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USING THERMAL INFRARED TEMPERATURE OVER SPARSE SEMI-ARID VEGETATION FOR SENSIBLE HEAT FLUX ESTIMATION.

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ABSTRACT

To estimate sensible heat flux using thermal infra-red temperature T_r over sparse semi-arid vegetation, acknowledge of either the corrective term kB^{-1} or the difference between radiometric and aerodynamic surface temperatures T_r-T_o is usually required. Several experimental data sets acquired over various sparse vegetation in semi-arid areas (fallow savannah and millet field of HAPEX-Sahel, grassland and shrubland of MONSOON' 90) were used here to study the experimental behavior of these variables. When considering the extreme variability of kB^{-1} and the difficulty in predicting its value, the relationship between T_r and T_o was more thoroughly studied and parameterized using the conceptual two-layer model of Shuttleworth & Wallace [7].

INTRODUCTION

The available energy at the soil-vegetation-atmosphere interface is basically converted into sensible and latent heat. Knowing the exact partition between both fluxes is a key component of hydrological, climatological and agricultural studies, from simple evapotranspiration estimation used in water and energy budget studies to more complex applications related to surface water stress (irrigation management, primary production, fire risk monitoring).

To this end, spatially distributed data are of great interest and thermal infrared surface temperature T_r obtained from spaceborne radiometers was widely used in the past years to estimate sensible heat flux H over various surfaces. Actually, H is theoretically related to the gradient of temperature between the surface (T_o) and the atmosphere (T_a) divided by an aerodynamic resistance. It is generally assumed that T_r can be used instead of T_o provided that an excess resistance is used [1], this correction being commonly expressed as a function of the dimensionless parameter kB^{-1}. However, most of the studies performed until now over sparse semi-arid vegetation do not agree on its value [2] [3] and, although some theoretical studies have been developed [4], its determinism is not yet well known.

The aim of this paper is to study the experimental behavior of kB^{-1} and of the difference T_r-T_o over two different semi-arid ecosystems. Then, the potential use of the conceptual two-layer model [7] to predict this behavior will be investigated.

THEORETICAL BASIS

The kB^{-1} parameter: The classical expression employed to express the sensible heat flux is:

$$H = \rho c_p \frac{T_o - T_a}{r_a} \quad \text{with} \quad r_a = \frac{\ln\left[(z_r - d)/z_o\right]}{ku_*} \tag{1}$$

where r_a is aerodynamic resistance calculated in neutral conditions, k the von Karman constant (0.4) u_* the friction velocity, z_r the reference height, d the displacement height, z_o the roughness length for momentum transfer and T_o the aerodynamic temperature measured at level $d+z_o$. As T_o is *a priori* not equal to T_r, (1) is generally updated to use thermal infra-red temperature:

$$H = \rho c_p \frac{T_r - T_a}{r_{ah}} \quad \text{with} \quad r_{ah} = \frac{\ln\left[(z_r - d)/z'_o\right]}{ku_*} = r_a + \frac{B^{-1}}{u_*} \tag{2}$$

B^{-1} is a dimensionless parameter defined as $kB^{-1}=\ln(z_o/z'_o)$. The roughness length for heat transfer z'_o is rigorously introduced to define a source of sensible heat located at level $d+z'_o$ and associated to a temperature T'_o [1]. Nevertheless, considering the difficulty to assess z'_o and T'_o, z'_o is generally considered as an adjustment parameter allowing the use of T_r such as in (2) [8].

In the case of dense and homogeneous crops, a kB^{-1} around 2 was found to give satisfactory results [1] but its value appears to be much more variable over sparse and/or heterogeneous vegetation, typically ranging from 1 to 12 [6][7].

Modeling approach: Experimental T_o and kB^{-1} values can be obtained when H, T_r, wind speed, air temperature and aerodynamic properties of the surface are known by inverting (1) and (2) respectively. Nevertheless, to study the sensitivity of T_o and kB^{-1} over a wide range of vegetation and climatic conditions, a two-layer model [7] was used to simulate H values in various conditions, since this model has shown to be well suited to sparse vegetation [9]. H is given by:

$$H = \rho c_p \frac{(T_s - T_a)/r_{as} + (T_f - T_a)/r_{af}}{1 + r_a/r_{as} + r_a/r_{af}} \tag{3}$$

where r_{as} is the aerodynamic resistance between the substrate and the canopy source height, r_{af} the bulk boundary resistance of the foliage. T_s and T_f are the substrate and foliage temperatures calculated in the model through energy balance equation as function of global radiation, surface resistance to evaporation from the substrate and stomatal resistance from the vegetation. Then, simulated values of T_o are given by inversion of (1) and simulated values of kB^{-1} are given by inversion of (2) assuming that $T_r = fT_f + (1-f)T_s$ where f is the vegetation fraction cover.

