ELSEVIER

Agricultural and Forest Meteorology 68 (1994) 93–105

AGRICULTURAL
AND
FOREST
METEOROLOGY

Determination of sensible heat flux over Sahelian fallow savannah using infra-red thermometry

J.-P. Lhomme*, B. Monteny, A. Chehbouni, D. Troufleau

ORSTOM, Laboratoire de Bioclimatologie, BP 11416, Niamey, Niger

(Received 1 December 1992; revision accepted 14 August 1993)

Abstract

The estimation of the partitioning of available energy from remote sensing techniques is addressed for a Sahelian fallow savannah. It is a composite vegetation consisting of shrubs of *Guiera senegalensis* scattered above a stand of sparse grass. A two-layer model is employed to estimate sensible heat flux (H) from radiometric surface temperature, with data collected during the HAPEX–Sahel international experiment, carried out in Niger in 1992. The model, based upon the assumption that the radiometric surface temperature (T_r) might be represented by the composite surface temperature (area-weighted mean of shrub and grass 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 grass and the shrubs δT. The estimates of the model compare fairly accurately with measurements obtained by the Bowen ratio–energy balance method, the root mean square error being about 52 W m^{-2}. Because δT is not easily measured from remote sensing systems, it has been shown that for the fallow savannah this temperature difference is linearly correlated to ($T_r - T_a$) with $r^2 = 0.94$. Therefore, it is possible to estimate sensible heat flux from ($T_r - T_a$) without additional component temperature measurements.

Introduction

Terrestrial surface–atmosphere interactions play an important role in determining climate. To understand how changes in surface characteristics modify surface–

* Corresponding author at: ORSTOM, 911 Avenue Agropolis, 34032 Montpellier, France.

SSDI 0168-1923(94)02113-K

atmosphere interactions it is crucial to determine accurately the partitioning of available energy into sensible and latent heat flux. Remote sensing techniques allow one to determine this partitioning. The method classically employed consists in estimating sensible heat flux from radiometric surface temperature and in calculating evaporation as a residual term of the energy balance equation. When this method is used over vegetated surface, one of its most critical aspects is to determine correctly the sensible heat flux. Assumptions are generally made, the most significant being that the radiometric surface temperature, as measured with a nadir-looking radiometer, is equivalent to the aerodynamic surface temperature, which is the temperature computed at the effective source height within the canopy (Choudhury, 1989). However, this assumption is difficult to accept because experimental data show large discrepancies between the two temperatures (Huband and Monteith, 1986).

This problem is particularly acute in the case of sparse vegetation. The dry soil can heat rapidly and hence become the major source of sensible heat. Many authors have shown that the radiometric surface temperature can increase rapidly while the sensible heat flux, and consequently the aerodynamic surface temperature, remain essentially the same magnitude (Kustas et al., 1989; Stewart et al., 1989; Kalma and Jupp, 1990; Monteny and Leroux, 1991). Working on a natural sparse vegetation in California, Kustas et al. (1989) suggested that this was the result of a shift in the source of sensible heat from the canopy to the soil and that the heat flux from the soil had to traverse an added resistance to heat transfer (kB^{-1}), which was made a function of radiometric temperature. Two-layer approaches, based upon the conceptual model of Shuttleworth and Wallace (1985), have also been applied to partially vegetated surface in order to account for the shift between aerodynamic and radiometric surface temperature (Kustas, 1990; Nichols, 1992). However, the results obtained by Kustas (1990), with data collected from a sparse cotton field, are relatively poor. Lhomme et al. (1994) developed and applied to a sparse millet crop in Niger a two-component model based on the same conceptual principles, but in which radiometric surface temperature is taken into account as the area-weighted mean of foliage and soil temperatures. This model leads to a simple expression of the sensible heat flux as a function of the temperature difference between the surface and the air corrected by a term proportional to the temperature difference between the soil and the vegetation.

The intent of this study is to evaluate the applicability of this model to a Sahelian fallow savannah, which is a composite vegetation consisting of a ground layer of sparse grass with scattered shrubs of *Guiera*. The data used in this study have been collected in the framework of the HAPEX–Sahel international experiment (Goutorbe et al., 1994), which took place in south-west Niger from August to October 1992. As for the SEBEX experiment (Wallace et al., 1991), carried out in the same region some years ago, the main objective of HAPEX–Sahel was to obtain data against which new parameterizations of land surface processes in semi-arid zones can be calibrated for use in global circulation models (GCM).

