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ABSTRACT

Single-source energy balance models are simple and particularly suited to assimilate mixed pixel remote sensing data. Mixed pixels are made up of a combination of two main elements, the soil and the vegetation. The use of single-source models implies that the reference temperature for the estimation of convective fluxes, the aerodynamic temperature, is linked to the available remotely sensed surface temperature. There are many relationships relating both temperatures in the literature, but few that try to find objective constraints on this link. These relationships account for the difference between both temperatures by dividing the roughness length for thermal turbulent transport by an expression known as "radiometric kB^{-1}", which depends mostly on Leaf Area Index (LAI). Acknowledging that the two temperatures should be similar for bare soil and high LAI conditions, we propose an empirical relationship between LAI and the ratio of the difference between the aerodynamic and the air temperatures and the difference between the surface and the air temperatures, also known as "β function". Nine datasets obtained in agricultural areas (four in south western France near Toulouse, four in south eastern France near Avignon, one in Morocco near

Marrakech) are used to evaluate this new relationship. They all span the entire cropping season, and LAI values range from 0 to about 5. This new expression of the β function is then compared to the β function retrieved from measured sensible heat flux and in-situ radiometric measurements as well as the β function simulated by a two-source SVAT model (ICARE). Its performance in estimating the sensible heat compares well to other empirical or semi-empirical functions, either based on a β function or a radiometric kB^{-1}.

1. INTRODUCTION

Assessing the turbulent fluxes of latent and sensible heat at the land surface is a crucial issue for both water resource management (computation of evapotranspiration) and meteorological forecasting (evolution of the planetary boundary layer). In order to compute these fluxes at a suitable spatial scale, estimation methods based on the use of remote sensing data are favoured. There is a large array of evapotranspiration estimation methods that use as input or constraint remotely sensed variables such as the NDVI (Courault et al., 2005; Gowda et al., 2008; Olioso et al., 2005). Evapotranspiration in potential conditions (i.e. not water limited) can be assessed with relatively good precision from in-situ (Cleugh et al., 2007) or remote sensing derived (Venturini et al., 2008) meteorological data, and, very often, NDVI. But when water stress occurs the latent and sensible heat fluxes are more difficult to assess. In those cases, there is a tight coupling between the evapotranspiration and the radiative surface temperature and, consequently, methods based on remote sensing data in the Thermal Infra Red (TIR) domain are favoured (Kalma et al., 2008). Those methods often compute the instantaneous latent heat flux as the residual of the energy budget and, in most cases, an expression of each individual term of the energy budget is proposed (Boulet et al., 2007):

$$Rn - G = H + LE \qquad (1)$$

While net radiation Rn and, to a lesser extent, soil heat flux G can be expressed directly as a function of the radiative surface temperature, the turbulent fluxes H (sensible heat) and LE (latent heat) depend on a mixed-surface (soil, air and vegetation) temperature source T_{aero}:

