Estimates of convective fluxes over sparse canopy from infrared temperature

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Abstract A two-layer model is developed and used to estimate sensible heat flux (H) from surface radiometric temperature (T_r) over a sparse millet crop grown in farming conditions in Niger. Surface temperature was measured with a nadir-looking radiometer and measurements of convective fluxes were made simultaneously by means of the Bowen ratio-energy balance method. The model, based upon the assumption that the radiometric surface temperature might be represented by the composite surface temperature (area-weighted mean of foliage and soil temperatures), leads to a simple formulation of H as a function of the temperature difference between the surface and the air ($T_r - T_a$) and the temperature difference between the soil and the foliage δT. The difference δT being not available in our experiment, it was assumed that δT could be estimated from $T_r - T_a$ by means of a statistical relationship of the type $y = ax^m$. Using one part of the data set, m and a were statistically determined by adjusting H estimated by the model to H measured. 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 compare fairly well with the values of H observed.

INTRODUCTION

Remote sensing in the thermal infrared 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 H from radiometric temperature and in calculating evaporation λE as a residual term of the energy balance equation, net radiation R_n and soil heat flux G being measured or calculated independently:

$$\lambda E = (R_n - G) - H \tag{1}$$

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 or on a regional scale. 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 & 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; Kustas *et al.*, 1989; Kalma & Jupp, 1990). Kustas (1990) developed a two-layer model for partial canopy cover, 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 estimate sensible heat flux from radiometric temperature over sparse crops. The basic equations are the same as those used in the classical two-layer model originally devised by Shuttleworth & Wallace (1985). 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.

THEORY

In a sparse crop represented by a two layer model (Fig. 1), the total sensible heat flux H is the sum of the contributions emanating from each layer: $H = H_f + H_s$, where H_f is the contribution emanating from the foliage and H_s is the contribution emanating from the substrate (essentially bare soil). Expressing H_f and H_s as a function respectively of foliage temperature T_f and substrate temperature T_s, it is possible to infer the following expression for the total flux of sensible heat:

$$H = \rho c_p(T_c - T_a)/(r_a + r_c) \quad (2)$$

where T_a is the air temperature at a reference height, T_c is a weighted mean of the temperatures of each layer

$$T_c = (r_{af}T_s + r_{as}T_f)/(r_{as} + r_{af}) \quad (3)$$

and the equivalent resistance r_c is expressed as:

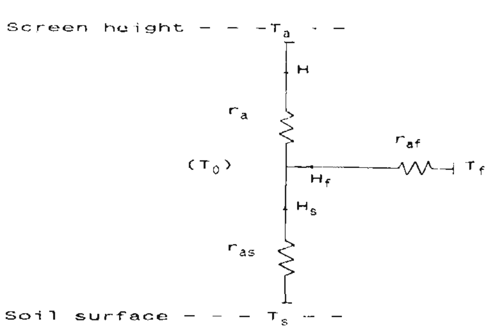

Fig. 1 Fluxes and potential-resistance network for a two-layer model of heat transfer. T_a is air temperature at a reference height, T_f is foliage temperature, T_s is substrate or soil temperature and T_0 is air temperature at canopy source height.

$$r_e = r_{af} \cdot r_{as}/(r_{af} + r_{as}) \quad (4)$$

r_{af} is the bulk boundary-layer resistance of the foliage per unit ground area, r_{as} is the aerodynamic resistance between the substrate and the canopy source height and r_a is the aerodynamic resistance between canopy source height and reference level.

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 & Jupp, 1990). If f represents the fractional area covered by the foliage, T_r can be written as:

$$T_r = fT_f + (1 - f)T_s \quad (5)$$

The relationship between T_c and T_r can be inferred from equations (3) and (5) and expressed as a function of the difference between the two component temperatures:

$$T_c - T_r = -c(T_s - T_f) \quad (6)$$

c being defined by $c = [1/(1 + x)] - f$, with $x = r_{af}/r_{as}$. Thus, sensible heat flux can be rewritten as:

$$H = \rho c_p[(T_r - T_a) - c\delta T]/(r_a + r_c) \quad \text{with} \quad \delta T = T_s - T_f \quad (7)$$

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

For calculating the stability-corrected aerodynamic resistance r_a we used the expression given by Choudhury *et al.* (1986) and recommended by Kalma & Jupp (1990) for pasture with incomplete cover. It is written as a function of the aerodynamic resistance r_{a0} in neutral conditions:

$$r_a = r_{a0}/(1 + \eta)^p \quad (8)$$

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

$$\eta = 5(z_r - d)g(T_s - T_a)/(T_a u^2) \quad (9)$$

where g is the gravitational acceleration, T_s is the surface temperature taken to be equal to T_r, u is the wind velocity at the reference height z_r and d the zero plane displacement.