2. Theory

2.1. Sensible heat flux formulation

Sensible heat exchange in a composite vegetation such as the fallow savannah is assumed to be well represented by a two-component model conceptually identical to the one-dimensional two-layer model classically used for sparse crops (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990). The herbaceous cover and the bare soil represent the bottom layer and the *Guiera* shrubs the upper layer. Figure 1 illustrates the proposed model. Four temperatures characterize the system: air temperature at a reference height above the shrub canopy (T_a), the temperature at the mean canopy source height (T_0), the temperature at the grass source height, taken to be equal to the composite temperature (soil and grass) of the substrate (T_s), and the temperature of the shrub canopy (T_f). The shrub canopy source height is situated at a height $d + z_0$ above the soil surface and the grass source at a height $d_g + z_{0g}$, d and z_0 being, respectively, the zero plane displacement and the roughness length of the shrub canopy (defined in relation to shrub height), and d_g and z_{0g} being the same parameters for the grass cover.

The surface radiometric temperature T_r, measured by an infra-red thermometer located vertically above the surface and high enough to see a representative area, is considered as the area-weighted mean of shrub and grass temperatures (Choudhury, 1989; Kalma and Jupp, 1990), and is written as

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

where f represents the fractional area covered by the shrubs of *Guiera*. A means of

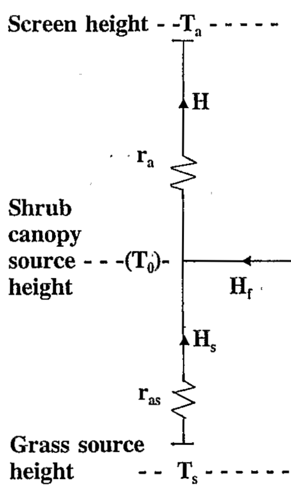

Fig. 1. Fluxes and potential-resistance network for a two-layer model of heat transfer from a Sahelian fallow savannah. T_a is air temperature at a reference height, T_f is shrub canopy temperature, T_s is substrate temperature and T_0 is air temperature at canopy source height (aerodynamic surface temperature).

combining the basic equations of the two-layer approach and Eq. (1), to infer an expression for the total flux of sensible heat, has been detailed by Lhomme et al. (1994). The following expression is obtained

$$H = \rho c_p[(T_r - T_a) - c\delta T]/(r_a + r_e) \quad \text{with } \delta T = T_s - T_f \tag{2}$$

The parameter c is defined by

$$c = [1/(1 + r_{af}/r_{as})] - f \tag{3}$$

where r_{af} is the bulk boundary-layer resistance of the shrub canopy per unit ground area and r_{as} is the aerodynamic resistance between the grass source height and the *Guiera* canopy source height. r_a is the aerodynamic resistance between canopy source height and reference level and r_e is an additional resistance expressed as

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

2.2. Resistance formulations

The formulations for the resistance terms r_a, r_{as} and r_{af} are needed to apply Eq. (2). The bulk boundary-layer resistance of the shrub canopy r_{af} is calculated by integrating the leaf boundary-layer conductance over the shrub height h, assuming leaf area index L_0 to be uniformly distributed with height (Choudhury and Monteith, 1988)

$$r_{af} = \alpha_w[w/u(h)]^{1/2}/\{4\alpha_0 L_0[1 - \exp(-\alpha_w/2)]\} \tag{5}$$

w is the *Guiera* leaf width (0.02 m), $u(h)$ is the wind speed at shrub height, and α_0 and α_w are two constant coefficients respectively equal to 0.005 and 2.5 in SI units.

The aerodynamic resistance r_{as} between the source height of the grass cover $(d_g + z_{0g})$ and the source height of the whole canopy $(d + z_0)$ is defined as the integral of the reciprocal of eddy diffusivity over the height range $[d_g + z_{0g},\ d + z_0]$ (Choudhury and Monteith, 1988; Shuttleworth and Gurney, 1990)

$$r_{as} = h\exp(\alpha_w)\{\exp[-\alpha_w(d_g + z_{0g})/h] - \exp[-\alpha_w(d + z_0)/h]\}/[\alpha_w K(h)] \tag{6}$$

$K(h)$ is the value of eddy diffusivity at shrub height. Zero plane displacements and roughness lengths are obtained from canopy height by making use of the empirical relationships given by Monteith and Unsworth (1990) for a homogeneous canopy. Wind speed and eddy diffusivity at shrub height (h) are calculated from the classical above-canopy relationships (Shuttleworth and Gurney, 1990).