Estimating the resistance and aerodynamic parameters: To account for unstability effects which cannot be neglected in semi-arid regions, r_a (or r_{ah}) and u_* were estimated with the integral diabatic correction function ψ_m and ψ_h using an iterative procedure. The aerodynamic properties of the surface (d and z_o) were computed according to Choudhury and Monteith [10] as functions of leaf area index (*LAI*) to account for the sparseness of vegetation.

EXPERIMENTAL DATA

Two data sets concerning five different sites were used in this work. The first concerns the HAPEX-Sahel experiment held in 1992 in Niger [5] from which two sites were used: the fallow savannah site (named here JAC92) and the millet site (MIL92). Additional data were available for 1991 season over a millet site (MIL91). The second data set comes from the MONSOON' 90 experiment [6] held in 1990 in the Walnut Gulch watershed in Arizona. Two sites were used here, namely Lucky Hills (LH90) and Kendall (KD90). Main vegetation characteristics are summarized in *Tab.1*.

Tab.1: *surface characteristics and main results obtained for each site. Concerning MIL92 & MIL91, vegetation characteristics are mean value over the observation period. se stands for standard error of estimated T_r-T_o. RMSE is root mean square error of estimated H using (a) optimal kB^{-1} value with equation (2), (b) experimental α using equation (4) and (c) simulated α using equation (4). All other notations are defined in the text.*

	JAC92	MIL92	MIL91	LH90	KD90
vegetation description:	shrub+ grass	millet	millet	bush+g rass	grass
h (m)	3.5	1.88	1.84	0.27	0.10
LAI (m^2/m^2)	0.50	1.69	2.17	0.50	0.50
f	0.17	0.38	0.25	0.28	0.44
nb of samples	1229	1011	648	23	35
observation period (day of year)	244-292	237-292	168-243	212-221	212-222
optimal kB^{-1}	7.9	5.1	10.2	3.3	3.0
RMSE(*a*) (W/m^2)	43	48	67	47	52
experimental α	0.76	0.67	0.79	0.59	0.40
se (° C)	0.51	0.68	0.75	1.28	2.26
RMSE(*b*) (W/m^2)	36	45	64	42	50
simulated α	0.76	0.65	0.69	0.57	0.45
se (° C)	0.25	0.51	0.57	0.38	0.40
RMSE(*c*) (W/m^2)	36	46	111	41	50

RESULTS

The experimental kB^{-1} and T_o behavior: For each site, the optimal kB^{-1} was defined as the value which gives the lower RMSE between observed and estimated *H* by means of (2). Values reported in *Tab.1* show that kB^{-1} is quite variable between sites but these values remains in the range previously observed over semi-arid areas [6][7]. However, even for a given site, instantaneous values of kB^{-1} (i.e. values obtained for each sample) are highly variable with climatic conditions (*Fig.1*) and can range from 0 to more than 20.

On the other hand, the variability of T_o obtained from (1) was studied and the difference T_r-T_o appeared well correlated to the difference T_r-T_a (*Fig.2-a*). The parameters of the linear regressions, especially the slope of the regression line α, are given in *Tab.1*. Knowing α for each site allows then the use of (1) where the difference T_r-T_o has been made apparent:

$$H = \rho c_p \frac{T_r - T_a - (T_r - T_o)}{r_a} = \rho c_p \frac{(1-\alpha)(T_r - T_a)}{r_a} \quad (4)$$

Thus the term (1-α) appears as a multiplicative corrective factor of the temperature gradient T_r-T_a. When α is close to 0 no correction needs to be applied to (1) to use T_r instead of T_o, then T_r-T_a is all the more decreased as α increases.

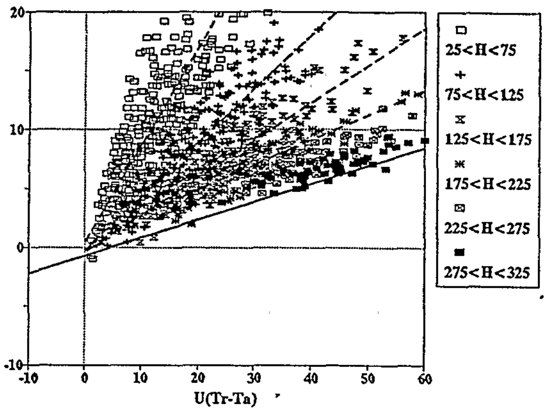

Fig.1: *instantaneous values of kB^{-1} obtained for JAC92 from equation (2) as a function of $u(T_r$-$T_a)$ and H. The relationship proposed in [3] kB^{-1}=0.17u(Tr-Ta) is shown as a solid line and regression lines for each H class values are shown in dashed lines.*

Predicting the α value: The two-layer model was recently used to study the determinism of the kB^{-1} parameter [11] and showed that this parameter was highly sensitive to structural characteristics of the vegetation but also to the level of water stress and climatic conditions, which confirms our experimental results. The same kind of work was conducted here to theoretically study the relation between T_r-T_o and T_r-T_a and particularly *i)* to verify that 2-layer model confirms the linear relationship between T_r-T_o and T_r-T_a and *ii)* to study how the slope of the regression line is dependent on the parameters and variables used in the model.

