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Estimation of sensible heat flux over sparsely vegetated surfaces

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Abstract

The approach of using remote sensing of surface temperature to estimate spatially distributed surface energy balance components is very attractive. This approach has been applied successfully over surfaces with near full vegetation cover. However, large discrepancies between measured and simulated surface fluxes have been observed over surfaces with sparse vegetation cover. The reason for these discrepancies is that the assumption that radiative surface temperature can be equated to aerodynamic surface temperature is not correct over sparsely vegetated surfaces. In this study an empirical model, relating radiative–aerodynamic surface temperature difference to radiative–air temperature gradient and leaf area index, was used to estimate sensible heat flux over sparse shrub in the Central East supersite during the Hydrologic and Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) measurement campaign. The result shows that this parameterization leads to reasonable estimates of sensible heat flux; the root mean square error (RMSE) was about 50 W m^{-2}. A second data set over sparse cotton in Arizona had a RMSE of about 20 W m^{-2}. Although the results of this study are encouraging, one should be cautious, however, because there is a need for additional investigation of this procedure.

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1. Introduction

Recently, increased emphasis has been placed on understanding the interaction between regional climate and the hydrological cycle in arid and semi-arid regions (Goutorbe et al., 1993; Kustas et al., 1994). Accurate partitioning of the available energy into sensible and

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latent heat flux is crucial to the understanding of the integrated land-surface processes and the atmospheric boundary layer (ABL) processes. This is very difficult in arid and semi-arid regions because neither the soil nor the vegetation totally dominates the exchange of water and heat with the atmosphere. The relative contributions to total sensible and latent heat flux from the soil and plant components may vary throughout the day and season (Massman, 1992). Consequently, several models, based on the generalization of the single-source approach, have been developed that attempt to estimate surface fluxes from sparsely vegetated areas (Shuttleworth and Wallace, 1985; Choudhury and Monteith, 1988; Van De Griend and Boxel, 1989; Shuttleworth and Gurney, 1990). These models rely on measurements of the surface components temperature, which are not routinely available from remote sensing (Nichols, 1992). The lack of these temperature data may be a major handicap in the application of these models for operational purposes.

Remote sensing of surface temperature (i.e. radiative surface temperature) together with some ground-based data has been widely used in conjunction with simple one-dimensional models to estimate components of the energy balance equation from field to regional scales (Jackson, 1985). This approach has been applied successfully over surfaces with near full vegetation cover. However, large discrepancies between measured and simulated latent and sensible heat flux have been observed over sparsely vegetated surfaces (Kustas, 1990) because radiative surface temperature (T_r) is not equal to aerodynamic surface temperature (T_0). Generally speaking, T_r is a function of the radiative and kinetic temperature of the surface, sensor view angle and surface morphology, while T_0 is a mathematical construct which depends upon the surface radiative and kinetic temperature, and on the thermodynamic properties of the air in contact with the surface (Hall et al., 1992).

Using data taken during the First Internation Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE), Vinning and Blad (1992) investigated whether a particular 'optimal' off-nadir measurement of radiative temperature can allow accurate estimation of aerodynamic temperature. They found that such an optimal angle is unpredictable. This can be expected since changing the sensor view angle will vary the proportion of shaded and illuminated soil and vegetation seen by the sensor (Chehbouni et al., 1994). Consequently, the relationship between the aerodynamic temperature and off-nadir radiative temperature varies with solar and view geometry, soil moisture, wind speed and direction and particularly vegetation cover and structure. This lack of a consistent relationship between aerodynamic temperature and remotely sensed radiative temperature led Hall et al. (1992) to conclude that deriving accurate surface fluxes from thermal infrared data is not feasible. Seguin (1993) suggested that the large discrepancy between observed and simulated surface fluxes could be corrected by a proper assessment of the different exchange mechanisms. A distinction needs to be made between the roughness lengths for heat and momentum. Heat transfer near a surface is controlled primarily by molecular diffusion, whereas momentum transfer takes place as result of both viscous shear and a local pressure gradient (Brutsaert, 1982). This difference results in an additional resistance to heat transfer called excess resistance (or its equivalent form, B^{-1}). Kustas et al. (1989) express empirically the excess resistance (r_s) in terms of air–surface temperature gradient as:

$$r_s = bu_a(T_r - T_a)$$

where u_a is the wind speed, and b is an empirical parameter that was originally set to 0.17 (Kustas et al., 1989) and later on to 0.11 (Kustas et al., 1994; Moran et al., 1994). Using data taken over different sites, Stewart et al. (1994) suggested that it may be possible to define an optimal value of the kB^{-1} that may be valid for all arid and semi-arid regions. Recently Troufleau et al. (1996) investigated this same issue using Hydrologic and Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) data. They reported that for even a given site, the kB^{-1} coefficient can vary during the course of a single day. In a recent theoretical investigation, Lhomme et al. (1996) reported that the excess resistance approach does not appear to be an appropriate tool to estimate sensible heat flux from radiative surface temperature over sparse vegetation.

Recently Chehbouni et al. (1996) investigated numerically the differences between aerodynamic and radiative temperatures for changing surface conditions. This was performed using coupled Soil-Vegetation-Atmosphere-Transfer (SVAT) (multi-layer model) and a vegetation functioning model. The numerical result showed that the ratio of radiative–aerodynamic temperature difference to the radiative–air gradient can be considered as a constant for a given day. However, the seasonal trend of this ratio changes with respect to the leaf area index (LAI). An empirical parameterization was then developed to derive aerodynamic surface temperature from radiative surface temperature, air temperature and the LAI. The objective of this study is to apply this parameterization to real data taken over a fallow savannah site during the HAPEX-Sahel experiment. Additional data taken over a second sparse surface in Arizona will also be used to verify the performance of the approach.

2. Sensible heat flux formulation

Over sparsely vegetated surfaces, sensible heat flux can be formulated in terms of aerodynamic surface temperature as:

$$H=\rho C_p\frac{T_o-T_a}{r_a} \qquad (1)$$

Using a two-layer scheme, sensible heat flux H can be formulated as the sum of the contributions emanating from each layer, i.e. from the foliage (H_f) and from the substrate (H_s) as:

$$H=H_s+H_f=\rho C_p\frac{T_s-T_o}{r_{as}}+\rho C_p\frac{T_f-T_o}{r_{af}} \qquad (2)$$

where ρ is the air density (kg m^{-2}), C_p the specific heat of air at constant pressure (J kg^{-1} K^{-1}). T_a (°C) is the air temperature at a reference height (z) above the surface; T_o (°C) is the aerodynamic surface temperature defined at the mean canopy source height. T_s (°C) is the temperature of the substrate (here grass + soil); T_f (°C) is the temperature of the shrub canopy. r_a (s m^{-1}) is the aerodynamic resistance, calculated between the level of the apparent sink for momentum and the reference height; r_{as} (s m^{-1}) is the substrate resistance and r_{af} (s m^{-1}) is the bulk boundary layer resistance of the shrub canopy per unit ground area. Aerodynamic surface temperature can be expressed by combining Eqs. (1) and (2) as:

$$T_o = \frac{T_a/r_a + T_s/r_{as} + T_f/r_{as}}{1/r_a + 1/r_{af} + 1/r_{as}} \tag{3}$$

The component surface temperatures needed to estimate aerodynamic surface temperature are not available from remote sensing. The measured quantity from a thermal infrared sensor is the radiative surface temperature which represents some kind of weighted average of the temperatures of surface elements. The problem, however, is that over sparsely vegetated surfaces, remotely sensed surface temperature cannot be equated to aerodynamic surface temperature. As reported by Kustas et al. (1989) and Prévot et al. (1994), the difference between the two quantities can reach 10 (°C). Beside the concept of excess resistance which was found to be unreliable, at least for HAPEX-Sahel data (Lhomme et al., 1996; Troufleau et al., 1996), the only possible way to estimate sensible heat flux from radiative surface temperature is to establish a relationship that links aerodynamic and radiative surface temperatures. In this context, sensible heat flux can be written as:

$$H = \rho C_p \beta \frac{T_r - T_a}{r_a} \tag{4}$$

where β is defined as the ratio between the aerodynamic–air temperature and radiative–air temperature gradients:

$$\beta = \frac{T_o - T_a}{T_r - T_a} \tag{5}$$

For values of LAI raging from 0.05 to 1, which is often the case for natural sparse vegetation in arid and semi-arid regions, Chehbouni et al. (1996) have shown that β is constant for a given day but it decreases in a consistent manner with increasing LAI. They developed the following formula between β with LAI

$$\beta = \frac{1}{\exp(L/(L - \mathrm{LAI})) - 1} \tag{6}$$

where L is an empirical factor which may depend on vegetation type and structure. It was set by least squares regression to a value of 1.5 (Chehbouni et al., 1996). It should emphasized, however, that if a difference in sign between $T_r - T_o$ and $T_r - T_a$ exists, this parameterization will not remove it on its own.

2.1. Resistance formulations

The formulations developed by Choudhury and Monteith (1988) have been used to compute canopy and substrate resistances. The bulk boundary-layer resistance for the shrub canopy was defined as:

$$r_{af} = \frac{\alpha_w \sqrt{w/u(h)}}{\{4\,\mathrm{LAI}\alpha_o(1 - \exp(-\alpha_w/2))\}} \tag{7}$$

where $u(h)$ is the wind speed (m s^{-1}) at the shrub canopy height h, obtained from the classical log-profile relationship, w is the shrub mean leaf width (0.02 m), α_w and α_o are two constant coefficients, respectively equal to 2.5 (dimensionless) and 0.005 m s^{-2}. The resistance of the substrate (grass here), which represents the aerodynamic resistance between the source height of the substrate cover ($d_s + z_{os}$) and the source height of the entire canopy (canopy + substrate) ($d + z_o$), was defined from the standard relation between the turbulent transfer coefficient, friction velocity and height as:

$$r_{as} = h\exp(\alpha_w)\left\{\exp\left(\frac{-\alpha_w(d_s+z_{os})}{h}\right) - \exp\left(\frac{-\alpha_w(d+z_o)}{h}\right)\right\}/(\alpha_w K(h)) \tag{8}$$

d and z_o being, respectively, the zero plane displacement height and roughness length of the shrub canopy (defined in relation to the shrub height), and d_s and z_{os} being the same parameters for the grass cover. $K(h)$ is the value of the eddy diffusivity (m^2 s^{-1}) at the shrub canopy height, obtained from its value at the reference height by assuming an exponential extinction with respect to the height (Brutsaert, 1982).

In neutral conditions the aerodynamic resistance above the surface can be formulated as:

$$r_{ao} = \{\ln(z-d)/z_o\}^2/(k^2 u_a) \tag{9}$$

where u_a is the wind speed at the reference height z, k is the Von Karman's constant (0.4); d is the displacement height and z_o is the roughness length for momentum transfer, both defined as a standard function of the canopy height h ($d = 0.56\ h$, $z_o = 0.1\ h$). One should note that there is no need to include the dimensionless bulk parameter kB^{-1} for the r_{ao} expression since a two-layer approach is used to express sensible heat flux and this is assumed to account for the bluff-body effect (Lhomme et al., 1994b). The formulation developed by Choudhury et al. (1986) has been used to perform stability correction as:

$$r_a = \frac{r_{ao}}{(1+\eta)^p} \tag{10}$$

where $p = 0.75$ in unstable conditions (i.e. $T_o - T_a > 0$), and $p = 2$ in stable conditions. η is a stability factor defined as:

$$\eta = \frac{5(z-d)g(T_o-T_a)}{T_a u_a^2} \tag{11}$$

By combining Eqs. (6), () and (9), the factor η can be expressed in terms of radiative surface temperature and β as:

$$\eta = \frac{5(z-d)g\beta(T_r-T_a)}{T_a u_a^2} \tag{12}$$

3. Data used

The international Hydrologic and Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) was held during the rainy season of 1992 in the southwest of Niger (see Goutorbe et al., 1993 for more details). One of the scientific objectives of the experiment was to investigate the effect of changing soil moisture and vegetation conditions on the surface radiation balance, the hydrological cycle and the feedback to the atmosphere.