In neutral conditions the aerodynamic resistance above the canopy is classically expressed as

$$r_{a0} = \{\ln[(z_r - d)/z_0] + kB^{-1}\} \ln[(z_r - d)/z_0]/(k^2 u) \tag{7}$$

where u is the wind speed at the reference height z_r, k is the Von Karman's constant (0.4) and kB^{-1} is the added resistance owing to bluff-body effect (Chamberlain, 1968). Since the two-layer approach is assumed to account for the bluff-body correction (recognition that the roughness lengths for heat and momentum are not equal), kB^{-1} is taken to be equal to 0. For the stability corrected aerodynamic resistance r_a, the formulation proposed by Choudhury et al. (1986) is employed

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

where η is defined by

$$\eta = 5(z_r - d)g(T_0 - T_a)/(T_a u^2) \tag{9}$$

g being the gravitational acceleration and T_0 being the aerodynamic surface temperature. $p = 3/4$ in unstable conditions and $p = 2$ in stable conditions.

T_0 being unknown a priori, a relationship has to be worked out to link $T_0 - T_a$ to $T_r - T_a$, because the radiometric temperature T_r is the only known surface temperature. To derive this relationship the following procedure has been employed. Setting the total sensible heat flux as the sum of the contributions of each layer and expressing the fluxes in each segment of the network (Fig. 1) as a function of temperatures yields the following equation

$$(T_0 - T_a)/r_a = (T_f - T_0)/r_{af} + (T_s - T_0)/r_{as} \tag{10}$$

Rearranging Eq. (10) and replacing resistances by conductances gives

$$T_0 = (g_a T_a + g_{as} T_s + g_{af} T_f)/(g_a + g_{as} + g_{af}) \tag{11}$$

In arid or semi-arid environments the vegetation temperature (shrubs in our case) is often close to air temperature (Nichols, 1992). For the fallow savannah, the regression line between shrub temperature T_f and air temperature T_a, calculated with the whole set of data (cf. Experimental data below), gives $T_f = 0.97\,T_a + 1.45$ with $r^2 = 0.90$. So, as a first approximation, we will admit that $T_f \approx T_a$. Assuming also that the radiometric surface temperature can be approximated by the composite surface temperature given by Eq. (1), we obtain

$$T_0 = [(g_a + g_{af})T_a + g_{as}(T_r - fT_a)/(1-f)]/(g_a + g_{af} + g_{as}) \tag{12}$$

Subtracting T_a from both sides of Eq. (12) and rearranging leads to

$$(T_0 - T_a) = \omega(T_r - T_a) \tag{13}$$

with

$$\omega = [1/(1-f)][g_{af}/(g_a + g_{as} + g_{af})] \tag{14}$$

The variation in the coefficient ω, as a function of wind velocity, is given in Table 2 for the fallow savannah considered in this study (taking g_a equal to $g_{a0} = 1/r_{a0}$). It appears that $T_0 - T_a$ represents about a quarter of $T_r - T_a$. However, we have to stress that Eq. (13) is only an approximate equation based upon the assumption that $T_f \approx T_a$. Because $T_0 - T_a$ is employed in a corrective term (Eq. (9)), we may suppose that the result obtained is accurate enough.[1]

[1] The total sensible heat flux can be expressed as a function of the aerodynamic surface temperature T_0 as: $H = \rho c_p(T_0 - T_a)/r_a$. Replacing $(T_0 - T_a)$, which is unknown, by its expression as a function of $(T_r - T_a)$ (Eq. (13)) yields: $H = \rho c_p \omega (T_r - T_a)/r_a$. This simple expression can be used to calculate H, but, as it is derived assuming that $T_f = T_a$, it is less accurate than Eq. (2).

2.3. Sensitivity of the model

The main input parameters of the model are: the fractional area covered by the shrubs (f), the leaf area index of the shrubs (L_0), the height of the shrubs (h) and the height of the grass cover (h_g). The sensitivity of the model to changes in these parameters has been assessed. Table 1 illustrates the effect of making changes of ±50% in these parameters on the calculated values of the additional resistance r_e and the coefficient c of Eq. (2). It appears that the additional resistance r_e is fairly sensitive to L_0 but much less to shrubs and grass heights. The coefficient c is sensitive to L_0 and f, but shows less sensitivity to changes in shrubs and grass heights.