Following Choudhury & 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 h and by dividing by the leaf area index L_0. Performing the integration we obtain:

$$r_{af} = \alpha_w[w/u(h)]^{1/2}/\{4\alpha_0 L_0[1 - \exp(-\alpha_w/2)]\} \quad (10)$$

where w is the leaf width and u(h) the wind velocity at canopy height level. α_w and α_0 are two coefficients respectively equal to 2.5 and 0.005 in S.I. units.

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 $d + z_0$, z_0 being the roughness length of the canopy. 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 & Wallace, 1991). We obtain (Choudhury & Monteith, 1988; Shuttleworth & Gurney, 1990):

$$r_{as} = h\exp(\alpha_w)\{\exp(-\alpha_w z_{0s}/h) - \exp[-\alpha_w(d + z_0)/h]\}/\alpha_w K(h) \quad (11)$$

z_{0s} is the roughness length of the substrate (bare soil) and K(h) is the value of eddy diffusivity at crop height.

From these results it is possible to calculate the value of coefficient c. It appears that the value of c is about 0.5 for a standard canopy such as a millet crop ($L_0 = 2$, $h = 2$ m, $w = 0.05$ m, and $f = 0.3$). Since the temperature difference δT between the substrate and the foliage can often reach over 10 °C, that means that the temperature gradient has to be corrected (reduced) by about 5 °C. This effect could explain why several authors have found that the surface radiometric temperature T_r can increase rapidly over sparse crops while the sensible heat flux remains essentially the same magnitude (Stewart *et al.*, 1989; Kustas *et al.*, 1989).

RESULTS

The data for this study were collected in 1991 over a millet field (Pennisetum typhoides) grown in farming conditions on the central site of the HAPEX-Sahel experiment (13°31'N, 2°39'E) in south-west Niger. The climate is typical of the Sahelian zone with summer rainfall. The soil is sand about 2 m deep. The crop was planted with a density of about 6 800 plants per ha.

The measurements took place in July (from DOY 187 to 209) between 8:00 h and 18:00 h. This period corresponds to stem elongation. 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 located 12 m above the soil surface and one heat flux plate buried at 3 cm depth. Surface temperature was recorded using a nadir-looking infrared thermometer with a 16° field of view located 12 m above the soil surface. Fluxes of latent and sensible heat and IR surface temperature were logged as hourly values. Wind speed at a reference height (set at 4 m above the soil surface) was calculated from the value measured at the near-by weather station using the log-profile relationship. Air temperature at this level above the millet crop was taken to be equal to that measured at the weather station.

In order to test the two-layer model described above, equation (7) was used to calculate sensible heat flux from T_r measured by the infrared radiometer. The structural characteristics of the crop were taken as constant ($h = 1.75$ m, LAI = 2.0, $f = 0.3$). Generally, measurements made from a mast above the canopy or from aircraft and satellite altitudes do not allow one to separate vegetation and soil temperatures. Hence δT is unknown. In our experiment soil and foliage temperature were not measured separately either. Consequently, a procedure was developed to account for δT without additional measurements. This procedure is based upon the proposal that δT has to increase with the temperature gradient above the canopy $(T_r - T_a)$. In semi-arid regions, on sandy soil, the surface layer dries rapidly after a rainfall, thus δT tends to increase when net radiation and the temperature gradient above the canopy increase. It was assumed that a relationship exists between δT and the temperature gradient $(T_r - T_a)$ and that this relationship is of the form:

$$\delta T = a(T_r - T_a)^m \tag{12}$$

m being a positive integer and a positive real number. Therefore, equation (7) can be rewritten in the form of an apparent Ohm's law:

$$H = \rho c_p \Omega (T_r - T_a)/(r_a + r_e) \quad \text{with } \Omega = 1 - ca(T_r - T_a)^{m-1} \tag{13}$$

