_c$ allows one to calculate more readily the sensible heat flux than the previous expression given by Lhomme *et al.* (1988). Comparisons of the predictions of the model with two sets of experimental data collected on two different crops show that this simplified model, based upon a reduced set of input parameters, gives good estimates of the daily sensible heat flux and fairly good estimates of its diurnal variation.

In the previous paper the potential limitations of this type of model due to the use of K-theory have already been discussed. The basic assumptions of the model and the new assumption used in this paper, of a constant leaf area distribution, limits the applicability to canopies horizontally and vertically homogeneous viewed by a radiometer with a small field of view. For horizontally homogeneous crops, but with a non-homogeneous leaf area distribution, it is always possible to use the original model (Lhomme *et al.*, 1988) and integrate numerically the different functions appearing in the theoretical formulae. We have also to point out that an advantage of this model, which has not been exploited so far, is that it can be applied to sparse canopies for which an important part of the bare soil beneath the canopy can be seen by the radiometer. The next step in this study, which is already in progress in the framework of the HAPEX-Sahel experiment, will be to apply this simplified model to a typical sparse crop of the sahelian regions, a dryland millet.

References

Baldocchi, D. D., Luxmoore, R. J. and Hatfield, J. L.: 1991, 'Discerning the Forest from the Trees: An Essay on Scaling Canopy Stomatal Conductance', *Agr. For. Meteorol.* **54**, 197–226.

Choudhury, B. J., Reginato, R. J. and Idso, S. B.: 1986, 'An Analysis of Infrared Temperature Observations over Wheat and Calculation of Latent Heat Flux'. *Agric. For. Meteorol.* **37**, 75–88.

Choudhury, B. J. and Monteith, J. L.: 1988, 'A Four-Layer Model for the Heat Budget of Homogeneous Land Surfaces', *Q. J. R. Meteorol. Soc.* **114**, 373–398.

Choudhury, B. J.: 1989, 'Estimating Evaporation and Carbon Assimilation Using Infrared Temperature Data: Vistas in Modelling', in G. Asrar (ed.), *Theory and Applications of Optical Remote Sensing*, Wiley, New York, pp. 628–690.

Goudriaan, J.: 1977, 'Crop Micrometeorology: A Simulation Study', Center for Agricultural Publishing and Documentation, Wageningen, 249 pp.

Huband, N. D. S. and Monteith, J. L.: 1986, 'Radiative Surface Temperature and Energy Balance of a Wheat Crop', *Boundary-Layer Meteorol.* **36**, 1–17.

Itier, B.: 1980, 'Une Méthode Simplifiée pour la Mesure du Flux de Chaleur Sensible', *J. Rech. Atmos.* **14**, 17–34.

Jones, H. G.: 1983, *Plants and Microclimate*, Cambridge University Press, New York.

Kalma, J. D. and Jupp, D. L. B.: 1990, 'Estimating Evaporation from Pasture Using Infrared Thermometry: Evaluation of a One-Layer Resistance Model', *Agric. For. Meteorol.* **51**, 223–246.

Kustas, W. P., Choudhury, B. J., Moran, M. S., Reginato, R. J., Jackson, R. D., Gay, L. W. and Weaver, H. L.: 1989, 'Determination of Sensible Heat Flux over Sparse Canopy Using Thermal Infrared Data', *Agric. For. Meteorol.* **44**, 197–216.

Lhomme, J. P., Katerji, N., Perrier, A. and Bertolini, J. M.: 1988, 'Radiative Surface Temperature and Convective Flux Calculation over Crop Canopies', *Boundary-Layer Meteorol.* **43**, 383–392.

Monteith, J. L. and Unsworth, M. H.: 1990, *Principles of Environmental Physics*, Edward Arnold, London, 91 pp.

Ross, J.: 1975, 'Radiative Transfer in Plant Communities', in J. L. Monteith (ed.), *Vegetation and the Atmosphere*, Academic Press, San Diego, Calif. pp. 13–55.

Shuttleworth, W. J. and Gurney, R. J.: 1990, 'The Theoretical Relationship between Foliage Temperature and Canopy Resistance in Sparse Crops', *Q. J. R. Meteorol. Soc.* **116**, 497–519.

Viney, N. R.: 1991, 'An Empirical Expression for Aerodynamic Resistance in the Unstable Boundary Layer', *Boundary-Layer Meteorol.* **56**, 381–393.