The influence of wind velocity on the main parameters of the two-layer model is shown in Table 2. It appears that for a typical fallow savannah and for a wind speed at a reference height of 3 m s^{-1} the additional resistance r_e is about 25 s m^{-1} (compared with 20 s m^{-1} for the aerodynamic resistance above the canopy in neutral conditions) and the coefficient c is 0.34. Because the temperature difference between the grass and the *Guiera* shrubs δT can sometimes reach over 15°C in the middle of the day, that means that the temperature difference $(T_r - T_a)$ has to be reduced by up to 5°C to calculate H.

3. Experimental data

3.1. Site

The fallow savannah was situated on the East–Central site of the HAPEX–Sahel experiment, near the village of Banizoumbou (13°31′N, 2°39′E) in the Sama Dey catchment. The soil is sandy around 2 m deep. Measurements were made in September and October 1992, which corresponds to the end of the rainy season and the start of the dry season. The fallow savannah site has not been cropped for about

Table 1
Sensitivity of the two main parameters (r_e and c) of the model to changes (±50%) in input parameters for three different values of wind speed at reference height. $f = 0.17$, $L_0 = 0.5$, $h = 3.5$ m and $h_g = 0.5$ m. n.c., no change

		$U = 1$ m s^{-1}		$U = 3$ m s^{-1}		$U = 5$ m s^{-1}	
		r_e	c	r_e	c	r_e	c
f	+50%	n.c.	−19%	n.c.	−24%	n.c.	−32%
	−50%	n.c.	+17%	n.c.	+26%	n.c.	+29%
L_0	+50%	−25%	+17%	−20%	+29%	−18%	+36%
	−50%	+47%	−35%	+36%	−50%	+29%	−57%
h	+50%	−9%	< 5%	−8%	< 5%	−6%	< 5%
	−50%	< 5%	−12%	< 5%	−18%	< 5%	−21%
h_g	+50%	−7%	−8%	−8%	−12%	−6%	−14%
	−50%	+5%	+6%	+8%	+12%	+12%	+14%

Table 2
Variation in resistances expressed in $s\,m^{-1}$, in coefficient c given by Eq. (3), and in coefficient ω given by Eq. (14), as a function of wind velocity at a reference height of 12 m. $h = 3.5$ m, $L_0 = 0.5$, $f = 0.17$, $h_g = 0.5$ m

	U ($m\,s^{-1}$)				
	1	2	3	4	5
r_{a0}	59	29	20	15	12
r_{af}	85	60	49	42	38
r_{as}	155	77	52	39	31
r_e	55	34	25	20	17
c	0.48	0.39	0.34	0.31	0.28
ω	0.22	0.24	0.26	0.27	0.27

7–8 years, allowing the natural vegetation to regenerate. It was regularly grazed by cattle and sheep. About 83% of the ground was covered by a sparse herbaceous canopy made up of a mixture of different grass species (predominantly *Aristida mutabilis, Aristida pallida, Eragrostis tremula, Ctenium elegans, Cenchrus biflorus*) with small patches of bare soil and some occasional trees. The remaining area (about 17%) was covered by woody shrubs of *Guiera senegalensis*, the mean height of which was about 3.5 m. The leaf area index of the *Guiera* shrubs was about 0.5 and was considered to remain relatively constant throughout the period of measurement. The percentage cover of shrubs was determined using a technique based on point quadrats (J.M. d'Herbès, personal communication, 1992). It is assumed that the bare soil and the trees do not significantly affect the average exchanges from the area. Therefore they are not accounted for in the modelling process. The data presented in this study were obtained during 6 weeks of daily measurements from 7 September (DOY 251) to 18 October (DOY 292). Some days were omitted because of instrumental failures. The last rainfall on the site (23 mm) occurred on 14 September. Grass height was about 0.2 m at the start of the measurement period and 0.6 m at the end.

3.2 Instrumentation

Evaporation and sensible heat flux were determined using an energy balance–Bowen ratio system containing one net radiometer (Radiation Energy Balance System, Q6, Campbell, UK), located 12 m above the soil surface, and four heat flux plates buried at 3 cm depth at random between the shrubs. The net radiometer was put high enough so that its field of view could contain approximately the area average proportions of shrubs and grass. Soil heat flux was calculated as the average of the four values disregarding the effect of heat storage in the top 3 cm. Vapor pressure gradients were measured by means of an HMP35A hygrometer (Vaisala sensor systems). The measuring heights were 4.5 m and 9.0 m above the soil surface. Air was alternately drawn by aspirating pumps through intakes at each height and routed to the Vaisala sensor. Air temperature was measured at the same two heights using shielded copper–constantan thermocouples. Measurements of surface temperature were recorded using two nadir-looking infra-red thermometers (Everest Interscience IRTs), with a 15° field of view. One was mounted at 9 m over the grass area, which means that a 5 m diameter circle was seen at the surface. Another infra-red thermometer was mounted at about 1 m above a *Guiera* shrub so that the measured temperature was exactly that of the shrub (the area of the shrub seen by the radiometer was about 0.3 m^2). All the measurements were sampled at 10 s intervals and logged as 20 min average values on a Campbell data acquisition system (Campbell Scientific, UK). From the two infra-red temperature measurements a composite surface temperatures was calculated as the area-weighted mean of shrub and grass temperature (Eq. (1) with $f = 0.17$). The temperature of the grass shaded by the *Guiera* shrubs was not sampled separately, assuming it does not significantly affect the composite temperature. The percentage of surface covered by the shrubs is relatively small (17%), and under these latitudes, at this time of the year, the fraction of shaded area is always small compared with the sunlit one, because of the high position of the sun during the midday hours.