$$H = \rho c_p \frac{T_{aero} - T_{air}}{r_{a,h}} \qquad (2)$$

where ρ is the air density, c_p the specific heat of air at constant pressure, T_{air} is the air temperature at a reference level above the canopy and $r_{a,h}$ the aerodynamic resistance for heat exchange. The temperature T_{aero} called aerodynamic temperature represents the average temperature of the air in the vicinity of the vegetation elements within the canopy, at the height of the aerodynamic level (defined as the sum of the displacement height and the roughness length for momentum). There is no measuring device for this temperature, which is usually inverted from turbulent flux measurements. Moreover, it can be significantly different from the ensemble directional radiometric surface temperature T_{surf} (as defined by Norman and Becker, 1995) which is usually derived from brightness temperature measurements made by a thermo-radiometer or infrared thermometer at nadir or at a specific view angle (Kustas and Anderson, 2009; Kustas et al., 2007; Stewart et al., 1994) and which is used to assess energy balance from remote sensing data. In general, the relationship between aerodynamic and surface temperatures is obtained through the use of a dual-source energy balance when either the vegetation or the soil bulk skin temperatures are known (Lhomme et al., 2000). Retrieving surface temperature for each of the different components of the surface (mostly soil and plants) is difficult, especially with current remote sensing platforms (Jia et al., 2003). The use of single-source models is therefore favoured over dual-source models to estimate pixel average turbulent fluxes from a mixed-pixel radiometric temperature. For those models, there is a need to develop robust yet simple methods to relate the aerodynamic temperature to the surface temperature. This has been subject of debate for a long time (e.g. see Carlson et al., 1995; Kalma and Jupp, 1990). Many formulations exist in the literature, and a comprehensive terminology and conversion formulae are proposed by Matsushima (2005). Historically, most expressions governing the relationship between the aerodynamic and the surface temperatures have been built on an analogy between wind and temperature profiles within the canopy. However, while the bottom boundary condition for wind (a null value at the height of the aerodynamic level) allows defining a roughness length for momentum exchange (z_{om}), the bottom value of the temperature profile, the aerodynamic temperature, is generally unknown. One assumes usually that a roughness length z_{or} (improperly named roughness length for thermal exchange) can be defined so that, at a height corresponding to the displacement height plus z_{or}, the surface temperature of the vegetation can be considered as representative of the aerodynamic temperature. The relationship between both roughness lengths translates into what Matsushima names the "radiometric kB^{-1}" (kB^{-1}_{radio}) which is written as $z_{or} = z_{om} \big/ e^{kB^{-1}_{radio}}$. In that case, the difference between the aerodynamic temperature and the surface temperature in the sensible heat flux formulation is expressed by an additional resistance (Lhomme et al., 1997):

$$H = \rho c_p \frac{T_{surf} - T_{air}}{r_{a,hm} + \dfrac{kB^{-1}_{radio}}{ku_*}} \Leftrightarrow H = \frac{\rho c_p k u_* \left(T_{surf} - T_{air}\right)}{\ln\left(\dfrac{z-d}{z_{or}}\right) - \Psi_h\left(\dfrac{z-d}{L}\right) + \Psi_h\left(\dfrac{z_{or}}{L}\right)} \tag{3}$$

where $r_{a,hm} = \left[\ln\left(\dfrac{z-d}{z_{om}}\right) - \Psi_h\left(\dfrac{z-d}{L}\right) + \Psi_h\left(\dfrac{z_{om}}{L}\right)\right] \Big/ ku_*$ is the aerodynamic resistance for heat exchange before kB^{-1} correction, u_* the friction velocity, k the von Karman constant, z the measurement height of the atmospheric forcing, d the displacement height, L the Monin Obhukhov length and ψ_h the stability correction function for heat transfer given by Paulson (1970). kB^{-1}_{radio} is derived according to the expected air temperature profile within the canopy and expressed as a function of meteorological data, *LAI* and plant height. Amongst the well known formulae, one can cite those from Blümel (Blümel, 1998), Massman (Massman, 1999 revisited by Su et al., 2001) and Lhomme (Lhomme et al., 2000).

Other authors have proposed a somewhat simpler, and easier to interpret, formulation of the relationship between T_{surf} and T_{aero}, called the "β function", originally proposed by Chehbouni et al. (1997). β is expressed solely in terms of the temperatures, independently from wind speed:

$$H = \rho c_p \beta \frac{T_{surf} - T_{air}}{r_{a,h}} \tag{4}$$

i.e.

