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# Estimating sensible heat flux from radiometric temperature over sparse millet

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## Abstract

A two-layer model was developed and used to estimate sensible heat flux over a sparse millet crop from surface radiometric temperature. The millet crop was grown in farming conditions on the central site of the HAPEX–Sahel experiment in southern Niger. Surface temperature was measured with a nadir-looking radiometer. Measurements of the convective fluxes of sensible and latent heat were made simultaneously by means of the energy balance–Bowen ratio method. It is assumed that infra-red surface temperature can be represented by a weighted sum of foliage and soil surface temperatures, the weighting factors being the fractional areas of foliage and soil surface. With this assumption, the basic equations of two-layer models lead to an expression of sensible heat flux $H$ close in form to the Ohm's law type formulation obtained from a one-layer approach, but in which the temperature difference between the surface and the air $T_r - T_a$ has to be corrected by a factor proportional to the temperature difference $\delta T$ between the foliage and the substrate. $\delta T$ being not available in our experiment, it was assumed that a statistical relationship linking $\delta T$ to $T_r - T_a$ of the type $\delta T = a(T_r - T_a)^m$ could be used. Using one part of the data set, $m$ and $a$ were statistically determined by adjusting $H$ estimated by the model to $H$ observed by the Bowen ratio method. The best adjustment gave $m = 2$ and $a = 0.10$. For the other part of the data set (different from the one employed to calibrate this relationship) it was found that $H$ estimated using the two-layer model with this empirical relationship compared fairly well with the values of $H$ observed.

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## 1. Introduction

Remote sensing in the thermal infra-red spectrum is now classically used to determine surface temperature and to estimate the components of the surface energy balance. The method generally employed consists in estimating sensible heat flux from radiometric temperature and in calculating evaporation as a residual term of the energy balance equation, net radiation and soil heat flux being measured or calculated independently. Estimating reliable values of sensible heat flux $H$ represents the most problematic aspect of this method. One-layer models have been widely used over the last decade to estimate $H$ on a local scale with various field crops (Hatfield et al., 1984, among others) or on a regional scale (Seguin et al., 1982a, b). $H$ is considered to be proportional to the difference between the radiometric temperature $T_r$ and the air temperature $T_a$ at a reference height, and inversely proportional to an aerodynamic resistance $r_a$. This resistance is calculated assuming that the radiometric temperature is identical to the aerodynamic surface temperature $T_0$, computed at the effective source height within the canopy (Choudhury, 1989).

Experimental data, however, show large discrepancies between the radiometric and aerodynamic surface temperatures (Huband and Monteith, 1986). This problem is particularly acute in the case of sparse vegetation. It has been shown that the use of single level representation of sparse vegetation generally overestimates the sensible heat flux (Stewart et al., 1989; Kalma and Jupp, 1990). Kustas et al. (1989), working on a natural vegetated surface composed of bushes and bare soil in California, found that the temperature difference $T_r - T_a$ increased rapidly from midmorning until the afternoon while the measured sensible heat flux remained essentially the same. Their results were explained by the fact that the increase of $T_r$ was primarily a result of the dry soil rapidly heating and hence becoming the major source of sensible heat. Therefore, they suggested that the shift of the source of sensible heat was responsible for an increase in the added resistance to heat transfer $kB^{-1}$, which was made a function of $T_r$. According to Kalma and Jupp (1990), the usefulness of $kB^{-1}$ in explaining the difference between $T_r$ and $T_0$ seems to be limited. Kustas (1990) developed a two-layer model based on an expression of $H$ derived by Smith et al. (1988), but he obtained poor results when it was applied to data collected from a sparse cotton field.

This paper investigates the applicability of a two-layer model to data collected from a sparse millet crop grown in Niger. The basic equations are the same as those used in the classical two-layer model originally devised by Shuttleworth and Wallace (1985), and applied to a sparse millet crop by Wallace et al. (1990). However, the original model is reinterpreted in order to express sensible heat flux as a function of radiometric temperature and the difference between substrate and foliage temperatures (Lhomme and Monteny, 1993). In this way it differs from the model developed by Kustas (1990).

## 2. Theory

### 2.1. Expressing sensible heat flux using a two-layer model

In a sparse crop represented by a two-layer model (Fig. 1), the total sensible heat

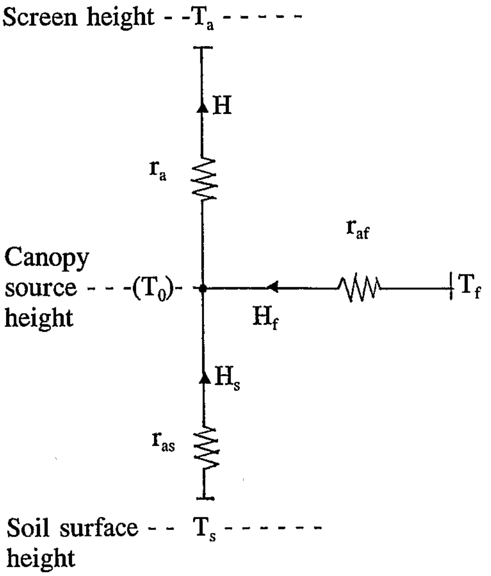

Fig. 1. Fluxes and potential-resistance network for a two-layer model of heat transfer. $T_a$ is air temperature at a reference height, $T_f$ is foliage temperature, $T_s$ is soil temperature and $T_0$ is air temperature at canopy source height.

