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

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THEORETICAL BASIS

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

$$H = \frac{\rho c_p}{r_a} \frac{T_o - T_a}{T_r} \ln \left( \frac{z_r - d}{z_o} \right)$$

(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 $d+z_o$. $T_o$ is a priori not equal to $T_r$, (1) is generally updated to use thermal infra-red temperature:

$$H = \frac{\rho c_p}{r_a} \frac{T_r - T_a}{r_{ah}} \ln \left( \frac{z_r - d}{z_o'} \right) = r_a + \frac{B^{-1}}{u_*}$$

(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:

$$H = \frac{(T_s - T_o)/r_{as} + (T_r - T_o)/r_{af}}{1 + r_{as}/r_{af} + r_a/\rho c_p}$$

(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. $T_r$ and $T_s$ 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 $T_0$ are given by inversion of (1) and simulated values of $k_B^{-1}$ are given by inversion of (2) assuming that $T_r=f(T_r+u(1-f)T_o)$ 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 $v_m$ and $v_h$ using an iterative procedure. The aerodynamic properties of the surface ($d$ and $z_0$) 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 consisting 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. $s$ std stands for standard error of estimated $T_r-T_o$. RMSE is root mean square error of estimated $H$ using (a) optimal $k_B^{-1}$ value with equation (2), (b) experimental $\alpha$ using equation (4) and (c) simulated $\alpha$ using equation (4). All other notations are defined in the text.

<table>
<thead>
<tr>
<th>JAC92</th>
<th>MIL92</th>
<th>MIL91</th>
<th>LH90</th>
<th>KD90</th>
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<tr>
<td>vegetation</td>
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<td>millet</td>
<td>millet</td>
<td>grass</td>
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<tr>
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<td>ras</td>
<td>ras</td>
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<td>1.88</td>
<td>1.84</td>
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<td>LAI (m²/m²)</td>
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<td>1.60</td>
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<tr>
<td>$f$</td>
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<td>0.25</td>
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<td>1011</td>
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<tr>
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<td>168-222</td>
<td>212-221</td>
<td>212-222</td>
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<tr>
<td>(day of year)</td>
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<td>292</td>
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<td>222</td>
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<td>48</td>
<td>67</td>
<td>47</td>
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<tr>
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<td>0.67</td>
<td>0.79</td>
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<tr>
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<td>0.75</td>
<td>1.28</td>
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<td>0.69</td>
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<tr>
<td>$se$ (°C)</td>
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<td>0.51</td>
<td>0.57</td>
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<tr>
<td>RMSE(c) (W/m²)</td>
<td>36</td>
<td>46</td>
<td>111</td>
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**RESULTS**

*The experimental $k_B^{-1}$ and $T_0$ behavior:* For each site, the optimal $k_B^{-1}$ 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 $k_B^{-1}$ 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 $k_B^{-1}$ (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 $T_0$ 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 $\alpha$, are given in Tab.1. Knowing $\alpha$ for each site allows then the use of (1) where the difference $T_r-T_o$ has been made apparent:

$$H = \rho c_p \left( T_r - T_a - (T_r - T_o) - \alpha (T_r - T_a) \right)$$

Thus the term $(1-\alpha)$ appears as a multiplicative corrective factor of the temperature gradient $T_r-T_a$. When $\alpha$ 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 $\alpha$ increases.

**Fig.1:** instantaneous values of $k_B^{-1}$ obtained for JAC92 from equation (2) as a function of $u(T_r-T_o)$ and $H$. The relationship proposed in [3] $k_B^{-1}=0.1u(T_r-T_o)$ is shown as a solid line and regression lines for each $H$ class values are shown in dashed lines.

**Predicting the $\alpha$ value:** The two-layer model was recently used to study the determinism of the $k_B^{-1}$ 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 $T_r-T_a$ and $T_r-T_a$ over the whole observation period leads to the conclusion that the slope of the regression line $\alpha$ only depends on structural parameters of the vegetation and that surface water stress and climatic conditions only are responsible for the variability of $T_r-T_a$ 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$^{-1}$], $T_a$ [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 $\alpha$ of the regression line. Nevertheless, the simulated $\alpha$ is sometimes 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 $\alpha$ 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 $T_r$ ( $\alpha$=0). Then $\alpha$ rapidly increases as the soil surface is covered by vegetation, $\alpha$ being higher in case of low vegetation cover for a given LAI. Finally $\alpha$ 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 $k^B$ around 2 found for dense canopy.

CONCLUSION

The work presented here proposed a way to estimate sensible heat flux $H$ from thermal infra-red temperature independent of the classical $k^B$ 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 $k^B$ method (RMSE(a)&(b) Tab.I) 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 $\alpha$ for a given site as well as to study the sensitivity of $\alpha$ to vegetation characteristics. Future work will try to validate this approach over other sites and to propose a simple parameterization of $\alpha$ as a function of LAI and $f$.

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