$$\beta = \frac{T_{aero} - T_{air}}{T_{surf} - T_{air}} \tag{5}$$

Even for isothermal surfaces, usually bare soils or very dense canopies, the aerodynamic temperature can be slightly different from the surface temperature, because the diffusion process for heat transfer adds to the convective exchange of air. There is therefore a difference between the effective eddy diffusivities for momentum and heat exchange, which can be again translated into an excess resistance function of an "aerodynamic kB^{-1}" or kB^{-1}_{aero}. The available kB^{-1} formulae, derived either empirically or from scalar and flux theoretical profiles in the canopy, account for both aspects: the difference between the aerodynamic and the radiometric temperatures (radiometric kB^{-1}) and the difference between momentum and heat exchange diffusion processes (aerodynamic kB^{-1}). For isothermal surfaces, one can expect that there is no radiometric component within the combined (radiometric and aerodynamic) kB^{-1}. The combined kB^{-1} retrieved for those surfaces from observations by solving for kB^{-1}_{radio} in Eq. 3 is fairly low (within the range 0-5 according to Verhoef et al. 1997, Massman 1999 and Yang et al., 2008). For strongly non-isothermal situations, which correspond in general to intermediate *LAI* values (LAI in the range 0.5-2), the combined kB^{-1} is much higher (in the range 10-30 according to the same authors). One can thus assume that kB^{-1}_{aero} is usually smaller than kB^{-1}_{radio} for all LAI values, or that the difference between the surface temperature and the aerodynamic temperature will have on average a much larger impact on the sensible heat flux than the difference between the diffusion processes for heat and momentum at the vicinity of the canopy. While the radiometric kB^{-1} do not discriminate between both differences (the difference between the aerodynamic and surface temperatures and the difference between the roughness lengths for momentum z_{om} and heat exchange z_{oh}), the β function allows us to separate both aspects and keep the difference between z_{oh} and z_{om} in the formulation of the aerodynamic resistance : $z_{oh} = z_{om} / e^{kB^{-1}_{aero}}$ and $r_{a,h} = r_{a,hm} + kB^{-1}_{aero} / ku_*$. Consequently, Eq. 4 can be rewritten as:

$$H = \rho c_p \beta \frac{T_{surf} - T_{air}}{r_{a,hm} + \frac{kB^{-1}_{aero}}{ku_*}} \Leftrightarrow H = \frac{\rho c_p \beta k u_* \left(T_{surf} - T_{air}\right)}{\ln\left(\frac{z-d}{z_{oh}}\right) - \Psi_h\left(\frac{z-d}{L}\right) + \Psi_h\left(\frac{z_{oh}}{L}\right)} \qquad (6)$$

One must also note that the published values of the radiometric kB^{-1} (kB^{-1}_{radio}) (Matsushima, 2005) according to Lhomme, Blümel and Massman/Su (see formulations in Table 1) can be converted into β values by combining equations 3 and 6:

$$\beta = \frac{r_{a,hm} + \frac{kB^{-1}_{aero}}{ku_*}}{r_{a,hm} + \frac{kB^{-1}_{radio}}{ku_*}} \qquad (7)$$

The Blümel and Massman/Su formulations depend on Leaf Area Index *LAI* through, mostly, the fraction cover (f_c) of the canopy and on two parameters difficult to assess, the component aerodynamic kB^{-1} for bare soil and for vegetation canopy, respectively (See Table 1). Since for bare soil and full cover conditions there is no large difference between both temperatures, the β function is fairly easily interpreted: β values are close to 1 for those bare soil and full cover conditions, that is, more generally, for all homogeneous isothermal surfaces, while for sparse vegetation β decreases. In those conditions, the soil temperature has a large impact on the radiative surface temperature whereas the aerodynamic temperature remains closer to a mix of air and vegetation temperatures and is less influenced by the soil temperature. Since the soil temperature around midday is generally higher than the vegetation temperature, the observed radiative surface temperature is often larger than the aerodynamic temperature around that time. Factors influencing β and $kB^{-1}{}_{radio}$ include LAI and other plant geometrical features such as height and fraction cover, friction velocity, time of the day, solar radiation etc. However, most studies agree on the fact that LAI is by far the main driving factor, at least for agricultural canopies for which the turbid medium (random leaf dispersion, Myneni et al., 1989) and permeable-rough transfer hypotheses are valid (Kustas et al., 2007; Verhoef, 1997). This is further confirmed by dual-source land surface models which predict the aerodynamic temperature through the classical dual-source approach (Shuttleworth and Wallace, 1985). The evolution of β as a function of *LAI* is presented in Figure 1a as obtained from an uncalibrated run of the ICARE SVAT model (Gentine et al., 2007) for the B124 wheat site in Morocco (see below). One can observe that the simulated shape of the $\beta(LAI)$ relationship decreases sharply from 1 when LAI increase to about 1, and increases more slowly for higher LAI, tending again to 1 for LAI well above 3. The lognormal distribution function is therefore a good candidate to represent the evolution of $1-\beta(LAI)$ for the whole range of LAI values. Consequently, we propose the following empirical relationship for β:

$$\beta = 1 - \frac{a}{LAI * b * \sqrt{2\pi}} \cdot e^{-\frac{\left(\ln(LAI) - c\right)^2}{2 * b^2}} \qquad (8)$$

where *a*, *b* and *c* are empirical coefficients that need to be calibrated.