flux $H$ is the sum of the contributions emanating from each layer, i.e. from the foliage ($H_f$) and from the soil surface ($H_s$). These two fluxes are, respectively, written as

$$H_f = \rho c_p (T_f - T_0)/r_{af} \tag{1}$$

$$H_s = \rho c_p (T_s - T_0)/r_{as} \tag{2}$$

where $T_f$ is the foliage temperature, $T_s$ is the substrate temperature, $T_0$ is the air temperature at canopy source height, called the aerodynamic surface temperature, $r_{af}$ is the bulk boundary-layer resistance of the foliage per unit ground area and $r_{as}$ is the aerodynamic resistance between the substrate and the canopy source height. Summing Eqs. (1) and (2) gives for the global sensible heat flux $H$

$$H = \rho c_p (T_e - T_0)/r_e \tag{3}$$

where $T_e$ is a weighted mean of the temperatures of each layer

$$T_e = (r_{af} T_s + r_{as} T_f)/(r_{as} + r_{af}) \tag{4}$$

and the equivalent resistance $r_e$ is expressed as

$$r_e = r_{af} \cdot r_{as}/(r_{af} + r_{as}) \tag{5}$$

$H$ can also be expressed as

$$H = \rho c_p (T_0 - T_a)/r_a \tag{6}$$

where $T_a$ is the air temperature at a reference height and $r_a$ is the aerodynamic resistance between canopy source height and reference level. Combining Eqs. (3) and (6) leads to

$$H = \rho c_p (T_e - T_a)/(r_a + r_e) \tag{7}$$

Equation (7), which has the form of Ohm's law, gives the sensible heat flux emanating from a composite surface represented by a two-layer model.

As a first approximation, the surface radiometric temperature $T_r$ measured by a radiometer located vertically above the surface might be considered as the area-weighted mean of foliage and soil temperatures (Choudhury, 1989; Kalma and Jupp, 1990). If $f$ represents the fractional area covered by the foliage, $T_r$ can be written as

$$T_r = fT_f + (1 - f)T_s \tag{8}$$

Because $T_e$, which appears in Eq. (7), cannot be directly measured, we have to work out the relationship between $T_e$ and $T_r$. This relationship can be inferred from Eqs. (4) and (8) and expressed as a function of the difference between the two component temperatures

$$T_e - T_r = -c(T_s - T_f) \tag{9}$$

$c$ being defined by

$$c = [1/(1 + x)] - f \text{ with } x = r_{af}/r_{as} \tag{10}$$

Sensible heat flux can be rewritten as

$$H = \rho c_p [(T_r - T_a) - c\delta T]/(r_a + r_e) \text{ with } \delta T = T_s - T_f \tag{11}$$

This equation shows that the sensible heat flux is not proportional to the temperature difference between the surface and the air, $T_r - T_a$. This difference must be corrected by a term proportional to the temperature difference between the substrate and the foliage.

### 2.2. Calculating the resistances and the value of c

In neutral conditions, assuming the roughness lengths for momentum and sensible heat to be the same, the aerodynamic resistance above the canopy is classically expressed as

$$r_{a0} = \ln^2[(z_r - d)/z_0]/(k^2 u) \tag{12}$$

where $u$ is the wind speed at the reference height $z_r$ and $k$ is the von Karman's constant (0.4). The zero plane displacement $d$ and the roughness length $z_0$ can be obtained from the canopy height $h$ by making use of the empirical relationships given by Monteith and Unsworth (1990): $d = 0.65h$ and $z_0 = 0.10h$. In non-neutral conditions the ratio between the stability corrected aerodynamic resistance and $r_{a0}$ is generally expressed as a function of the bulk Richardson number (Viney, 1991). We have used the expressions given by Choudhury et al. (1986) and recommended by Kalma and

Jupp (1990) for pasture with incomplete cover. They are written as

$$r_a = r_{a0}/(1+\eta)^p \tag{13}$$

with $p = 3/4$ in unstable conditions and $p = 2$ in stable conditions, $\eta$ being defined by

$$\eta = 5(z_r - d)g(T_s - T_a)/(T_a u^2) \tag{14}$$

where $g$ is the gravitational acceleration and $T_s$ is the surface temperature taken to be equal to $T_r$.

