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1 **An empirical expression to relate aerodynamic and surface temperatures for use within**
2 **single-source energy balance models**

3

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10

11 **ABSTRACT**

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

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

32

33 1. INTRODUCTION

34 Assessing the turbulent fluxes of latent and sensible heat at the land surface is a crucial issue
35 for both water resource management (computation of evapotranspiration) and meteorological
36 forecasting (evolution of the planetary boundary layer). In order to compute these fluxes at a
37 suitable spatial scale, estimation methods based on the use of remote sensing data are
38 favoured. There is a large array of evapotranspiration estimation methods that use as input or
39 constraint remotely sensed variables such as the NDVI (Courault et al., 2005; Gowda et al.,
40 2008; Olioso et al., 2005). Evapotranspiration in potential conditions (i.e. not water limited)
41 can be assessed with relatively good precision from in-situ (Cleugh et al., 2007) or remote
42 sensing derived (Venturini et al., 2008) meteorological data, and, very often, NDVI. But when
43 water stress occurs the latent and sensible heat fluxes are more difficult to assess. In those
44 cases, there is a tight coupling between the evapotranspiration and the radiative surface
45 temperature and, consequently, methods based on remote sensing data in the Thermal Infra
46 Red (TIR) domain are favoured (Kalma et al., 2008). Those methods often compute the
47 instantaneous latent heat flux as the residual of the energy budget and, in most cases, an
48 expression of each individual term of the energy budget is proposed (Boulet et al., 2007):

$$49 \quad R_n - G = H + LE \quad (1)$$

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

$$53 \quad H = \rho c_p \frac{T_{aero} - T_{air}}{r_{a,h}} \quad (2)$$

54 where ρ is the air density, c_p the specific heat of air at constant pressure, T_{air} is the air
 55 temperature at a reference level above the canopy and $r_{a,h}$ the aerodynamic resistance for heat
 56 exchange. The temperature T_{aero} called aerodynamic temperature represents the average
 57 temperature of the air in the vicinity of the vegetation elements within the canopy, at the
 58 height of the aerodynamic level (defined as the sum of the displacement height and the
 59 roughness length for momentum). There is no measuring device for this temperature, which is
 60 usually inverted from turbulent flux measurements. Moreover, it can be significantly different
 61 from the ensemble directional radiometric surface temperature T_{surf} (as defined by Norman
 62 and Becker, 1995) which is usually derived from brightness temperature measurements made
 63 by a thermo-radiometer or infrared thermometer at nadir or at a specific view angle (Kustas
 64 and Anderson, 2009; Kustas et al., 2007; Stewart et al., 1994) and which is used to assess
 65 energy balance from remote sensing data. In general, the relationship between aerodynamic
 66 and surface temperatures is obtained through the use of a dual-source energy balance when
 67 either the vegetation or the soil bulk skin temperatures are known (Lhomme et al., 2000).
 68 Retrieving surface temperature for each of the different components of the surface (mostly
 69 soil and plants) is difficult, especially with current remote sensing platforms (Jia et al., 2003).
 70 The use of single-source models is therefore favoured over dual-source models to estimate
 71 pixel average turbulent fluxes from a mixed-pixel radiometric temperature. For those models,
 72 there is a need to develop robust yet simple methods to relate the aerodynamic temperature to
 73 the surface temperature. This has been subject of debate for a long time (e.g. see Carlson et

74 al., 1995; Kalma and Jupp, 1990). Many formulations exist in the literature, and a
 75 comprehensive terminology and conversion formulae are proposed by Matsushima (2005).
 76 Historically, most expressions governing the relationship between the aerodynamic and the
 77 surface temperatures have been built on an analogy between wind and temperature profiles
 78 within the canopy. However, while the bottom boundary condition for wind (a null value at
 79 the height of the aerodynamic level) allows defining a roughness length for momentum
 80 exchange (z_{om}), the bottom value of the temperature profile, the aerodynamic temperature, is
 81 generally unknown. One assumes usually that a roughness length z_{or} (improperly named
 82 roughness length for thermal exchange) can be defined so that, at a height corresponding to
 83 the displacement height plus z_{or} , the surface temperature of the vegetation can be considered
 84 as representative of the aerodynamic temperature. The relationship between both roughness
 85 lengths translates into what Matsushima names the “radiometric kB^{-1} ” (kB^{-1}_{radio}) which is
 86 written as $z_{or} = z_{om} / e^{kB^{-1}_{radio}}$. In that case, the difference between the aerodynamic temperature
 87 and the surface temperature in the sensible heat flux formulation is expressed by an additional
 88 resistance (Lhomme et al., 1997):