The objectives of the present paper are threefold:

1- to retrieve β variations with LAI from observations for nine experimental cultural cycles where seasonal evolution of factors governing β is available and LAI values range from 0 to well above 2, and by doing so, assess the variability in shapes and scales of the $\beta(LAI)$ relationship,

2- to compare several formulae of $\beta(LAI)$, including the new one (Eq. 8; hereafter referred to as the Boulet et al. expression) , against observed trends and

3- to compare the performances of the various formulae in computing sensible heat flux from observed in-situ radiometric surface temperature.

The new Boulet et al. expression (Eq. 8) of the β function will be first calibrated over the values of β derived from experimental data acquired on the B124 wheat site in Morocco (i.e. values will be obtained for *a*, *b* and *c* in Eq. 8). Next, it will be tested on data acquired over eight other crop cycles in South of France.

2. STUDY SITES

All study sites cover an entire agricultural season, from bare soil to harvest.

The first dataset was collected at the B124 site (31.67250°N, 7.59597°W) in the R3 irrigation perimeter in the Haouz semi-arid plain in Morocco during the SudMed project (Chehbouni et al., 2008, Duchemin et al., 2006) in 2004. The climate is semi-arid with an average annual rainfall of the order of 150 mm. The chosen field (number B124) was cultivated with winter wheat and its size (4 ha) exceeded the basic fetch requirements. LAI and vegetation height ranged from 0 in January to 4.5 and 0.8m at maximum development (April), respectively (See Boulet et al., 2007, for more information on this dataset).

The second dataset was collected over two cultivated plots, Auradé (43°54’97’’N, 01°10’61’’E) and Lamasquère (43°49’65’’N, 01°23’79’’E), separated by 12 km and located near Toulouse (South West France). The climate is Mediterranean with an average annual rainfall of the order of 620 mm for both 2006 and 2007, which can be considered as “average” years as far as rainfall is concerned. The Auradé plot was cultivated with winter wheat (Triticum aestivum L., maximum LAI: 3.8, maximum height: 0.68 m) from Oct-2005 to Jun-2006 and with sunflower (Helianthus annuus L., maximum LAI: 2.0, maximum height: 1.27 m) from Apr-2007 to Sept-2007. The Lamasquère plot was cultivated with maize (Zea mays L., maximum LAI: 3.3, maximum height: 2.3 m) used for silaging from May-2006 to Aug-2006 and with winter wheat from Oct-2006 to Jul-2007 (maximum LAI: 4.5, maximum height: 0.83 m). This site was irrigated in 2006 when maize was cultivated. For a complete description of the site characteristics, management practices, biomass inventories, vegetation area measurements, instrumentation setup and fluxes calculation procedures see Beziat et al. (2009).

The third dataset was acquired on the Avignon 'Flux and Remote Sensing Observation Site', located in Provence, in southeastern France (N 43,92°; E 4,88°; altitude 32 m). The region is also characterized by a typical Mediterranean climate (annual climatic mean of 14° C for temperature and of 680 mm for precipitation). However, during the 2004-2007 period the yearly average for rain was 450 mm with a high variability (313 mm – 745 mm). During the observational period the crop rotation was: Durum Wheat (Triticum durum, maximum LAI: 4.0, maximum height: 1.0 m) from January till June 2004, Peas (Pisum sativum, maximum LAI: 2.9, maximum height: 0.43 m) from April till June 2005, Durum Wheat (maximum LAI: 5.5, maximum height: 0.75 m) again from November 2005 to June 2006 and Sorghum (Sorghum bicolor, maximum LAI: 3.0, maximum height: 1.16 m) from May to August 2007. Irrigation was applied in particular to the Sorghum and Peas crops.

All sites were equipped with a tower where standard meteorological forcing data were acquired. Plant height and total (green and dry) Leaf Area Index were measured every month or so by planimetry and hemispherical photography and the resulting values have been interpolated to daily estimates. Half hourly sensible heat fluxes were measured with a Campbell Sci. CSAT3 (B124, Auradé and Lamasquère sites) or a Young 81000 (Avignon site) 3D sonic anemometer. Auradé, Lamasquère and Avignon are part of the CarboEurope-IP Regional Experiment (Dolman et al., 2006) and the CarboEurope-IP Ecosystem Component. In that context, the data were used for analyzing CO_2 surface – atmosphere exchanges and production for fields with a large interannual rotation of crop types (e.g. Kutsch et al., 2010). For those sites, the Level 3 flux products (i.e. non gapfilled) were used.