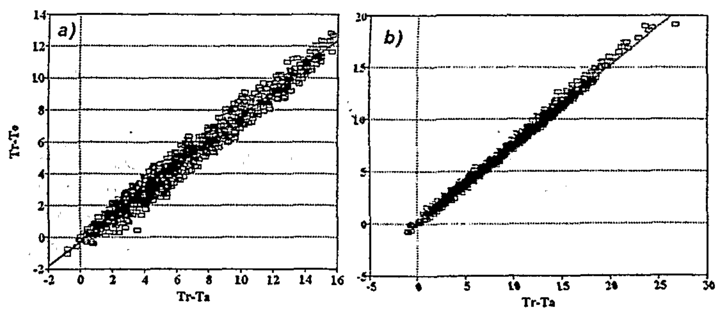

Fig.2: *linear relationship between T_r-T_o and T_r-T_a for JAC92 obtained with a) experimental data and b) simulated data.*

The quality of the regressions obtained for a given site between observed T_r-T_o and T_r-T_a over the whole observation period leads to the conclusion that the slope of the regression line α only depends on structural parameters of the vegetation and that surface water stress and climatic conditions only are responsible for the variability of T_r-T_o and for the residual dispersion. To confirm this assumption, we generate an input data set made of random values attributed to the climatic and water stress variables of the model. In fact, a sensitivity analysis allow us to retain only five main "driving" variables. A data set of 1000 samples was then generated with values randomly chosen in a range representative of each variable: wind speed [1-7 m.s-1], Ta [20-40°C], global radiation [200-1000 W.m-2], air vapour pressure deficit [500-3000 mb] and surface soil resistance to evaporation [0-4000 s.m-1]. *H*, T_o and T_r were finally simulated over the whole data set and the regression parameters of T_r-T_o against T_r-T_a were computed for a variety of vegetation conditions.

Fig.2-b shows the results obtained in the case of JAC92 vegetation characteristics. The simulated relationship between T_r-T_o and T_r-T_a is in perfect agreement with experimental data, considering either the linear shape of the relationship and the value of the slope α of the regression line. Nevertheless, the simulated α is sometime slightly different from the experimental one *(Tab.1)* but they both follow the same tendency *(Fig.3)*.

Fig.4 gives an example of the simulated variations of α with *LAI* and *f*. Further studies are now needed to propose a simple way to parameterize the curves displayed but a few comments can already be made. First, the simulations confirm that in case of bare soil T_o must be very close to T_r (α≈0). Then α rapidly increases as the soil surface is covered by vegetation, α being higher in case of low vegetation cover for a given *LAI*. Finally α approaches a stable value between 0.2 and 0.3 for high *LAI* whatever the vegetation cover. This result must be compared to the constant kB^{-1} around 2 found for dense canopy.

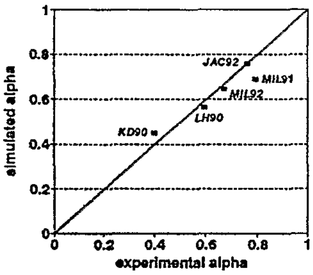

Fig.3: simulated versus experimental α values.

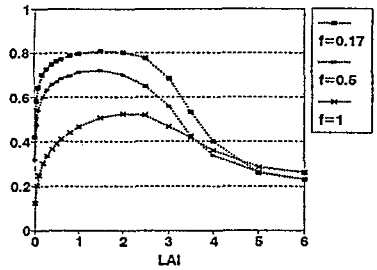

Fig.4: simulated sensitivity of α to LAI and fraction cover f

CONCLUSION

The work presented here proposed a way to estimate sensible heat flux *H* from thermal infra-red temperature independent of the classical kB^{-1} correction. Actually, this parameter appears fairly variable over sparse semi-arid vegetation, depending on vegetation characteristics but also climatic variables. On the other hand, estimating T_r-T_o as a simple linear function of T_r-T_a appeared to give as accurate estimation of *H* as the kB^{-1} method (RMSE*(a)&(b) Tab.1)* without any dependence on climatic or water stress conditions. This accuracy was even shown to be significantly improved if a two-parameters (slope and intercept) affine function was used [8]. Furthermore, two-layer model reproduced quite well experimental results and can be used to estimate the slope α for a given site as well as to study the sensitivity of α to vegetation characteristics. Future work will try to validate this approach over other sites and to propose a simple parameterization of α as a function of *LAI* and *f*.

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