Data from the fallow savanna sub-site of the Central East supersite were used in this study. The shrubs have a crown height of about 3.5 m and cover about 17% of the surface, the rest of the surface is covered by a sparse herbaceous canopy made up of a mixture of different grass species. The mean grass height varied from about 0.2 m at the beginning of September to about 0.6 in mid-October. The leaf area index of the shrubs was about 0.5 during the entire study period (J.M. d'Herbès, personal communication, 1992).

From September to October 1992, a Bowen ratio–energy balance system, containing one net radiometer (REBS Q6) located at 12 m above the surface and four heat flux plates buried at 3 cm depth were used. Vapor pressure gradients were measured using a Vaisala Hygrometer. The measuring heights were 4.5 and 9 m. Air was drawn by aspirating pumps alternately 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. The temperature of the shrubs was measured using an infrared thermometer (model 4000, Everest Interscience Inc, Tucson, USA) with 15° field of view mounted at 1 m above the shrub so that the surface seen by the sensor was about 0.3 m^2. A similar radiometer was mounted at 9 m above the grass, so that the area of grass and soil seen by the sensor was about 4.4 m^2. All the instruments were sampled at 10-s intervals and logged as 20-min values on a Campbell data acquisition system (see Monteny et al., 1996 for more details). Hourly values of the data taken from 8 a.m. to 6 p.m. were used in the present study.

4. Results

Radiative surface temperature, T_r, was assumed to be represented as an area weighted mean of shrub and grass–soil temperatures (Choudhury et al., 1986; Kalma and Jupp, 1990; Lhomme et al., 1994a-b). For the 7 weeks of the experiment, aerodynamic surface temperature was determined using two different methods: (i) using component surface temperatures and resistances (Eq. (3)), and will be called the computed aerodynamic temperature; (ii) through Eq. (2), using measured sensible heat flux, air temperature and estimating aerodynamic resistance from Eqs. (10) and (11); an iteration is needed since the stability factor (η) depends also on aerodynamic temperature. This temperature will be called the inverted aerodynamic temperature. Fig. 1, presents a comparison between the inverted and the computed aerodynamic surface temperature for the 7 weeks of the field campaign. One can see that aerodynamic surface temperature obtained using Eq. (3) compares fairly well with that obtained by inversion of sensible heat flux measurements. This indicates that sensible heat flux over sparse shrub can be estimated using a two-layer model, which confirms the results obtained by Lhomme et al. (1994b). In Fig. 2 the differences between radiative and inverted aerodynamic temperature are compared with the differences between radiative and air temperature. The difference can exceed 10°C, and the deviation of T_0 from T_r increased linearly as the magnitude of $T_r - T_a$ increased. In spite of some scatter due to the noise associated with the Bowen ratio measurements, there

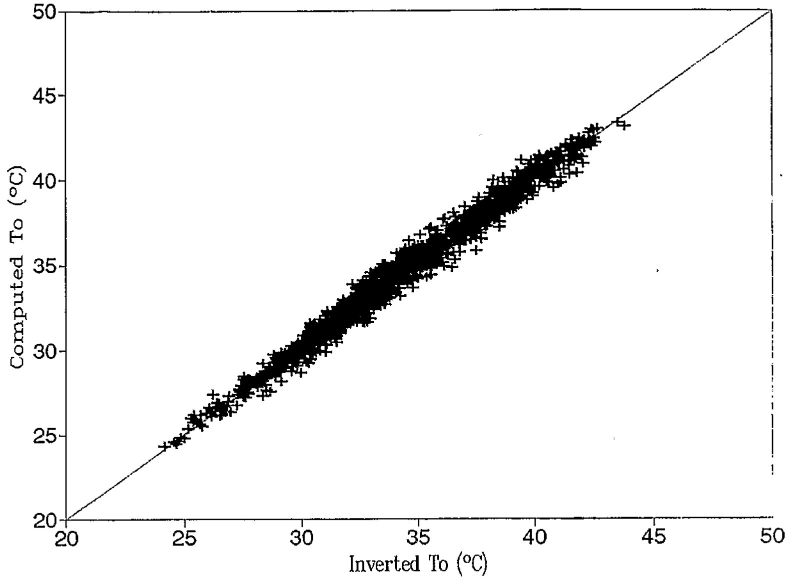

Fig. 1. Cross plot between aerodynamic surface temperature inverted from sensible heat flux measurements and that computed using components surface temperature (Eq. (3)) over sparse shrub in the Central East supersite, during the 7 weeks of the measurements campaign.

