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Relationship between Radiative and Aerodynamic Surface Temperature over sparsely vegetated surfaces: Estimation of sensible heat flux

Chehbouni A.[1], Lo Seen D.[2], Njoku E.G[2],. Lhomme J-P.[1], Monteny B[1], Kerr Y.H[3]

[1]*ORSTOM, Laboratoire d' hydrologie, 911 Avenue Agropolis B.P. 5045, 34032, Montpellier, France;*
Phone (33) 67 61 75 23, Fax (33) 67 61 18 06, Email ghani@orstom.orstom.fr;
[2]*Jet Propulsion Laboratory, California Institute of Technology, USA;* [3]*CESBIO, Toulouse, France*

ABSTRACT

Radiative surface temperature has been widely used in past to estimate surface energy balance components from field to regional scales. 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 assimilated to aerodynamic surface temperature is not correct over sparsely vegetated surfaces. In this study an empirical parameterization relating aerodynamic surface temperature to radiative temperature and the LAI is used to estimate sensible heat flux over sparse shrub in the central east site during the Hapex Sahel experiment. The result shows that this parameterization leads to reasonable estimates of sensible heat flux, the RMSE was about 50 Wm^2.

INTRODUCTION

Remotely sensed surface temperature (i.e. radiative surface temperature) has been widely used in estimating components of the energy balance equation from field to regional scales. The general approach consists of estimating the sensible heat flux and available energy from micrometeorological and visible/thermal infrared remotely sensed data. The latent heat flux is then derived as the residual term of the one-dimensional energy balance equation. This approach has been applied successfully over surfaces with near full vegetation cover; however, large discrepancies between measured and simulated latent heat fluxes have been observed over sparsely vegetated surfaces. The reason for these discrepancies is that over sparsely vegetated surfaces, the assumption that radiative surface temperature (T_r) is not to aerodynamic surface temperature (T_o) is not correct. Generally speaking, T_r is a function of radiative and kinetic temperature of the surface, sensor view angle and surface morphology; while T_O 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. The key question concerns the distinction between the roughness lengths for heat and momentum. This is due to the dissimilarity between heat and momentum transfer mechanisms. 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. This difference results in an additional resistance to heat transfer called excess resistance (or its equivalent form, kB^{-1}). Reference [2] express empirically the excess resistance (r_s) in terms of air-surface temperature gradient as: $r_s = b\ u_a\ (T_r - T_a)$, u_a is the wind speed, and b is an empirical parameter that was originally set to 0.17 and later on to 0.11 [3]. Recently Reference [6] investigate this same issue using data taken during the Hapex Sahel experiment. They reported that for even a given site, the B^{-1} coefficient can vary during the course of a single day. In recent theoretical investigation, Reference [4] reported that the excess resistance approach does not appear to be an appropriate tool to correctly estimate sensible heat flux from radiative surface temperature over sparse vegetation.

In recent numerical study, Chehbouni et al., (1995) (personal communication), investigate the temporal variation of the relationship between radiative and aerodynamic surface temperature. This investigation was performed using a SVAT model coupled to an ecological model (vegetation functioning model). The numerical result showed that the ratio of radiative-aerodynamic temperature gradient to radiative-air one, can be considered as a constant for a given day. However the seasonal trend of this ratio changes with respect to that of the leaf area index (LAI). An empirical parameterization was then developed to formulate aerodynamic surface temperature in terms of radiative surface temperature and LAI. The objective of this study is to apply this parameterization to data taken over fallow Savannah site during the Hapex Sahel experiment.

MODELING APPROACH

Sensible heat over sparsely vegetated surfaces can be formulated using a two layer approach as:

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

where ρ is the air density (kg m^{-2}), c_p the specific heat of air at constant pressure ($JKg^{-1}K^{-1}$), r_a (sm^{-1}) is the aerodynamic resistance, calculated between the level of the apparent sink for momentum and the reference height. T_a (°C) is the air temperature at a reference height (z) above the surface, and T_O (°C) is the aerodynamic surface temperature defined at the mean canopy source height. By assuming that total sensible heat flux is the sum of the contributions of each layer, aerodynamic temperature can be expressed as :

$$T_o = \frac{T_a / r_a + T_s / r_{as} + T_f / r_{af}}{1 / r_a + 1 / r_{as} + 1 / r_{af}} \quad (2)$$

where T_s is the temperature of the substrate (here grass+soil), T_f is the temperature of the shrub canopy. r_{as} is the substrate resistance and r_{af} is the bulk boundary layer resistance of the shrub canopy per unit ground area.