Following Choudhury and Monteith (1988) the bulk boundary-layer resistance of the foliage $r_{af}$ is calculated by integrating the leaf boundary-layer conductance over the canopy height and by dividing by the leaf area index $L_0$. The leaf boundary-layer resistance is calculated as (Jones, 1983)

$$r_b(z) = [w/u(z)]^{1/2}/\alpha_0 \tag{15}$$

where $w$ is the leaf width ($w \approx 0.05\ m$ for millet), $u(z)$ is the wind velocity at level $z$ and $\alpha_0$ is a constant coefficient (= 0.005 in SI units for one side of the leaf). Wind velocity is assumed to decrease exponentially through the canopy

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

a typical value of $\alpha_w$ for agricultural crops being 2.5. Performing the integration and assuming leaf area index to be uniformly distributed with height we obtain (Choudhury and Monteith, 1988)

$$r_{af} = \alpha_w[w/u(h)]^{1/2}/\{4\alpha_0 L_0[1 - \exp(-\alpha_w/2)]\} \tag{17}$$

The aerodynamic resistance $r_{as}$ between the soil surface and the canopy source height is defined as the integral of the reciprocal of eddy diffusivity $K(z)$ over the height range 0 to $d + z_0$. In spite of many studies questioning the validity of $K$-theory for within-canopy transfer it seems that, for practical purposes, $K$-theory remains an adequate approximation of turbulent transport in sparse crops (Dolman and Wallace, 1991). Assuming $K(z)$ to follow the same exponential decreasing within the canopy as wind velocity, we obtain (Choudhury and Monteith, 1988; Shuttleworth and Gurney, 1990)

$$r_{as} = h\exp(\alpha_w)\{\exp(-\alpha_w z_{0s}/h) - \exp[-\alpha_w(d + z_0)/h]\}/\alpha_w K(h) \tag{18}$$

$z_{0s}$ is the roughness length of the substrate (bare soil). Typical values for soil roughness would be in the range of 0.005–0.02 m (Choudhury, 1989). $K(h)$ is the value of eddy diffusivity at crop height, given by

$$K(h) = k^2(h - d)u(h)/\ln[(h - d)/z_0] \tag{19}$$

The wind speed $u(h)$ at crop height is calculated from the classical log-profile relationship.

The basic assumptions of this two-level aerodynamic model and its sensitivity to different parameterizations have been examined in detail by Shuttleworth and Gurney (1990). Table 1 shows the effect of changing (±50%) the value of coefficients $\alpha_0$ (Eq. (15)) and $\alpha_w$ (Eq. (16)) on the two main parameters of the model. These

Table 1
Sensitivity of the two main parameters of the model ($r_e$ and $c$) to changes (±50%) in coefficients $\alpha_0$ and $\alpha_w$ ($L_0 = 2$, $h = 2\,m$, $f = 0.3$, $u = 3\,m\,s^{-1}$)

| | | | $r_e$ | $c$ |
|---|---|---|---|---|
| $\alpha_0 = 0.005$ | (+50%) | 0.0075 | −28% | +15% |
| | (−50%) | 0.0025 | +62% | −30% |
| $\alpha_w = 2.5$ | (+50%) | 3.75 | +43% | +24% |
| | (−50%) | 1.25 | −36% | −26% |

changes give variations in the order 40% for $r_e$ and 20% for $c$, which is quite noticeable. In Table 2, the influence of wind velocity on the value of resistances and coefficient $c$ is assessed for a canopy with approximately the same characteristics as a millet crop. In the same table, the magnitude of the stability correction (difference between $r_a$ and $r_{a0}$) is assessed for a temperature difference of 10°C between the surface and the air. Such a difference frequently occurs during the midday hours (cf. Table 5). It appears that the stability correction has a very strong effect on the calculation of the aerodynamic resistance. This effect is enhanced by the fact that the surface temperature $T_s$, which appears in the stability correction (Eq. (14)), is taken to be equal to the radiometric surface temperature $T_r$ instead of the aerodynamic temperature $T_0$, which is unknown. Because $T_r$ is expected to be greater than $T_0$ in unstable conditions, $r_a$ calculated in this way has to be lower than the true value.

Table 3 shows the influence of the fraction of ground covered by the vegetation on the value of $c$. From these results it appears that the value of $c$ is about 0.5 for a canopy such as the millet crop. Because the temperature difference $\delta T$ between the substrate and the foliage can often reach over 10°C, that means that the temperature difference $T_r - T_a$ has to be corrected (reduced) by about 5°C. This effect could explain why several authors have found that the surface temperature $T_r$ can increase rapidly over sparse crops while the sensible heat flux remains essentially the same magnitude (Kustas et al., 1989; Stewart et al., 1989; Monteny and Leroux, 1991).