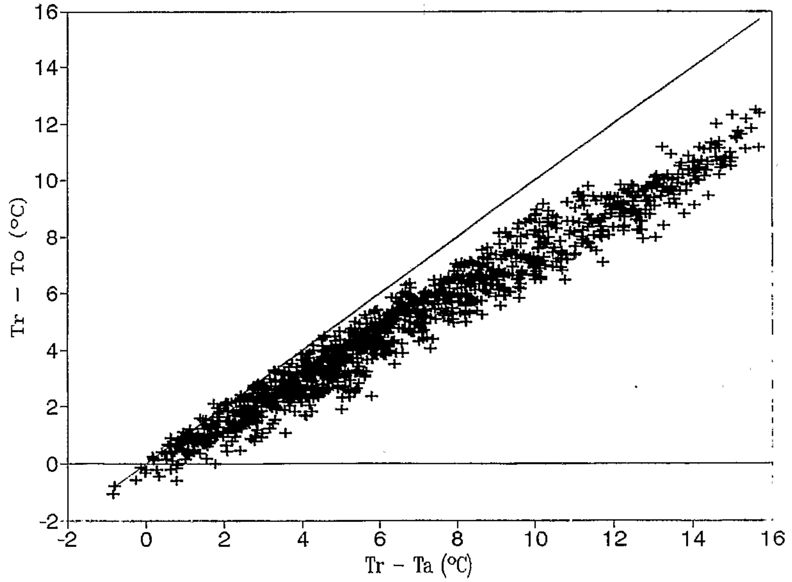

Fig. 2. Comparison between radiative–air temperature differences and radiative–inverted aerodynamic temperature differences over sparse shrub in the Central East supersite, during the 7 weeks of the measurements campaign.

is a clear evidence of the existence of a functional relationship between $T_r - T_0$ and $T_r - T_a$. Kustas (1990) reported that the magnitude of $T_r - T_0$ is directly related to the amount of radiation received by the surface, which mainly depends on solar angles and vegetation characteristics, especially on the LAI of the canopy. The fact that $T_r - T_0$ varies linearly with $T_r - T_a$ throughout the season, may be explained by two considerations: first, the dependence on solar position may be included in the surface–air temperature gradient; second, the LAI of the shrub remained constant during the 7 weeks of the measurement.

The parameterization described in Eq. (6) is used in conjunction with Eq. (5) to estimate aerodynamic temperature during the 7 weeks of the measurements. This temperature will be called the parameterized aerodynamic temperature. The difference between the parameterized and the inverted aerodynamic temperature is presented in Fig. 3. The root mean square error (RMSE) between the two temperatures was about 1.5°C, which can be considered as acceptable considering the range of the errors associated with remote sensing measurement of surface temperature (± 2°C). The parameterized aerodynamic temperature, in conjunction with aerodynamic resistance derived from Eq. (10), was used to compute sensible heat flux. In Fig. 4, the sensible heat flux is compared with that obtained from Bowen ratio measurements, during the entire campaign period. The overall agreement between the model simulations and the field data was generally satisfactory. The average RMSE for the 7 weeks of data was about 50 W m^{-2}, which is very close to the RMSE obtained using the computed aerodynamic temperature (Eq. (3)), i.e. using a two-layer model (Lhomme et al., 1994b).