4. Model validation

4.1. Results

The diurnal variations in the energy balance components obtained by the Bowen ratio system are shown in Fig. 2 for 2 typical days of the experiment: DOY 256 (12 September), 2 days before the last rainfall which occurred on 14 September, and DOY 290 (16 October), 32 days after the last rainfall. On DOY 256, evaporation (λE) is relatively high, exceeding 400 W m^{-2} in the middle of the day. Consequently sensible heat flux (H) is low, most of the time lower than 100 W m^{-2}. DOY 290 shows the reduced evaporation which is lower than 200 W m^{-2} during the midday hours and which is exceeded by sensible heat flux.

In Fig. 3 we compare the measured values of H with the values estimated by a one-layer approach

$$H = \rho c_p (T_r - T_a)/r_a \tag{15}$$

The surface temperature (T_r) is taken as being equal to the composite surface temperature (Eq. (1)). The aerodynamic resistance (r_a) is calculated by means of Eqs. (8) and (9) and the added resistance because of bluff body effect is estimated from $kB^{-1} = 2$ (Garratt, 1978; Kalma and Jupp, 1990). The observed values of sensible heat flux are diurnal values averaged over 20 min periods. The agreement between measured and estimated H (shown in Fig. 3) is very poor and the conclusion is clear: single-level representation of partially vegetated surfaces, such as the fallow savannah, considerably overestimates sensible heat flux.

In order to overcome this difficulty the two-layer model described above has been applied for estimating sensible heat flux. Figure 4 shows the results obtained for the 6 weeks of the experiment, from 7 September (DOY 245) to 18 October (DOY 292). In spite of a significant scatter the agreement between estimated and observed values is

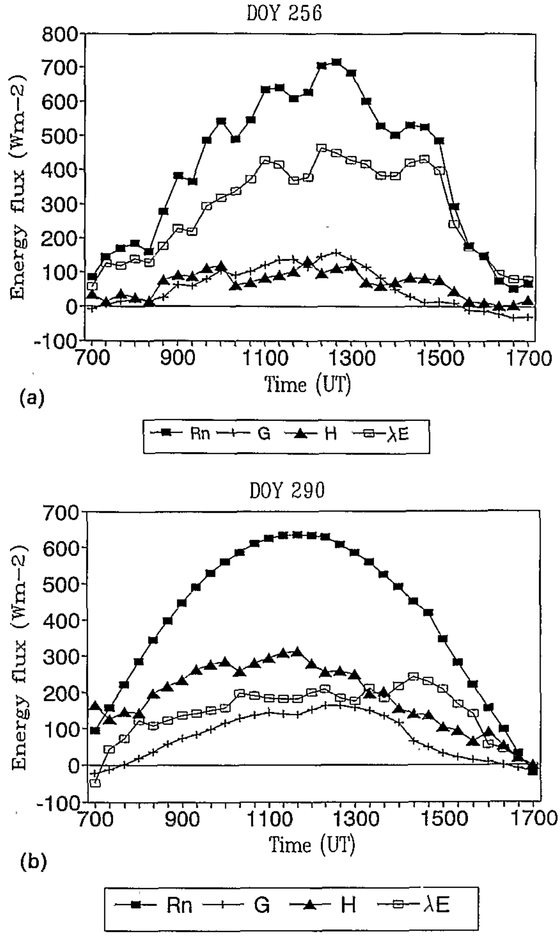

Fig. 2. Diurnal variations in energy budget components for: (a) 12 September (DOY 256), near the end of the rainy season; (b) 16 October (DOY 290), 32 days after the last rainfall.

fairly good and much better than with a one layer approach. The scatter might be a result of inaccurate measurements by the Bowen ratio–energy balance system as well as model estimates, since in fact it is rather difficult to obtain reliable measurements of convective fluxes over a tall and sparse vegetation such as the fallow savannah. The scatter might also be attributed to uncertainties in the measurement of surface temperature. To measure the goodness of fit between estimated and observed values we calculated the root mean square error (RMSE), which has been shown generally to be a good indicator of model performance (Willmott, 1982, cited by Kustas et al., 1989). The values of the RMSE corresponding to each subset of data are given in Table 3. They range from 41 W m^{-2} to 58 W m^{-2} with a mean value of 52 W m^{-2}, which can be considered as a good result over this type of vegetation.