Table 2
Variation in resistances expressed in $s\,m^{-1}$ and in coefficient $c$ given by Eq. (10), as a function of wind velocity at a reference height $z_r = 4\,m$ ($L_0 = 2$, $h = 2\,m$, $f = 0.3$, $T_a = 30°C$, $T_r = 40°C$)

| $u\,(m\,s^{-1})$ | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $r_{a0}$ | 35 | 17 | 12 | 9 | 7 |
| $r_a$ | 2.0 | 2.7 | 3.0 | 3.2 | 3.2 |
| $r_{af}$ | 29 | 21 | 17 | 15 | 13 |
| $r_{as}$ | 165 | 82 | 55 | 41 | 33 |
| $r_e$ | 25 | 17 | 13 | 11 | 9 |
| $c$ | 0.55 | 0.50 | 0.46 | 0.44 | 0.41 |

Table 3
Variation in coefficient $c$ (dimensionless) given by Eq. (10) as a function of the fraction $f$ of ground cover ($L_0 = 2$, $h = 2\,\mathrm{m}$, $u = 3\,\mathrm{m\,s^{-1}}$ at $z_r = 4\,\mathrm{m}$)

| $f$ | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|---|---|---|---|---|---|
| $c$ | 0.66 | 0.56 | 0.46 | 0.36 | 0.26 |

## 3. Prediction of the model

### 3.1. The data

The data for this study were collected in 1991 over a millet field (*Pennisetum typhoides*) grown in farming conditions near the village of Banizoumbou (13°31′N, 2°39′E), in southwest Niger. This place corresponds to the central site of the HAPEX–Sahel experiment which took place in 1992 (Goutorbe et al., 1994). The climate is typical of the Sahelian zone with summer rainfall. In 1991, the annual amount of rainfall registered at the weather station in Banizoumbou was 522 mm. The crop was planted in mid-April 1991 with a density of about 6800 plants ha$^{-1}$. The soil is sand about 2 m deep.

The measurements were carried out from 17 June (DOY 168) to 31 August (DOY 243). Evaporation and sensible heat flux were determined using a Bowen ratio system containing temperature and humidity sensors at approximately 0.5 m and 2.5 m above the crop surface, one net radiometer (Radiation Energy Balance System, Q6, Campbell, UK), located 12 m above the soil surface, and one heat flux plate buried at 3 cm depth. The site had a fetch of about 250 m. Air temperature was measured using shielded copper–constantan thermocouples and vapour pressure was measured by a hygrometer (HMP35A; Vaisala sensor systems, Helsinki, Finland). Air was aspirated by pumps through intakes at each height, and alternatively driven to the Vaisala sensor. Surface temperature was recorded using a nadir-seeking infra-red thermometer with a 16° field of view located 12 m above the soil surface, which means that a 6.8 m diameter circle was sampled at the soil surface. Fluxes of latent and sensible heat and infra-red surface temperature were logged as 20 min values on a Campbell data acquisition system and then converted into hourly values. Measurements took place between 08:00 and 18:00 h on most days of the period of measurement. Some days were omitted because of instrumental failures. Because the Bowen ratio flux data are essential for testing the model, two figures (Figs. 2 and 3) were drawn to illustrate their internal consistency. In Fig. 2, a time series of daylight values of net radiation and latent heat flux is plotted over the course of the experiment for the days with clear sky conditions. In Fig. 3, hourly values of $R_n$ and $\lambda E$ are plotted against time for 3 consecutive clear days. These figures show an orderly progression of evapotranspiration rate with time at the scale of daily and hourly values.

Climatic data at the weather station were logged as hourly values throughout the day (Monteny, 1992). Because wind speed at the millet site was not measured, it was estimated from the value measured at the nearby weather station, situated about 1 km from the site of the experiment. The log-profile relationship was used to transform the wind speed values from 2 m above the soil surface at the weather station to a reference

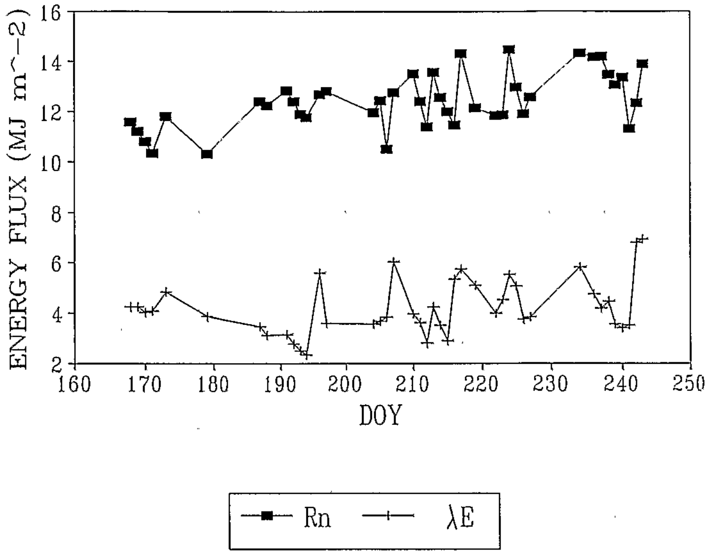

Fig. 2. Time series of daylight values of net radiation ($R_n$) and evapotranspiration rate ($\lambda E$) over the course of the experiment. Only the days with $R_n$ ranging from 10 to 15 MJ m$^{-2}$ were retained.