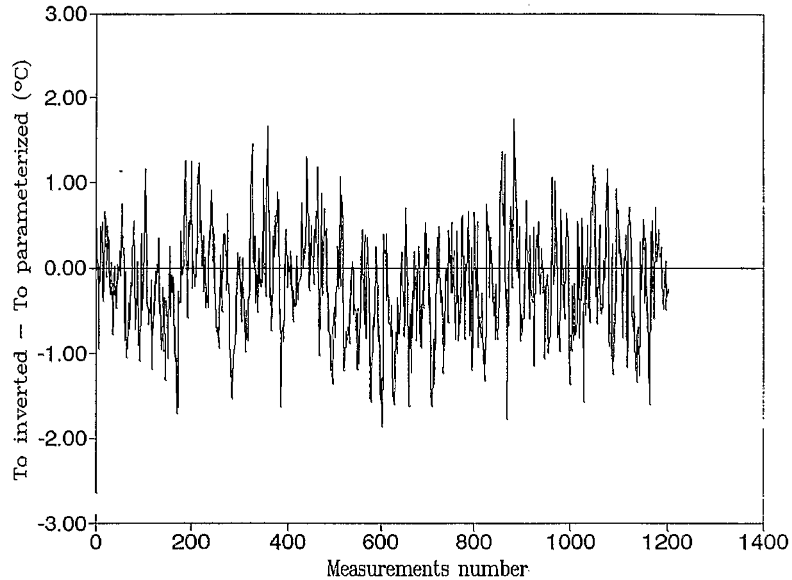

Fig. 3. Difference between the parameterized aerodynamic temperature (Eqs. (5) and (6)) and that inverted from sensible heat flux measurements, during the 7 weeks of the measurements campaign.

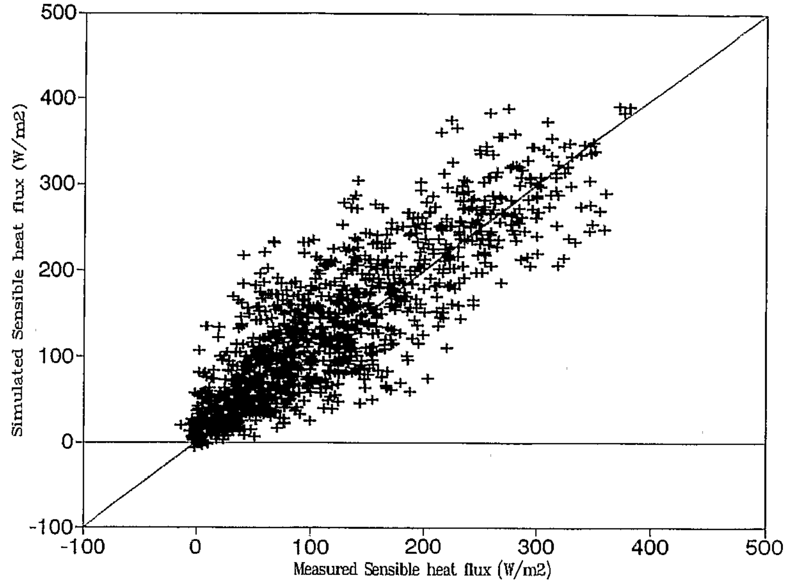

Fig. 4. Comparison between Bowen ratio based sensible heat flux with that simulated using Eq. (4), over sparse shrub in the Central East supersite, during the 7 weeks of the measurements campaign.

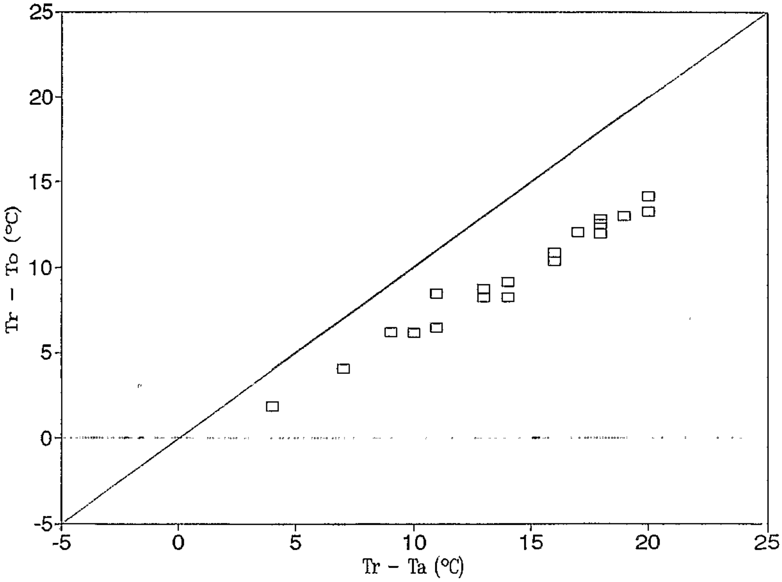

Fig. 5. Differences between radiative and air temperatures compared against the differences between radiative and inverted aerodynamic surface temperature, over sparse cotton in Arizona.