For all sites, TIR data were acquired with a nadir looking 60° Field Of View Apogee IRTS-P (R3 and SudOuest sites) or an Heitronics KT15 (Avignon site) Infra Red Thermoradiometer and a Kipp and Zonen CNR1 hemispherical pyrgeometer. For the R3 B124 site, the IRTS-P device has been calibrated using an Everest black body during the experiment and prior to the experiment in a laboratory with an adjustable ambient temperature. Retrieved surface temperatures from both instruments showed a bias of 0.21°C and a Root Mean Square Difference of 1.16°C for instantaneous values at midday. Surface temperature estimates from the CNR1 were used for this site. The KT15 instrument in Avignon was calibrated in the laboratory calibration facilities by looking at a black-body at various temperatures. An error analysis of the whole calibration-measurement chain gave an accuracy of 0.4°C.

3. PROCEDURE FOR RETRIEVING β

For all sites, retrieved β function values estimated from observations, β_{obs}, are derived from measured sensible heat H_{obs}, surface temperature $T_{surf,obs}$ and meteorological data such as air temperature $T_{air,obs}$ that influence the aerodynamic resistance $r_{a,obs}$ calculated using the Monin-Obukhov Similarity Theory:

$$\beta_{obs} = \frac{r_{a,obs} H_{obs}}{\rho c_p \left(T_{surf,obs} - T_{air,obs}\right)} \tag{9}$$

where $r_{a,obs}$ is computed using measured friction velocity values. Therefore:

$$r_{a,obs} = \frac{\left[\ln\left(\frac{z-d}{z_{om} / e^{kB^{-1}_{aero}}}\right) - \Psi_h\left(\frac{z-d}{L_{obs}}\right) + \Psi_h\left(\frac{z_{om} / e^{kB^{-1}_{aero}}}{L_{obs}}\right) \right]}{k u_{*,obs}} \tag{10}$$

Where L_{obs} is the Monin Obhukhov length estimated from observations and $u_{*,obs}$ the measured friction velocity.

In order to assess either β (from Eq. 8) or the radiometric kB^{-1}, one would need in theory a full determination of the three main variables: z_{om}, d and $z_{oh}=z_{om}/exp(kB^{-1}_{aero})$. This is feasible from single-direction radiometric measurements only for bare soil and full cover conditions since in the latter cases aerodynamic and surface temperatures can be considered as identical ($kB^{-1}_{radio}=kB^{-1}_{aero}$ or β=1). For all other conditions, z_{om} and z_{oh} can be retrieved from u_* and scale temperature $T_* = H / \rho c_p u_*$ measurements only if T_{aero} is already well known, i.e. if the radiometric kB^{-1} is known. As a consequence, we decided to use the following expressions from Colaizzi et al. (2004) and Pereira et al. (1999) to compute z_{om} and d:

$$d = h\left(1 - 2\frac{1 - e^{-0.5LAI}}{LAI}\right) \tag{11}$$

$$z_{om} = he^{-0.5LAI}\left(1 - e^{-0.5LAI}\right) \tag{12}$$

where h is the vegetation height.

Given d, one can derive an estimated roughness length $z_{om,obs}$ according to:

$$z_{om,obs} \cong (z-d)e^{-\frac{ku_{obs}}{u_{*,obs}}-\Psi_m\left(\frac{z-d}{L_{obs}}\right)} \tag{13}$$

where u_{obs} is the wind velocity at reference height. We checked that z_{om} values obtained by Eq. 12 are valid, i.e. consistent with $z_{om,obs}$ obtained by Eq. 13 (not shown).