height of 4 m at the millet site. For the input data to be coherent, air temperature measured at the weather station was also used as the reference temperature at the millet site. This horizontal translation is justified by the very good correlation existing between the temperature ($T_{ab}$) measured with the Bowen ratio system at 2.5 m above

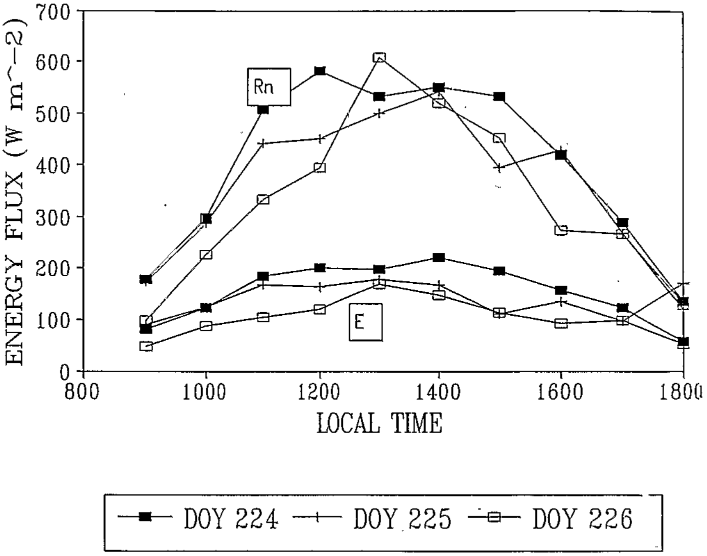

Fig. 3. Diurnal variations in net radiation ($R_n$) and evapotranspiration rate ($\lambda E$) for 3 consecutive clear days.

Table 4
Details on the periods of observation

| Period | Dates (DOY) | Number of hourly observations | Crop height (m) | LAI | Foliage cover (%) |
|---|---|---|---|---|---|
| I. Tillering | 168–181 | 100 | 0.85 | 2.0 | 30 |
| II. Elongation | 187–209 | 228 | 1.75 | 2.0 | 30 |
| III. Flowering/ maturation | 210–243 | 321 | 2.20 | 2.2 | 20 |

the crop surface and the temperature ($T_a$) measured at the weather station. The equation fitted over all the period of measurement is: $T_a = 1.00\ T_{ab}$, with $r^2 = 0.988$. The extrapolation of wind speed over a distance of 1 km horizontally is perhaps more questionable, but no other means was available for estimating wind related variables.

The whole set of data was divided into three periods. The first one (period I) corresponds to tillering. The second one (period II) corresponds to the period of stem elongation, and the third one (period III) corresponds to flowering and maturation. For each period, the structural characteristics of the crop were taken as constant. They are given in Table 4 along with the number of hourly observations. Table 5 lists some of the pertinent data obtained for a typical day (DOY 191) of period II, 2 days after a rainy event of 4 mm on DOY 189. The measured evaporation on DOY 189 and 190 being, respectively, 2.4 mm and 0.9 mm, we may suppose that a great part of the 4 mm of precipitation were consumed before DOY 191.

### 3.2. Analysis and results

A simple one-layer model and the two-layer model described above were succes-

Table 5
List of data (hourly mean values) for DOY 191 (10 July). $R_n$ is net radiation, $G$ is soil heat flux, $H$ is sensible heat flux, $\lambda E$ is latent heat flux, $T_r$ is radiometric surface temperature, $T_a$ and $u$ are, respectively, air temperature and wind speed registered at the weather station. The total amount of evaporation on this day was 1.1 mm

| Local time | $R_n$ (W m$^{-2}$) | $G$ (W m$^{-2}$) | $H$ (W m$^{-2}$) | $\lambda E$ (W m$^{-2}$) | $T_r$ (°C) | $T_a$ (°C) | $u$ (m s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 09:00 | 197 | 23 | 124 | 50 | 28.0 | 27.2 | 2.0 |
| 10:00 | 300 | 54 | 155 | 91 | 32.7 | 28.6 | 2.8 |
| 11:00 | 386 | 80 | 195 | 112 | 36.7 | 29.7 | 3.5 |
| 12:00 | 458 | 102 | 235 | 121 | 39.9 | 30.1 | 4.0 |
| 13:00 | 394 | 96 | 199 | 99 | 40.5 | 30.7 | 3.7 |
| 14:00 | 547 | 128 | 299 | 120 | 45.2 | 31.6 | 3.4 |
| 15:00 | 479 | 117 | 263 | 99 | 45.2 | 32.8 | 3.4 |
| 16:00 | 394 | 92 | 208 | 94 | 43.2 | 32.7 | 3.6 |
| 17:00 | 270 | 59 | 153 | 58 | 39.8 | 32.6 | 3.1 |
| 18:00 | 139 | 27 | 80 | 32 | 35.4 | 32.2 | 2.4 |