The component surface temperatures needed to express aerodynamic surface temperature are not available from remote sensing. The measured quantity from a TIR sensor is the radiative surface teemperature 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 assimilated to aerodynamic surface temperature. The only possibility to estimate sensible heat flux from radiative surface temperature is to establish a relationship that link aerodynamic to radiative surface temperature. By defining the coefficient β as the ratio between radiative-air temperature gradient and radiative-aerodynamic one, sensible heat flux can be reformulated in terms of a new parameter as:

$$H = \rho C_p \frac{\beta(T_r - T_a)}{r_a} \quad (3)$$

where β is defined as

$$\beta = \frac{T_o - T_a}{T_r - T_a} \quad (4)$$

For values of LAI raging from 0.05 to 1, which is generally the case for natural sparse vegetation in arid and semi-arid regions, our numerical study have shown that β decreases in a consistent manner with increasing LAI (Chehbouni et al., 1995, personal communication). Thus, a working formula was determined by regressing β with LAI which, from the figure shown in the appendix, should be nonlinear. The resulting expression was formulated as:

$$\beta = \frac{1}{\exp(L / (L - LAI)) - 1} \quad (5)$$

where L is an empirical factor which should depend on vegetation type and structure. It was set by least squares regression to a value of 1.5.

DATA USED

Data from the fallow Savannah sub-site in the Hapex-Sahel study [1] area were used in this analysis. 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. From September to October 1992, a Bowen ratio-energy balance system was used to derive surface energy fluxes. The temperature of the shrubs was measured using an infrared thermometer (Everest Interscience IRTs, 15 degrees 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 25 m^2. All the measurements were sampled at 10s intervals and logged as 20 mn values on a Campbell data acquisition system. However, hourly values of the data taken from 8 A.M. to 6 P.M. were used in this study.

RESULTS

In this study radiative surface temperature, T_r, is assumed to be represented as an area weighted mean of shrub and grass temperatures. For the seven weeks of the experiment, aerodynamic surface temperature is determined using two different methods: i) through (2), using component surface temperatures and resistances; ii) through (1), using measured sensible heat flux, air temperature, and estimating aerodynamic resistance, an iteration is needed since r_a depends also on aerodynamic temperature. In Fig. 1, the difference between radiative and air temperature is compared to the difference between radiative and aerodynamic (from (2)) temperature. This figure shows that difference can exceed 10 °C, and the deviation of T_o from T_r grew linearly as the magnitude of T_r -T_a increased. There is, therefore, a clear evidence of the existence of a functional relationship between T_r -T_o and T_r -T_a. Reference [3] reported that the magnitude of T_r -T_o is directly related to the amount of radiation received by the surface, which mainly depend on solar angles and vegetation characteristics, especially the LAI of the canopy. The idea behind relating T_r -T_o directly to T_r -T_a is to decouple the dependence on solar position from that on vegetation status. The fact that T_r -T_o varies, throughout the season, linearly with T_r -T_a may explained by two considerations: first, the dependence on solar position may included in the surface-air temperature gradient;

second, the LAI of the shrub remained constant during the seven weeks of the experiment.

The parameterization described in (5) is used in conjunction with (4) to compute aerodynamic temperature during the seven weeks of the experiment. The parameterized aerodynamic temperature is then used to compute sensible heat flux. In Fig. 2, simulated sensible heat flux is compared to that obtained from bowen ratio measurements, during the entire season. The overall agreement between the model simulations and the field data is generally satisfactory. The average RMSE during the 7 weeks of the experiment was about 50 Wm^{-2}, which is very close to the RMSE obtained using aerodynamic temperature derived from (2).

DISCUSSION AND CONCLUSION

Thermal infrared remotely sensed surface are increasingly being used in operational models to evaluate the spatial variation in the energy balance components. While this approach has been found to be successful over surfaces with near full vegetation cover, its performance has been questioned over sparsely vegetated surface. The problem has been that over partial cover conditions, the assumption that consists on assimilating aerodynamic surface temperature to remotely sensed surface temperature is not correct. In this study, a parameterization involving radiative surface temperature and LAI has been used to estimate aerodynamic surface temperature, and therefore sensible heat flux over sparsely vegetated surfaces. The result showed that this method performed correctly over the fallow Savannah site However Additional studies are needed to test the universality of (5), 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 remotey data to estimate surface temperature and LAI, makes this approach very attractive for operational monitoring of surface fluxes in arid and semi-arid areas.