$$89 \quad H = \rho c_p \frac{T_{surf} - T_{air}}{r_{a,hm} + \frac{kB^{-1}_{radio}}{ku_*}} \Leftrightarrow H = \frac{\rho c_p ku_* (T_{surf} - T_{air})}{\ln\left(\frac{z-d}{z_{or}}\right) - \Psi_h\left(\frac{z-d}{L}\right) + \Psi_h\left(\frac{z_{or}}{L}\right)} \quad (3)$$

90 where $r_{a,hm} = \left[\ln\left(\frac{z-d}{z_{om}}\right) - \Psi_h\left(\frac{z-d}{L}\right) + \Psi_h\left(\frac{z_{om}}{L}\right) \right] / ku_*$ is the aerodynamic resistance for
 91 heat exchange before kB^{-1} correction, u_* the friction velocity, k the von Karman constant, z the
 92 measurement height of the atmospheric forcing, d the displacement height, L the Monin
 93 Obhukhov length and ψ_h the stability correction function for heat transfer given by Paulson
 94 (1970). kB^{-1}_{radio} is derived according to the expected air temperature profile within the canopy
 95 and expressed as a function of meteorological data, LAI and plant height. Amongst the well

96 known formulae, one can cite those from Blümel (Blümel, 1998), Massman (Massman, 1999
97 revisited by Su et al., 2001) and Lhomme (Lhomme et al., 2000).

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

$$102 \quad H = \rho c_p \beta \frac{T_{surf} - T_{air}}{r_{a,h}} \quad (4)$$

103 i.e.

$$104 \quad \beta = \frac{T_{aero} - T_{air}}{T_{surf} - T_{air}} \quad (5)$$

105 Even for isothermal surfaces, usually bare soils or very dense canopies, the aerodynamic
106 temperature can be slightly different from the surface temperature, because the diffusion
107 process for heat transfer adds to the convective exchange of air. There is therefore a difference
108 between the effective eddy diffusivities for momentum and heat exchange, which can be again
109 translated into an excess resistance function of an “aerodynamic kB^{-1} ” or kB^{-1}_{aero} . The
110 available kB^{-1} formulae, derived either empirically or from scalar and flux theoretical profiles
111 in the canopy, account for both aspects: the difference between the aerodynamic and the
112 radiometric temperatures (radiometric kB^{-1}) and the difference between momentum and heat
113 exchange diffusion processes (aerodynamic kB^{-1}). For isothermal surfaces, one can expect
114 that there is no radiometric component within the combined (radiometric and aerodynamic)
115 kB^{-1} . The combined kB^{-1} retrieved for those surfaces from observations by solving for kB^{-1}_{radio}
116 in Eq. 3 is fairly low (within the range 0-5 according to Verhoef et al. 1997, Massman 1999
117 and Yang et al., 2008). For strongly non-isothermal situations, which correspond in general to

118 intermediate LAI values (LAI in the range 0.5-2), the combined kB^{-1} is much higher (in the
 119 range 10-30 according to the same authors). One can thus assume that kB^{-1}_{aero} is usually
 120 smaller than kB^{-1}_{radio} for all LAI values, or that the difference between the surface temperature
 121 and the aerodynamic temperature will have on average a much larger impact on the sensible
 122 heat flux than the difference between the diffusion processes for heat and momentum at the
 123 vicinity of the canopy. While the radiometric kB^{-1} do not discriminate between both
 124 differences (the difference between the aerodynamic and surface temperatures and the
 125 difference between the roughness lengths for momentum z_{om} and heat exchange z_{oh}), the β
 126 function allows us to separate both aspects and keep the difference between z_{oh} and z_{om} in the
 127 formulation of the aerodynamic resistance : $z_{oh} = z_{om} / e^{kB^{-1}_{aero}}$ and $r_{a,h} = r_{a,hm} + kB^{-1}_{aero} / ku_*$.
 128 Consequently, Eq. 4 can be rewritten as:

$$129 \quad H = \rho c_p \beta \frac{T_{surf} - T_{air}}{r_{a,hm} + \frac{kB^{-1}_{aero}}{ku_*}} \Leftrightarrow H = \frac{\rho c_p \beta ku_* (T_{surf} - T_{air})}{\ln\left(\frac{z-d}{z_{oh}}\right) - \Psi_h\left(\frac{z-d}{L}\right) + \Psi_h\left(\frac{z_{oh}}{L}\right)} \quad (6)$$