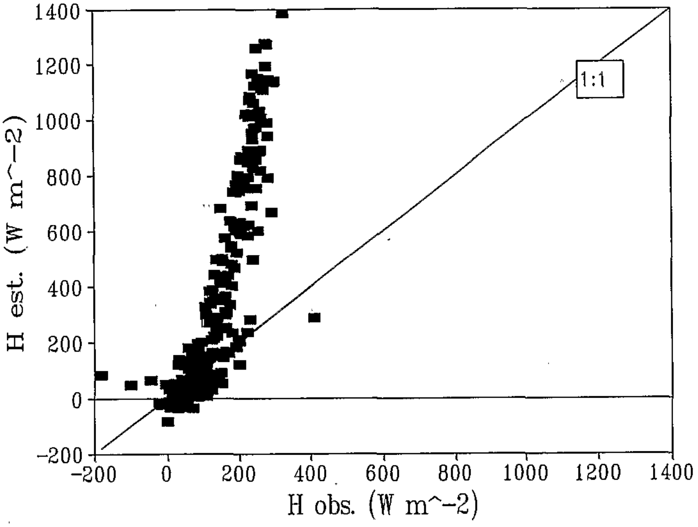

Fig. 4. For period II, comparison of $H$ (W $m^{-2}$) estimated, using a one-layer model with $kB^{-1} = 2$, vs. $H$ observed (RMSE = 384 W $m^{-2}$). The line represents perfect agreement.

sively tested against the Bowen ratio data. To measure the goodness of fit of the estimated values of $H$ to the values observed by the Bowen ratio method, we used the root mean square error (RMSE) defined by

$$\mathrm{RMSE} = \left[\sum_{i=1}^{n}(H_{\mathrm{est}} - H_{\mathrm{obs}})^2/n\right]^{1/2} \tag{20}$$

$n$ being the number of observations. The RMSE has been shown generally to be a good indicator of model performance (Willmott, 1982, cited by Kustas et al., 1989).

In a single-layer model $H$ is given by a simplified version of Eq. (11) where $\delta T = 0$ and $r_e = 0$. Figure 4 shows the results obtained for period II, when $r_a$ is calculated by the expressions given by Choudhury et al. (1986), the added resistance resulting from bluff body effect being estimated from $kB^{-1} = 2$ (Garratt, 1978; Kustas et al., 1989; Kalma and Jupp, 1990). This model clearly overestimates $H$. The RMSE calculated is 384 W $m^{-2}$ for a mean $H_{\mathrm{obs}}$ of 136 W $m^{-2}$. The conclusion is clear. In agreement with many other authors (Stewart et al., 1989, among others), the single level representations of sparse canopies appears to be completely inappropriate for estimating sensible heat flux from radiometric measurements of surface temperature.

In order to test the coupled two-layer model described in the first part of this paper, Eq. (11) was used to calculate sensible heat flux from $T_r$ measured by the infra-red radiometer. In our experiment soil and foliage temperatures were not measured separately, hence $\delta T$ is unknown. Generally, measurements made from aircraft and satellite altitudes do not allow one to separate vegetation and soil temperatures. Consequently, a procedure was developed to account for $\delta T$ without additional measurements. This procedure is based upon the proposal that $\delta T$ has to increase with the temperature difference between the canopy and the air ($T_r - T_a$). In the

Table 6
Determination of parameters $m$ and $a$ of Eq. (21) by fitting Eq. (11) to observed data of sensible heat flux $H$. For each $m$ and each subset of data, the value of $a$ retained and presented in the table is that which minimizes the Root Mean Square Error (RMSE) between estimated and observed values of $H$. The corresponding RMSE expressed in W m$^{-2}$ is also given

| Data set | Number of data points | $m = 1$ | | $m = 2$ | | $m = 3$ | |
|---|---|---|---|---|---|---|---|
| | | $a$ | RMSE | $a$ | RMSE | $a$ | RMSE |
| I A | 50 | 0.60 | 48 | 0.09 | 43 | 0.01 | 41 |
| II A | 120 | 1.21 | 62 | 0.11 | 61 | 0.01 | 101 |
| III A | 162 | 0.90 | 94 | 0.11 | 74 | 0.01 | 82 |

current experiment the soil was sand and the surface layer dries rapidly after a rain event, thus $\delta T$ tends to increase when the net radiation and the surface temperature increase. It was assumed that $\delta T$ and the temperature difference between the canopy and the air were linked by the following relationship

$$\delta T = a(T_r - T_a)^m \qquad (21)$$

$m$ being a positive integer and $a$ a positive real number.