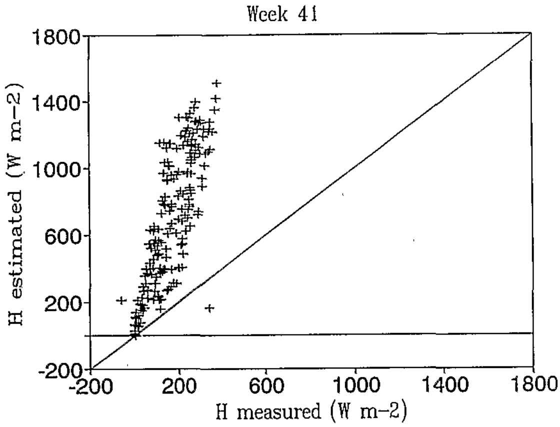

Fig. 3. For week 41 (DOY 279–285), comparison of sensible heat flux (H) estimated using a one-layer approach with $kB^{-1} = 2$ vs. H measured by the energy balance–Bowen ratio system. The data are values integrated over 20 min from 08:00 to 17:00 UT. The line represents perfect agreement.

4.2. Model extension

From experimental data it appears that a close relationship links the temperature difference between the substrate and the shrub canopy ($T_s - T_f$) to the temperature difference between the surface and the air ($T_r - T_a$), T_r being the radiometric surface temperature calculated by Eq. (1). In Fig. 5, $T_s - T_f$ has been plotted against $T_r - T_a$, for the whole set of experimental data ($n = 1019$). A regression line of the type $y = \beta x + \alpha$ fits very well to data points with $\alpha = 0.76$ and $\beta = 1.0$. The coefficient of determination is 0.94. These results are not completely surprising because T_f is often close to T_a and T_r is strongly correlated to T_s (because f is relatively small). Since $T_s - T_f$, in Eq. (2), can be replaced by a linear function of $T_r - T_a$, sensible heat flux can be expressed as

$$H = \rho c_p[(1 - c\beta)(T_r - T_a) - c\alpha]/(r_a + r_e) \qquad (16)$$

This formula, in which $T_s - T_f$ has disappeared, is potentially interesting because the separation of vegetation and substrate temperatures is still a difficult task when surface temperature is measured from high-altitude sensors. In Table 3 we compare the estimates of sensible heat flux calculated by the semi-empirical equation derived above (Eq. (16)) with the estimates obtained with the basic equation of the model (Eq. (2)). Examining the RMSE values between estimated and observed H, it appears that the semi-empirical equation gives as good agreement as the basic equation, because the mean RMSE is the same with both methods (52 W m^{-2}).

5. Conclusion

This paper investigates the estimation of sensible heat flux from radiometric surface