We choose emissivity values (between 0.96 for a bare soil and 0.98 for a vegetation at full cover) for the computation of surface temperature from brightness temperature measurements and a null value for the aerodynamic kB^{-1} ($e^{kB^{-1}_{aero}} = 1$) so that retrieved β_{obs} values deduced from Eq. 9 tend to one for very high LAI values (and therefore retrieved radiometric kB^{-1} will be close to zero when solving for $kB^{-1}{}_{radio}$ in Eq. 7), which is what is expected for full cover conditions. Values close to zero for the radiometric kB^{-1} can be found elsewhere in the literature, notably for quasi-bare soils, as suggested both by Massman (1999)(in his paper the radiometric kB^{-1} tends to 0 when LAI=0 or LAI>>2) and Matsushima (2005) in spite of the large Reynolds numbers encountered in typical agricultural bare soil situations. Of course, overall retrieval results and performances depend strongly on the accuracy of the surface temperature measurements, and this should be investigated further, but it is beyond the scope of this short paper. On the other hand, neglecting $kB^{-1}{}_{aero}$ also leads to the best performance in estimating sensible heat flux for all LAI values and all sites (not shown) which justifies our choice. Yang et al. (2008) found values of the aerodynamic kB^{-1} for bare soils between -5 (at night) and 5 (around midday) with an average between 0 and 5 for positive values of observed sensible heat flux. In what follows, β_{obs} values are computed for unstable conditions selected on the basis of the following rules: $H_{obs}>0$, total incoming solar radiation >10 W/m^2 and $T_{surf,obs}>T_{air,obs}$. Retrieved β_{obs} values from Eq. 9 between -1 and 2 are kept since they represent realistic values of the temperature profile within the canopy and the soil/vegetation mixed/ensemble contribution (this represents >85% of all H_{obs} data between 10am and 4pm for the R3 B124 dataset).

4. RESULTS FOR WHEAT AND OTHER CROPS

4.1. Results for the R3 B124 wheat site (calibration of Eq. 8)

Median values of the scattered β_{obs} values are shown for each 0.5 LAI interval on Figure 1a, together with β values simulated by the ICARE dual source SVAT model applied to the R3 B124 site without any calibration of ICARE, β values interpolated along LAI values from individual β estimates proposed by Matsushima (2005) as well as β values obtained from Eq. 8 (also referred to as "Boulet et al."), whose a, b and c coefficients are manually adjusted to fit β_{obs} values: a=1.7, b=c=0.8. Error bars are shown for observed β values by assuming for Eq. 9 an error of 1K on $T_{surf,obs}$, 10% on $u_{*,obs}$ and z_{om} and 10 W/m^2 on H_{obs}.

β values converted from Eq. 7 based on the three kB^{-1} expressions proposed by Blümel, Massman/Su and Lhomme are also shown in Figure 1a.

For well developed vegetation (say, above LAI=2), all expressions are fairly similar or at least show consistent trends. For sparse and less developed vegetation however (LAI<1, figure 1b, where all single "observed" retrieved β values are shown instead of median values), there is a large difference between the Blümel, Massman/Su, Matsushima and Lhomme expressions, on the one hand, and ICARE outputs, the proposed Boulet et al. expression and the observations, on the other hand. Note that ICARE has not been calibrated to the R3 dataset, therefore only the overall shape of the $\beta(LAI)$ relationship is being used to introduce Eq. 8, not its particular scaling/extent properties (a, b and c values) which are derived from β_{obs} values. The differences between both groups of estimates could be explained by the fact that for the

Blümel, Massman/Su and Lhomme expressions, when *LAI* tends towards 0, the turbulent behavior gives more weight to the aerodynamic kB^{-1} for a bare soil according to Brutsaert (1982) which tends to underestimate β (Yang et al., 2008). As a consequence, the sensible heat flux simulated from the different formulae for β using the observed surface temperature (Equation 4), as one would do with remote sensing observations, is closer to the observed sensible heat for the proposed new formula compared to the three previous ones, especially for quasi bare soil (LAI<0.5) conditions. This appears clearly on Figure 2, where the resulting sensible heat flux is estimated by using the various formulae for kB^{-1} or β together with Eqs. 3 and 4 respectively are shown. On this figure, the sensible heat flux values away from the 1:1 line for the Blümel, Massman/Su, Matsushima and Lhomme expressions correspond to those conditions (LAI<0.5).