Because $m$ and $a$ are not known a priori, one part of the data set (A) was used to calibrate Eq. (21). We determined the values of $m$ and $a$ for which the best fit was obtained between the values of $H$ estimated by Eq. (11) and those obtained by the Energy balance–Bowen ratio method. The other part of the data set (B) was used to test Eq. (11) with the values of $m$ and $a$ obtained in this way. For each period (I, II and III) we put alternate day records in set A and set B. For a fixed $m$, $a$ was varied from 0 to 2 with a step of 0.01 and the value retained was that which minimized the RMSE. The results obtained for $m = 1, 2$ and 3 are shown in Table 6. It is clear that the best fit was for $m = 2$, i.e. for a quadratic function linking $\delta T$ to $T_r - T_a$. For $m = 2$, the value of $a$ corresponding to the lowest RMSE is nearly the same for each subset of data (around 0.10). Thus, we can infer that Eq. (21), with $m = 2$ and $a \approx 0.10$, represents a good estimate of $\delta T$, valid for the entire growing cycle of the millet crop studied.

Figures 5, 6 and 7 show the comparison of $H$ estimated vs. $H$ observed for the other subset of data (B) of each period (I, II and III). For each subset of data the quadratic function ($m = 2$) was used to estimate $\delta T$, with the value of $a$ obtained from the other subset of data of the same period. For instance, Fig. 5 shows the comparison between $H$ observed and $H$ estimated for subset B of period *I*, parameter a being estimated from subset A of the same period. Table 7 gives some statistics concerning the agreement between $H$ estimated and $H$ observed. The ratio RMSE on the mean value of $H$ observed, for data sets I B, II B and III B, is, respectively, 0.49, 0.39 and 0.55, which is much better than the result obtained using a one-layer model (the ratio was 2.8 for data set II). However, the model systematically seems to under-estimate $H$, the mean $H$ differences ($\langle H_{est} - H_{obs} \rangle$) being always negative. The best agreement and the

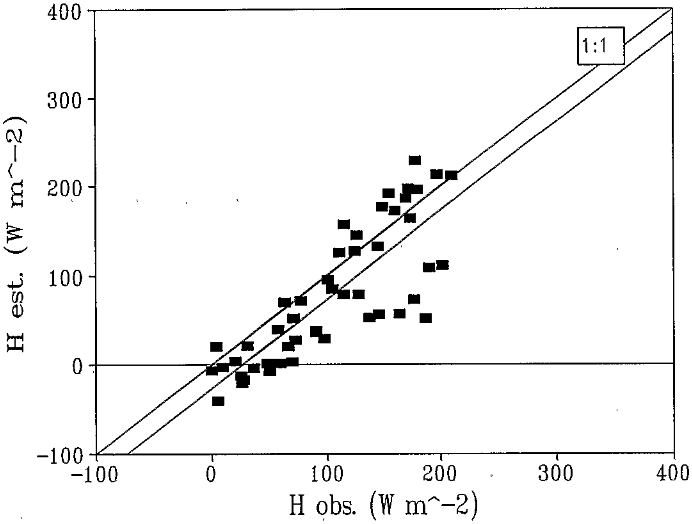

Fig. 5. For data subset I B, comparison of $H$ estimated (using Eqs. (11) and (21) with $m = 2$) vs. $H$ observed, with the corresponding regression line. Parameter $a$ is estimated from subset I A ($a = 0.09$).

least amount of scatter appears to be for data set II B (stem elongation). The agreement is less good for period III B (flowering, maturation), which might be explained by a large amount of dry leaves, or by the soil partially covered with weeds. However, considering that the values of air temperature and wind speed used in the flux calculation are those measured at the 1 km distant weather station,

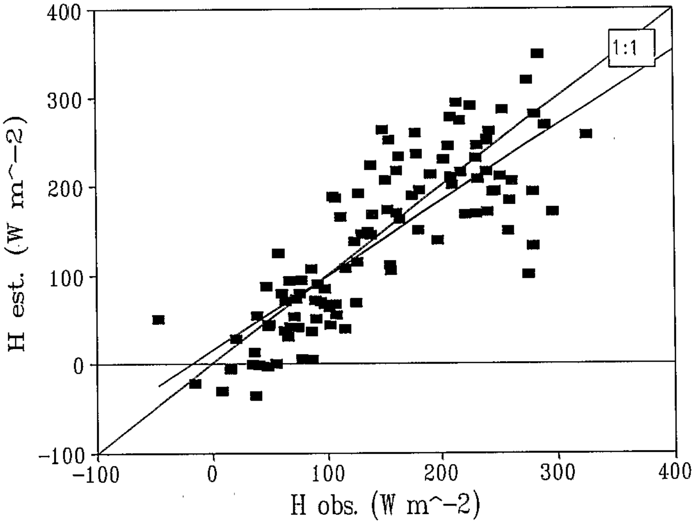

Fig. 6. For data subset II B, comparison of $H$ estimated (using Eqs. (11) and (21) with $m = 2$) vs. $H$ observed, with the corresponding regression line. Parameter $a$ is estimated from subset II A ($a = 0.11$).