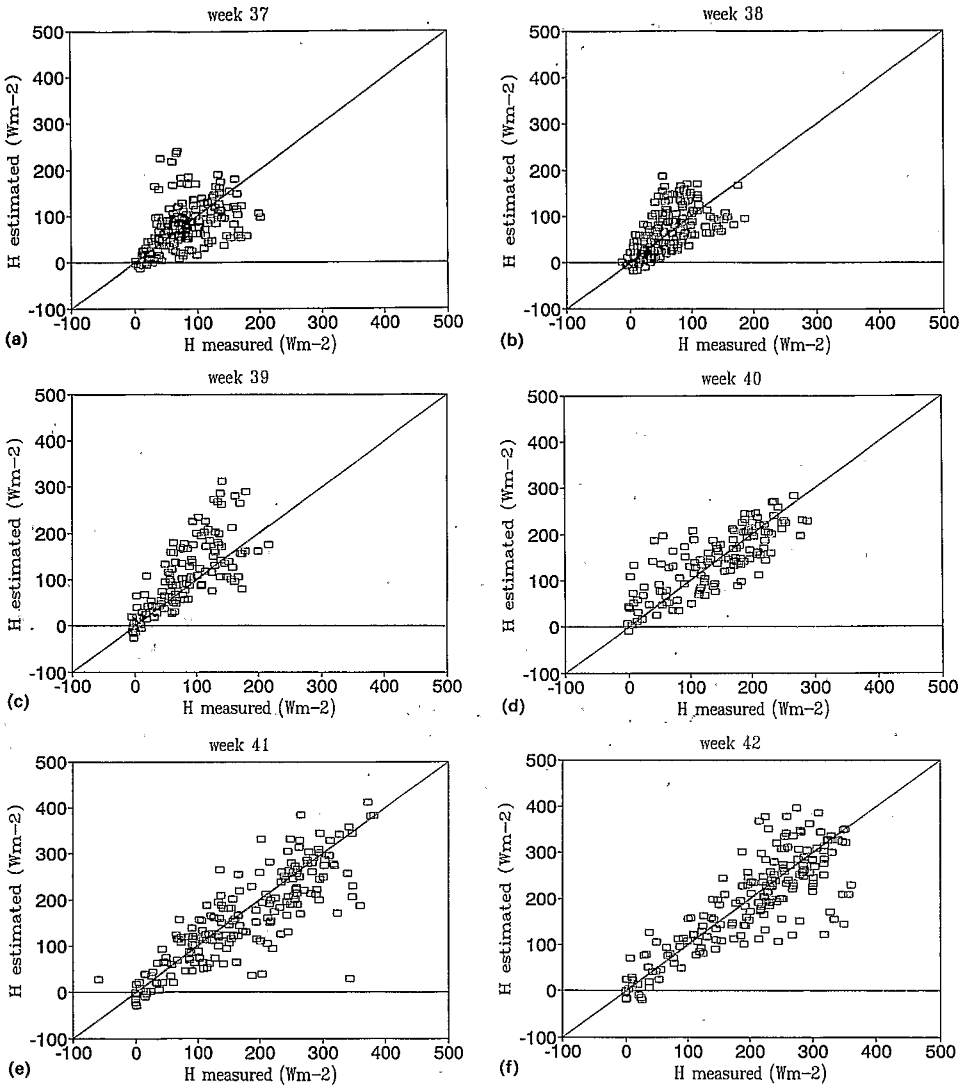

Fig. 4. Comparison of sensible heat flux (H) estimated from Eq. (2) vs. H measured by the energy balance–Bowen ratio system for the 6 weeks of the experiment. The data are values integrated over 20 min from 08:00 to 17:00 UT. The line represents perfect agreement.

temperature over a Sahelian fallow savannah, made up of a sparse cover of grass scattered with shrubs of *Guiera*. A two-layer model (Lhomme et al., 1994) has been developed from the basic equations of the two-layer approach (Shuttleworth and Wallace, 1985) and from a linearized form of the infra-red surface temperature (T_r). It leads to an expression of sensible heat flux (Eq. (2)), close in form to the one-layer formulation, but in which the temperature difference between the surface

Table 3
Root mean square error (RMSE) between the sensible heat flux (diurnal values averaged over 20 min) measured by the Bowen ratio–energy balance system and H estimated by the model

Week	RMSE ($W\,m^{-2}$)	
	H estimated by Eq. (2)	H estimated by Eq. (16)
37	50	52
38	41	41
39	57	52
40	47	49
41	58	58
42	58	58
average	52	52

and the air ($T_r - T_a$) has to be reduced by a term proportional to the temperature difference between the substrate and the shrub canopy ($\delta T = T_s - T_f$). An equivalent resistance (r_e) has also to be added to the aerodynamic resistance (r_a). Sensible heat flux estimated by means of that equation compares fairly well (RMSE $\approx 52\,W\,m^{-2}$) with values obtained by the Bowen ratio–energy balance method.

Since measurements made from high-altitude sensors generally do not allow separation of shrub and grass temperatures, a procedure was developed to account for δT without additional measurements. It was found that δT is very well correlated with ($T_r - T_a$) and that a regression line of the type $y = \beta x + \alpha$ yields good estimates of δT ($r^2 = 0.94$). Therefore, this statistical relationship put in the basic flux equation (Eq. (2)) allows estimation of sensible heat flux directly from the temperature gradient ($T_r - T_a$) without additional measurements of temperature. The coefficients of the regression line certainly depend on vegetation