130 One must also note that the published values of the radiometric kB^{-1} (kB^{-1}_{radio}) (Matsushima,
 131 2005) according to Lhomme, Blümel and Massman/Su (see formulations in Table 1) can be
 132 converted into β values by combining equations 3 and 6:

$$133 \quad \beta = \frac{r_{a,hm} + \frac{kB^{-1}_{aero}}{ku_*}}{r_{a,hm} + \frac{kB^{-1}_{radio}}{ku_*}} \quad (7)$$

134 The Blümel and Massman/Su formulations depend on Leaf Area Index LAI through, mostly,
 135 the fraction cover (f_c) of the canopy and on two parameters difficult to assess, the component
 136 aerodynamic kB^{-1} for bare soil and for vegetation canopy, respectively (See Table 1). Since
 137 for bare soil and full cover conditions there is no large difference between both temperatures,

138 the β function is fairly easily interpreted: β values are close to 1 for those bare soil and full
 139 cover conditions, that is, more generally, for all homogeneous isothermal surfaces, while for
 140 sparse vegetation β decreases. In those conditions, the soil temperature has a large impact on
 141 the radiative surface temperature whereas the aerodynamic temperature remains closer to a
 142 mix of air and vegetation temperatures and is less influenced by the soil temperature. Since
 143 the soil temperature around midday is generally higher than the vegetation temperature, the
 144 observed radiative surface temperature is often larger than the aerodynamic temperature
 145 around that time. Factors influencing β and kB^{-1}_{radio} include LAI and other plant geometrical
 146 features such as height and fraction cover, friction velocity, time of the day, solar radiation etc.
 147 However, most studies agree on the fact that LAI is by far the main driving factor, at least for
 148 agricultural canopies for which the turbid medium (random leaf dispersion, Myneni et al.,
 149 1989) and permeable-rough transfer hypotheses are valid (Kustas et al., 2007; Verhoef, 1997).
 150 This is further confirmed by dual-source land surface models which predict the aerodynamic
 151 temperature through the classical dual-source approach (Shuttleworth and Wallace, 1985).
 152 The evolution of β as a function of LAI is presented in Figure 1a as obtained from an
 153 uncalibrated run of the ICARE SVAT model (Gentine et al., 2007) for the B124 wheat site in
 154 Morocco (see below). One can observe that the simulated shape of the $\beta(LAI)$ relationship
 155 decreases sharply from 1 when LAI increase to about 1, and increases more slowly for higher
 156 LAI, tending again to 1 for LAI well above 3. The lognormal distribution function is therefore
 157 a good candidate to represent the evolution of $1-\beta(LAI)$ for the whole range of LAI values.
 158 Consequently, we propose the following empirical relationship for β :

$$159 \quad \beta = 1 - \frac{a}{LAI * b * \sqrt{2\pi}} \cdot e^{-\frac{(\ln(LAI) - c)^2}{2*b^2}} \quad (8)$$

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

161 The objectives of the present paper are threefold:

162 1- to retrieve β variations with LAI from observations for nine experimental cultural
163 cycles where seasonal evolution of factors governing β is available and LAI values
164 range from 0 to well above 2, and by doing so, assess the variability in shapes and
165 scales of the $\beta(LAI)$ relationship,

166 2- to compare several formulae of $\beta(LAI)$, including the new one (Eq. 8; hereafter
167 referred to as the Boulet et al. expression) , against observed trends and

168 3- to compare the performances of the various formulae in computing sensible heat flux
169 from observed in-situ radiometric surface temperature.