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Appendix:Simulation of seasonal variation of β coefficient with respect to LAI

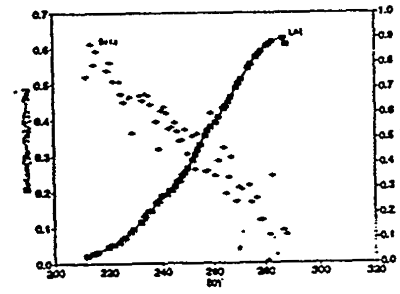


Figure 1: Cross plot between radiative-air temperature differences with radiative-aerodynamic ones

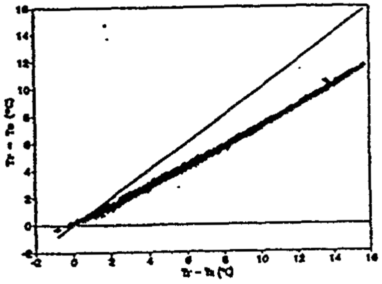
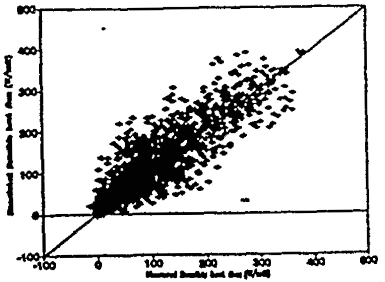


Figure 2: Comparison between measured and simulated sensible heat flux over thefallow savannah site.



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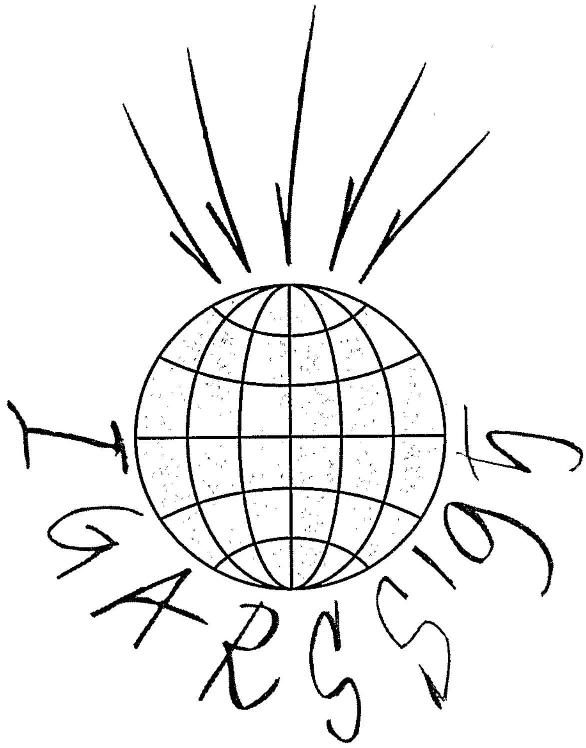

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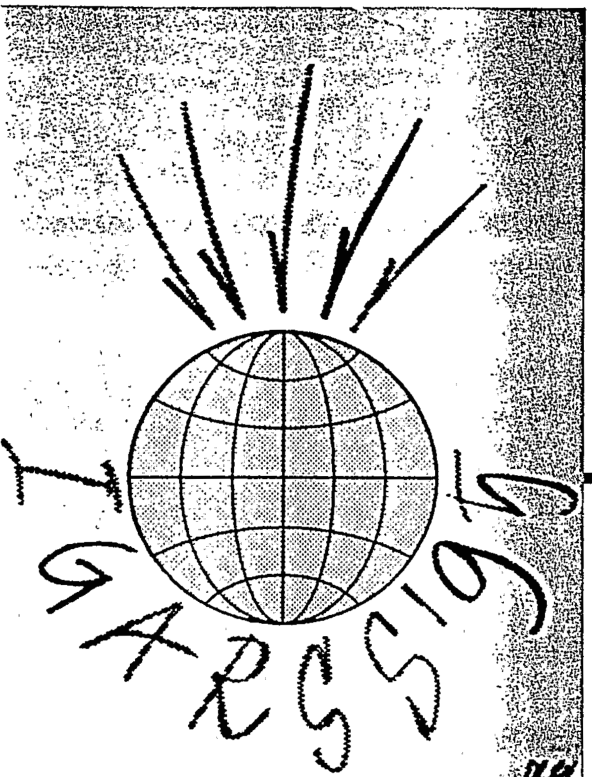

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