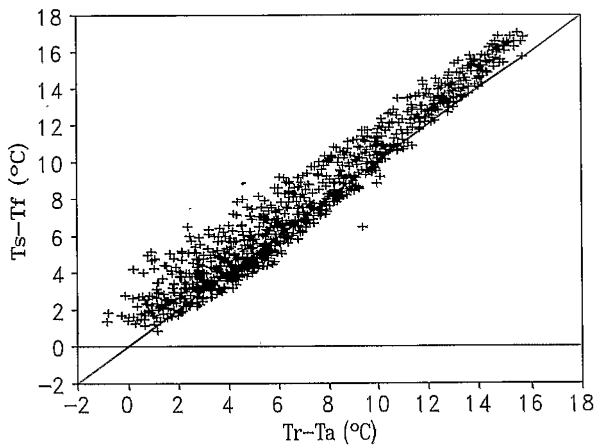

Fig. 5. The temperature difference between the substrate and the shrub canopy ($T_s - T_f$) is plotted against the difference between surface radiometric temperature and air temperature ($T_a - T_r$) for the whole set of data ($n = 1019$). The data are diurnal values averaged over 20 min. The line represents perfect agreement.

and soil characteristics. However, we may presume that the linear relationship, valid over fallow savannah, is likely to operate with appropriate coefficients over other types of sparse vegetation, provided the relative area of shrubs (f) is relatively small.

References

Chamberlain, A.C., 1968. Transport of gases to and from surfaces with bluff and wave-like roughness elements. Q. J. R. Meteorol. Soc., 94: 318–332.

Choudhury, B.J., 1989. Estimating evaporation and carbon assimilation using infrared temperature data: vistas in modelling. In: G. Asrar (Editor), Theory and Applications of Optical Remote Sensing. Wiley, New York, pp. 628–690.

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., 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.

Garratt, J.R., 1978. Transfer characteristics for a heterogeneous surface of large aerodynamic roughness. Q. J. R. Meteorol. Soc., 104: 491–502.

Goutorbe, J.P., Lebel, T., Tinga, A., Bessemoulin, P., Brower, J., Dolman, A.J., Engman, E.T., Gash, J.H.C., Hoepffner, M., Kabat, P., Kerr, Y., Monteny, B.A., Prince, S., Saïd, F., Sellers, P. and Wallace, J.S., 1994. HAPEX–Sahel: large scale study of land atmosphere interaction in the semi-arid tropics. Annales Geophysicae (in press).

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.

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., 1990. Estimates of evapotranspiration with a one- and two-layer model of heat transfer over partial canopy cover. J. Appl. Meteorol., 29: 704–715.

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., Monteny, B. and Amadou M., 1994. Estimating sensible heat flux from radiometric temperature over sparse millet. Agric. For. Meteorol., 68: 77–91.

Monteith, J.L. and Unsworth, M.H., 1990. Principles of Environmental Physics. Edward Arnold, London, 291 pp.

Monteny, B. and Leroux, X., 1991. Paramétrisation de l'évapotranspiration d'une jachère à *Guiera.* ORSTOM, Niamey, 13 p. multigr.

Nichols, W.D., 1992. Energy budgets and resistances to energy transport in sparsely vegetated rangeland. Agric. For. Meteorol., 60: 221–247.

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.

Shuttleworth, W.J. and Wallace, J.S., 1985. Evaporation from sparse crops — an energy combination theory. Q. J. R. Meteorol. Soc., 111: 839–855.

Stewart, J.B., Shuttleworth, W.J., Blyth, K. and Lloyd, C.R., 1989. FIFE: A comparison between aerodynamic surface temperature and radiometric surface temperature over sparse prairie grass. 19th Conf. Agric. For. Meteorol., Charleston, South Carolina, March 1989, pp. 144–146.

Wallace, J.S., Wright, I.R., Stewart, J.B. and Holwill, C.J., 1991. The Sahelian energy balance experiment (SEBEX): ground based measurements and their potential for spatial extrapolation using satellite data. Adv. Space Res., 11(3): 141–191.

Willmott, C.J., 1982. Some comments on the evaluation of model performance. Bull. Am. Meteorol. Soc., 63: 1309–1313.

Reprinted from

AGRICULTURAL AND FOREST METEOROLOGY

An International Journal

Agricultural and Forest Meteorology 68 (1994) 93–105

Determination of sensible heat flux over Sahelian fallow savannah using infra-red thermometry

J.-P. Lhomme*, B. Monteny, A. Chehbouni, D. Troufleau

ORSTOM, Laboratoire de Bioclimatologie, BP 11416, Niamey, Niger

(Received 1 December 1992; revision accepted 14 August 1993)