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

174 2. STUDY SITES

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

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

183 The second dataset was collected over two cultivated plots, Auradé (43°54'97"N,
184 01°10'61"E) and Lamasquère (43°49'65"N, 01°23'79"E), separated by 12 km and located
185 near Toulouse (South West France). The climate is Mediterranean with an average annual
186 rainfall of the order of 620 mm for both 2006 and 2007, which can be considered as "average"
187 years as far as rainfall is concerned. The Auradé plot was cultivated with winter wheat
188 (*Triticum aestivum* L., maximum LAI: 3.8, maximum height: 0.68 m) from Oct-2005 to Jun-
189 2006 and with sunflower (*Helianthus annuus* L., maximum LAI: 2.0, maximum height: 1.27
190 m) from Apr-2007 to Sept-2007. The Lamasquère plot was cultivated with maize (*Zea mays*
191 L., maximum LAI: 3.3, maximum height: 2.3 m) used for silaging from May-2006 to Aug-
192 2006 and with winter wheat from Oct-2006 to Jul-2007 (maximum LAI: 4.5, maximum
193 height: 0.83 m). This site was irrigated in 2006 when maize was cultivated. For a complete
194 description of the site characteristics, management practices, biomass inventories, vegetation
195 area measurements, instrumentation setup and fluxes calculation procedures see Beziat et al.
196 (2009).

197 The third dataset was acquired on the Avignon 'Flux and Remote Sensing Observation Site',
198 located in Provence, in southeastern France (N 43,92°; E 4,88°; altitude 32 m). The region is
199 also characterized by a typical Mediterranean climate (annual climatic mean of 14° C for
200 temperature and of 680 mm for precipitation). However, during the 2004-2007 period the
201 yearly average for rain was 450 mm with a high variability (313 mm – 745 mm). During the
202 observational period the crop rotation was: Durum Wheat (*Triticum durum*, maximum LAI:
203 4.0, maximum height: 1.0 m) from January till June 2004, Peas (*Pisum sativum*, maximum
204 LAI: 2.9, maximum height: 0.43 m) from April till June 2005, Durum Wheat (maximum LAI:
205 5.5, maximum height: 0.75 m) again from November 2005 to June 2006 and Sorghum
206 (*Sorghum bicolor*, maximum LAI: 3.0, maximum height: 1.16 m) from May to August 2007.
207 Irrigation was applied in particular to the Sorghum and Peas crops.

208 All sites were equipped with a tower where standard meteorological forcing data were
209 acquired. Plant height and total (green and dry) Leaf Area Index were measured every month
210 or so by planimetry and hemispherical photography and the resulting values have been
211 interpolated to daily estimates. Half hourly sensible heat fluxes were measured with a
212 Campbell Sci. CSAT3 (B124, Auradé and Lamasquère sites) or a Young 81000 (Avignon site)
213 3D sonic anemometer. Auradé, Lamasquère and Avignon are part of the CarboEurope-IP
214 Regional Experiment (Dolman et al., 2006) and the CarboEurope-IP Ecosystem Component.
215 In that context, the data were used for analyzing CO₂ surface – atmosphere exchanges and
216 production for fields with a large interannual rotation of crop types (e.g. Kutsch et al., 2010).
217 For those sites, the Level 3 flux products (i.e. non gapfilled) were used.

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

228 3. PROCEDURE FOR RETRIEVING β

229 For all sites, retrieved β function values estimated from observations, β_{obs} , are derived from
230 measured sensible heat H_{obs} , surface temperature $T_{surf,obs}$ and meteorological data such as air

231 temperature $T_{air,obs}$ that influence the aerodynamic resistance $r_{a,obs}$ calculated using the Monin-
 232 Obukhov Similarity Theory:

$$233 \quad \beta_{obs} = \frac{r_{a,obs} H_{obs}}{\rho c_p (T_{surf,obs} - T_{air,obs})} \quad (9)$$

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

$$235 \quad r_{a,obs} = \frac{\left[\ln \left(\frac{z-d}{z_{om}/e^{kB_{aero}^{-1}}} \right) - \Psi_h \left(\frac{z-d}{L_{obs}} \right) + \Psi_h \left(\frac{z_{om}/e^{kB_{aero}^{-1}}}{L_{obs}} \right) \right]}{ku_{*,obs}} \quad (10)$$

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

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

$$246 \quad d = h \left(1 - 2 \frac{1 - e^{-0.5LAI}}{LAI} \right) \quad (11)$$

$$247 \quad z_{om} = h e^{-0.5LAI} (1 - e^{-0.5LAI}) \quad (12)$$

248 where h is the vegetation height.