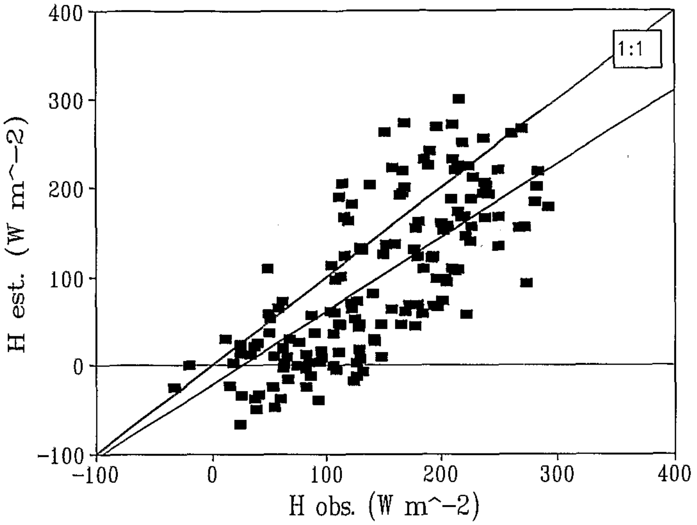

Fig. 7. For data subset III B, comparison of $H$ estimated (using Eqs. (11) and (21) with $m = 2$) vs. $H$ observed, with the corresponding regression line. Parameter $a$ is estimated from subset III A ($a = 0.11$).

we may conclude that the agreement between $H$ estimated and $H$ observed is fairly good.

## 4. Conclusion

For estimating sensible heat flux from radiometric surface temperature $T_r$ over partial canopy cover, it has been shown that a simple Ohm's law type formulation based on a typical one-layer model does not work. In dry conditions, sensible heat

Table 7
Some statistics on the estimates of the model, expressed in W m$^{-2}$. $n$ is the number of data points for each subset of data. $\langle H_{obs} \rangle$ is the mean value of observed sensible heat flux. $\langle H_{est} - H_{obs} \rangle$ is the mean difference between estimated and observed $H$. RMSE is the root mean square error. $CL$ is the 95% confidence limits on the mean $H$ differences (calculated from 1.96 RMSE/$n^{1/2}$). $H_e = a + bH_0$ is the regression line between estimated and observed $H$. $r^2$ is the coefficient of determination of the regression line and $s_y$ is the standard error of $y$ ($H_{est}$)

| Data set | I B | II B | III B |
|---|---|---|---|
| $n$ | 50 | 108 | 159 |
| $\langle H_{obs} \rangle$ | 103 | 150 | 143 |
| $\langle H_{est} - H_{obs} \rangle$ | –27 | –9 | –46 |
| RMSE | 50 | 58 | 78 |
| CL | 14 | 11 | 12 |
| $H_{est} = a + bH_{obs}$ | $a = -27, b = 1.0$ | $a = 15, b = 0.84$ | $a = -22, b = 0.83$ |
| $r^2$ | 0.69 | 0.63 | 0.51 |
| $s_y$ | 43 | 56 | 63 |

primarily emanates from the soil surface and only a two-layer scheme can allow for the shift of the sensible heat source from the foliage to the soil. The basic equations of a two-layer scheme were used with the assumption that the IR temperature could be correctly represented by an area-weighted mean of foliage and soil temperatures. In these conditions, we have shown that the temperature difference between the surface and the air in the flux equation must be corrected by a term proportional to the temperature difference $\delta T$, between the soil and the foliage.

The separation of vegetation and soil temperatures is generally a difficult task when surface temperature is measured from high-altitude sensors, which may limit the applicability of two-layer representation for estimating sensible heat flux. Nevertheless, in the case of a sparse millet crop grown in Niger and in the absence of separate measurements of soil and foliage temperatures, it has been possible to fit a statistical relationship linking $\delta T$ to the temperature difference between the canopy and the air of the type $\delta T = a(T_r - T_a)^m$ with $m = 2$ and $a \approx 0.10$. The basic flux equation derived from the two-layer approach (Eq. (11)), together with this statistical relationship, has proved to give satisfactory estimates of sensible heat flux over the sparse millet crop considered in this study.

As a concluding remark, it seems worthwhile pointing out that the set of available data was not completely adequate for testing the basic equation of the two-layer approach (Eq. (11)), as the experimental design did not measure all of the variables involved in the model, principally soil and foliage temperatures. Equation (21) is typically empirical and is used to estimate these missing values. So, the model presented does not pretend to be entirely mechanistic but rather semi-empirical. At the risk of denigrating the generality of this analysis we have to stress that the procedure used to fit this equation could compensate for other effects. So, the fairly good agreement between observed and estimated data could be associated with the technique of estimating parameters $a$ and $m$. The only way to solve the question would be to test the model with a data set in which the three temperatures (surface, soil and foliage) are simultaneously measured.

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# Estimating sensible heat flux from radiometric temperature over sparse millet

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