4.1. Application to β expression over agricultural field

To test the applicability of this parameterization to other sparse vegetated surfaces, a data set for a cotton field was used (Kustas, 1990). Cotton covered about 20% of the surface, the leaf area index was about 0.4 and the cotton was 0.3 m height, plants were spaced 1 m apart and the furrow depth was about 0.2 m. A large difference between the temperatures of transpiring cotton and illuminated soil was observed. Surface temperature was measured using an infrared radiometer onboard an aircraft flying at an altitude of 150 m, which corresponds to a pixel size of about 40 m. Profiles of wind speed and temperature were determined at five levels above the surface (i.e. 1.2 m, 1.4 m, 1.8 m, 2.4 m and 3 m). An eddy correlation method was used to obtain latent and sensible heat flux.

Measured sensible heat with air temperature and aerodynamic resistance is used to invert for aerodynamic surface temperature. In Fig. 5, the differences between radiative and inverted aerodynamic temperature are compared with the differences between radiative and air temperature which shows that for this data set also, $T_r - T_0$ varied linearly with respect to $T_r - T_a$. A cross plot between inverted aerodynamic temperature and that obtained by combining Eqs. (5) and (6) is presented in Fig. 6. The RMSE between the two temperatures was about 0.65 (°C). Fig. 7 presents a comparison between measured sensible heat flux and that estimated using Eq. (4) combined with Eqs. (6), () and (10). The average RMSE for the estimated sensible heat flux values was about 18 W m^{-2} for measured values ranging from about 50 to 250 W m^{-2}. These results indicate that the approach developed here may be applicable to other arid and semi-arid surfaces.

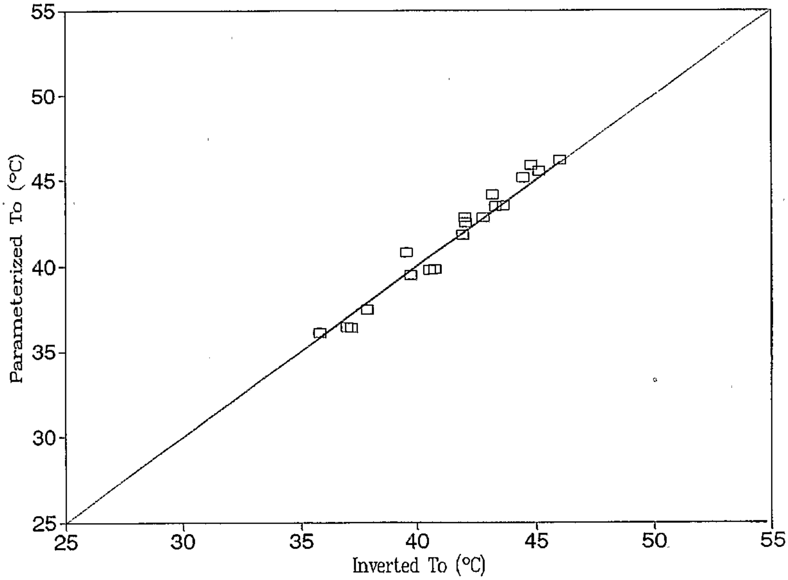

Fig. 6. Cross plot between parameterized aerodynamic surface temperature and inverted aerodynamic surface temperature over sparse cotton in Arizona.