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

$$250 \quad z_{om,obs} \cong (z - d) e^{-\frac{ku_{obs}}{u_{*,obs}} \Psi_m \left(\frac{z-d}{L_{obs}} \right)} \quad (13)$$

251 where u_{obs} is the wind velocity at reference height. We checked that z_{om} values obtained by Eq.
252 12 are valid, i.e. consistent with $z_{om,obs}$ obtained by Eq. 13 (not shown).

253 We choose emissivity values (between 0.96 for a bare soil and 0.98 for a vegetation at full
254 cover) for the computation of surface temperature from brightness temperature measurements
255 and a null value for the aerodynamic kB^{-1} ($e^{kB^{-1}_{aero}} = 1$) so that retrieved β_{obs} values deduced
256 from Eq. 9 tend to one for very high LAI values (and therefore retrieved radiometric kB^{-1} will
257 be close to zero when solving for kB^{-1}_{radio} in Eq. 7), which is what is expected for full cover
258 conditions. Values close to zero for the radiometric kB^{-1} can be found elsewhere in the
259 literature, notably for quasi-bare soils, as suggested both by Massman (1999)(in his paper the
260 radiometric kB^{-1} tends to 0 when LAI=0 or LAI>>2) and Matsushima (2005) in spite of the
261 large Reynolds numbers encountered in typical agricultural bare soil situations. Of course,
262 overall retrieval results and performances depend strongly on the accuracy of the surface
263 temperature measurements, and this should be investigated further, but it is beyond the scope
264 of this short paper. On the other hand, neglecting kB^{-1}_{aero} also leads to the best performance in
265 estimating sensible heat flux for all LAI values and all sites (not shown) which justifies our
266 choice. Yang et al. (2008) found values of the aerodynamic kB^{-1} for bare soils between -5 (at
267 night) and 5 (around midday) with an average between 0 and 5 for positive values of observed
268 sensible heat flux. In what follows, β_{obs} values are computed for unstable conditions selected
269 on the basis of the following rules: $H_{obs}>0$, total incoming solar radiation $>10 \text{ W/m}^2$ and
270 $T_{surf,obs}>T_{air,obs}$. Retrieved β_{obs} values from Eq. 9 between -1 and 2 are kept since they
271 represent realistic values of the temperature profile within the canopy and the soil/vegetation

272 mixed/ensemble contribution (this represents >85% of all H_{obs} data between 10am and 4pm
273 for the R3 B124 dataset).

274

275 4. RESULTS FOR WHEAT AND OTHER CROPS

276 4.1. Results for the R3 B124 wheat site (calibration of Eq. 8)

277 Median values of the scattered β_{obs} values are shown for each 0.5 LAI interval on Figure 1a,
278 together with β values simulated by the ICARE dual source SVAT model applied to the R3
279 B124 site without any calibration of ICARE, β values interpolated along LAI values from
280 individual β estimates proposed by Matsushima (2005) as well as β values obtained from Eq.
281 8 (also referred to as “Boulet et al.”), whose a , b and c coefficients are manually adjusted to
282 fit β_{obs} values: $a=1.7$, $b=c=0.8$. Error bars are shown for observed β values by assuming for
283 Eq. 9 an error of 1K on $T_{surf,obs}$, 10% on $u^*,_{obs}$ and z_{om} and 10 W/m² on H_{obs} .

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

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

295 Blümel, Massman/Su and Lhomme expressions, when LAI tends towards 0, the turbulent
 296 behavior gives more weight to the aerodynamic kB^{-1} for a bare soil according to Brutsaert
 297 (1982) which tends to underestimate β (Yang et al., 2008). As a consequence, the sensible heat
 298 flux simulated from the different formulae for β using the observed surface temperature
 299 (Equation 4), as one would do with remote sensing observations, is closer to the observed
 300 sensible heat for the proposed new formula compared to the three previous ones, especially
 301 for quasi bare soil ($LAI < 0.5$) conditions. This appears clearly on Figure 2, where the resulting
 302 sensible heat flux is estimated by using the various formulae for kB^{-1} or β together with Eqs. 3
 303 and 4 respectively are shown. On this figure, the sensible heat flux values away from the 1:1
 304 line for the Blümel, Massman/Su, Matsushima and Lhomme expressions correspond to those
 305 conditions ($LAI < 0.5$).