One must note that if we ignore the β correction (i.e. by setting β=1 or $kB_{radio}^{-1} = 0$ for all *LAI* values) the root mean square error RMSE between observed and simulated sensible heat fluxes increases from ~50 to ~80 W/m^2 for the entire season. This confirms that taking into account the difference between the aerodynamic and the surface temperature is crucial to deriving accurate turbulent heat fluxes.

4.2. Results for 8 agricultural seasons in Southern France (validation).

The different expressions for β are tested for the 3 other sites, i.e. 8 growing seasons and different vegetation and climate conditions. We assume that the adjusted values of the three parameters for the new formulation (a=1.7, b=c=0.8) can provide a good estimate of $\beta(LAI)$ fluctuations for agricultural areas. These values are therefore kept for all sites. Results are shown in Figure 3. Surface temperature is estimated either from the hemispherical (CNR1) or the directional (KT15, IRTS-P) sensors, as specified in the captions. In general, the hemispherical device produces a $\beta(LAI)$ relationship closer to the expected concave-up shape.

For all sites, the new formulation (Eq. 8) fits fairly well the observed β, except for Lamasquère in 2007, which means that the calibrated values for *a*, *b* and *c* at the R3 B124 site are well suited for other sites. For sunflower, corn and sorghum however (Figure 3c, e and f), the trend in $\beta(LAI)$ matches the observed trend but not the observed amplitude, and the value for *a* should therefore be lower for those cover types. This might be due to the size and shape of the leaves, or to the fact that these canopies show more defined geometrical features (rows, preferred orientation of leaves and flowers…) and are less easily described by turbid medium (for radiation) or permeable-rough interfacial layer (for turbulent transfer) theories. It is also possible to adjust the *a*, *b* and *c* values to fit more closely the observed $\beta(LAI)$ curve. Adjusted values for *a* range between 1.2 and 1.7, and adjusted values for *b* and *c* between 0.5 and 0.8, but do not translate into a significant improvement in computing sensible heat flux.

Since the primary objective of the β formulation is to provide accurate estimates of sensible heat fluxes from observed surface temperature, one needs to assess the resulting performance in using the various β models to simulate *H*. However, it should be noted that the accuracy of those estimates depends primarily on the precision on surface and air temperatures, wind speed, roughness length and the validity of the Monin-Obukhov Similarity Theory.

The performance in estimating sensible heat flux for all sites was assessed using the various β formulations. Results are shown in Table 2. All formulations perform well for some sites and much less well for others, but the new formulation shows comparable or better performances than the others as indicated by the small number of RMSE values above 60 W/m^2 as well as the high number of values under 50 W/m^2. The simplicity of this formulation and the fact that it allows tuning at least one parameter (*a*) to provide realistic values of the difference between the aerodynamic and the surface temperature are two advantages of this formulation. One must note that, for both the Blümel and Massman formulations, the poorly known parameters corresponding to the aerodynamic kB^{-1} for bare soil and full cover (which are found to be close to zero here) can be adjusted as well as the parameter of the exponential decay of the Beer Lambert law used to convert *LAI* to fraction cover, but in our simulations the results did not prove to be very sensitive to the latter (not shown). Again, all formulations perform well for canopies well described by the turbid medium theory, and less for plants with more defined geometrical features or larger intercropping patterns (Barillot et al., 2011).

5. CONCLUSION

An empirical formulation of the difference between the aerodynamic and surface temperatures as a function of Leaf Area Index has been proposed, which represents in a realistic way the observed variations and leads to satisfactory performance in simulating the sensible heat flux compared to other existing formulations. It should be noted though that the observed variations in this difference were assessed using a null aerodynamic kB^{-1}, based on the fact that the radiometric kB^{-1} should be close to zero (or β close to one) for bare soil and full cover conditions. However, the assumption that the difference between the surface temperature and the aerodynamic temperature will have on average a much larger impact on the sensible heat than the difference between the diffusion processes for heat and momentum at the vicinity of the canopy should be investigated more thoroughly since there is no agreement on what value should be used for the aerodynamic kB^{-1} for bare soil, intermediate cover and fully covering vegetation, respectively (Verhoef, 1997). In particular, there is no evidence whatsoever that the roughness length for heat exchange should be a constant fraction of the roughness length for momentum for all LAI values, as it is commonly assumed in SVAT models.

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