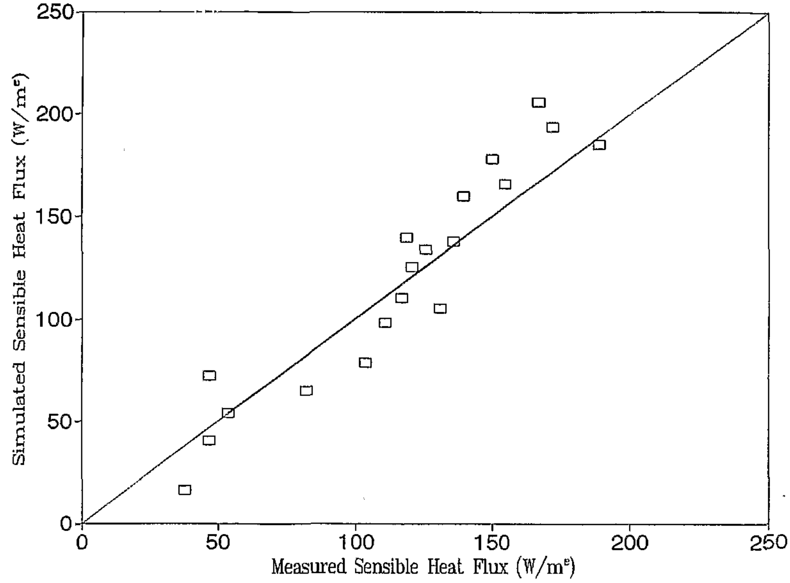

Fig. 7. Comparison between simulated and eddy correlation based sensible heat flux over sparse cotton in Arizona.

5. Discussion and conclusion

The use of remote sensing surface temperature to evaluate the energy balance components over sparsely vegetated surfaces is bound to fail if the difference between radiative and aerodynamic surface temperature is ignored. This difference is due in part to the fact that the resistance to momentum flux is different from that of heat flux. Momentum transfer is by viscous forces as well as pressure forces, while heat transfer is by diffusion only. The analysis performed by Prévot et al. (1994) and Lhomme et al. (1996) showed that the kB^{-1} factor depends on different surface parameters as well as on atmospheric parameters.

Recent studies have shown that the accuracy of using radiative surface temperature to estimate surface energy flux can be greatly improved if an excess resistance is added to the aerodynamic resistance. This resistance was generally expressed in terms of the kB^{-1} factor. The method generally used consists of substituting radiative surface temperature for aerodynamic surface temperature, and adjusting the expression of kB^{-1} to fit sensible heat flux measurements. Beside the fact that such expressions tend to be restricted to the type of conditions for which they were obtained, the problem is that the kB^{-1} factor was never meant to allow the substitution of aerodynamic temperature by radiative surface temperature in sensible heat flux formulation. As pointed out by Troufleau et al. (1996), this parameter was suggested originally to take into account only the fact that the roughness length for heat is lower than that of momentum. In this regard, Norman and Becker (1995) reported that the difficulties encountered with the parameterization of the excess resistance result from the confusion between radiative and convective processes.

In the present study, a parameterization involving the LAI has been used to derive radiative–aerodynamic temperature difference from radiative–air temperature gradient. This approach was motivated by the fact that LAI is a pertinent parameter that plays a key role in the two-layer based scheme, whereas it is not used in one-layer based one. Thus, LAI should be included in any attempt to estimate aerodynamic surface temperature from radiative surface temperature over sparsely vegetated surfaces (Prévot et al., 1994). As reported by Kalma and Jupp (1990), the difference between radiative and aerodynamic surface temperature depends also on atmospheric stability/instability and on solar zenith angle. Since temperature gradient contains information about atmospheric stability and solar angle, the dependence to both factors may be taken into account by considering a relationship between radiative–aerodynamic temperature difference and radiative–air temperature gradient.

At first glance, an equation between T_r, T_0, T_a and LAI seems to have limited application outside the conditions under which it was derived. Nevertheless, this parameterization which was originally developed using only simulated data (Chehbouni et al., 1996), performed correctly in both the HAPEX and Arizona sites. However, additional studies are needed to test the universality of Eq. (6), and to investigate how the L parameter changes with vegetation type and conditions. Finally, the simplicity of this approach combined with the possibilities of using remote sensing to estimate surface temperature and LAI (Asrar et al., 1984) makes it very attractive for operational monitoring of surface fluxes in arid and semi-arid areas.

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