Since m and a are not known a priori, one part of the data set (A) was used to calibrate equation (12) by determining the values of m and a for which the best fit was obtained between the values of H estimated by equation (13) and the values of H measured by the Energy balance-Bowen ratio method. The other part of the data set (B) was used to test equation (13) with the values of m and a obtained in this way. We put alternate hourly records in set A and set B. To determine the best fit of the values of H estimated by the model to the values measured by the Bowen ratio method the following procedure was used. 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 (root mean square error). The results obtained for $m = 1$, 2 and 3 are shown in Table 1 (for $m > 3$ the results were very poor and are not shown). It is clear that the best fit was for $m = 2$, i.e. for a quadratic function linking δT to $T_r - T_a$. For $m = 2$, the value of a corresponding to the lowest RMSE is nearly the same for each sub-set of data (around 0.10). Thus, we can infer that equation (12), with $m = 2$ and $a \approx 0.10$, represents a good estimate of δT on the millet crop studied.

Figure 2 shows the comparison of H estimated using the quadratic function ($m = 2$) versus H observed for each sub-set of data (A and B). Figure 2a shows the comparison between H observed and H estimated for sub-set A, parameter a being estimated from sub-set B, and Fig. 2b shows the same comparison for sub-set B, a being estimated from sub-set A. The agreement between H estimated and H observed can be considered as fairly good (the RMSE is about 60 W m^{-2}) if we take into

Table 1 Determination of parameters m and a of equation (12). For both sub-sets of data A and B and each m, the value of a retained and presented in the table is that which minimizes the Root Mean Square Error RMSE (W m^{-2}) between estimated and observed values of H.

	Number of data points	m = 1		m = 2		m = 3	
		a	RMSE	a	RMSE	a	RMSE
A	114	1.29	62	0.11	61	0.01	108
B	114	1.21	64	0.10	58	0.01	105

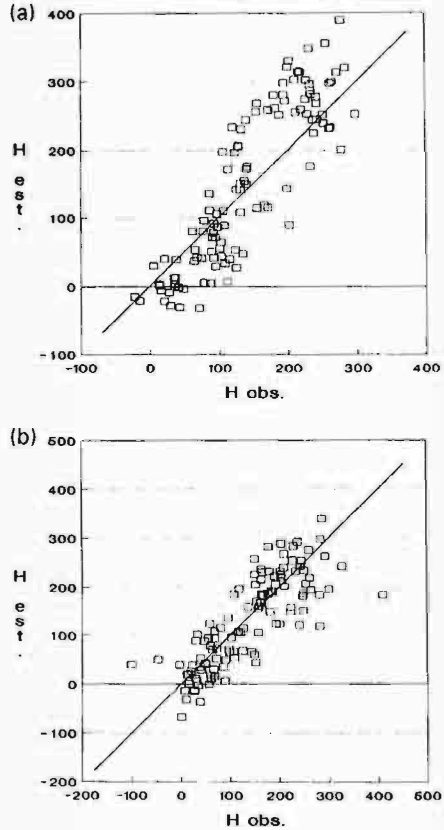

Fig. 2 Comparison of H (W m^{-2}) estimated using a two-layer model versus H observed. In (a), sub-set A is used with parameters m and a estimated from sub-set B (m = 2 and a = 0.10), the RMSE is 65. In (b), sub-set B is used, parameters m and a being estimated from sub-set A (m = 2 and a = 0.11), the RMSE is 58.

account the fact that the values of air temperature and wind speed used in the calculation are those measured at the near-by weather station.

CONCLUSION

For estimating sensible heat flux from radiometric surface temperature T_r over partial canopy cover a two-layer scheme was 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 an Ohm's law type formulation, relating sensible heat flux to the temperature gradient $T_r - T_a$ above the canopy, can still be used provided the temperature gradient is corrected by a term proportional to the temperature difference δT between the foliage and the soil. Since the separation of vegetation and soil temperatures is generally a difficult task when surface temperature is measured from high-altitude sensors, a statistical relationship linking δT to the temperature gradient above the canopy of the type $\delta T = a(T_r - T_a)^m$

is proposed. The basic flux equation derived from the two-layer approach (equation (7)), together with this statistical relationship with m = 2 and a = 0.10, has proved to give satisfactory estimates of sensible heat flux over a sparse millet crop grown in Niger.

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