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

311 4.2. Results for 8 agricultural seasons in Southern France (validation).

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

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

330

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

336 The performance in estimating sensible heat flux for all sites was assessed using the various β
337 formulations. Results are shown in Table 2. All formulations perform well for some sites and
338 much less well for others, but the new formulation shows comparable or better performances
339 than the others as indicated by the small number of RMSE values above 60 W/m^2 as well as
340 the high number of values under 50 W/m^2 . The simplicity of this formulation and the fact that
341 it allows tuning at least one parameter (a) to provide realistic values of the difference between
342 the aerodynamic and the surface temperature are two advantages of this formulation. One

343 must note that, for both the Blümel and Massman formulations, the poorly known parameters
344 corresponding to the aerodynamic kB^{-1} for bare soil and full cover (which are found to be
345 close to zero here) can be adjusted as well as the parameter of the exponential decay of the
346 Beer Lambert law used to convert *LAI* to fraction cover, but in our simulations the results did
347 not prove to be very sensitive to the latter (not shown). Again, all formulations perform well
348 for canopies well described by the turbid medium theory, and less for plants with more
349 defined geometrical features or larger intercropping patterns (Barillot et al., 2011).

350

351 5. CONCLUSION

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

366

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381

382 REFERENCES

- 383 Barillot, R., Louarn, G., Escobar-Gutierrez, A.J., Huynh, P., Combes, D., 2011. How good is
 384 the turbid medium-based approach for accounting for light partitioning in contrasted
 385 grass-legume intercropping systems ? *Ann. Bot.*, 108(6): 1013-1024.
- 386 Beziat, P., Ceschia, E. and Dedieu, G., 2009. Carbon balance of a three crop succession over
 387 two cropland sites in South West France. *Agr. For. Met.*, 149(10): 1628-1645.
- 388 Blümel, K., 1998. Estimation of sensible heat flux from surface temperature wave and one-
 389 time-of-day air temperature observation. *Boundary-Layer Meteorol.*, 86(2): 193-232.
- 390 Boulet, G., Chehbouni, A., Gentine, P., Duchemin, B., Ezzahar, J. and Hadria, R., 2007.
 391 Monitoring water stress using time series of observed to unstressed surface
 392 temperature difference. *Agr. For. Met.*, 146(3-4): 159-172.
- 393 Brutsaert, W., 1982. Evaporation into the atmosphere. Environmental fluid mechanics.
 394 Kluwer Academic Publishers, Dordrecht / Boston / London, 299 pp.

- 395 Carlson, T.N., Taconet, O., Vidal, A., Gilles, R.R., Olioso, A. and Humes, K., 1995. an
396 overview of the workshop on thermal remote-sensing held at La-Londe-Les-Maures,
397 France, September 20-24, 1993. *Agr. For. Met.*, 77(3-4): 141-151.
- 398 Chehbouni, A., LoSeen, D., Njoku, E.G., Lhomme, J.P., Monteny, B. and Kerr, Y.H., 1997.
399 Estimation of sensible heat flux over sparsely vegetated surfaces. *J. Hydrol.*, 189(1-4):
400 855-868.
- 401 Chehbouni, A., Escadafal, R., Duchemin, B., Boulet, G., Simonneaux, V., Dedieu, G.,
402 Mougnot, B., Khabba, S., Kharrou, H., Maisongrande, P., Merlin, O., Chaponniere,
403 A., Ezzahar, J., Er-Raki, S., Hoedjes, J., Hadria, R., Abourida, A., Cheggour, A.,
404 Raibi, F., Boudhar, A., Benhadj, I., Hanich, L., Benkaddour, A., Guemouria, N.,
405 Chehbouni, A.H., Lahrouni, A., Olioso, A., Jacob, F., Williams, D.G. and Sobrino,
406 J.A., 2008. An integrated modelling and remote sensing approach for hydrological
407 study in arid and semi-arid regions: the SUDMED programme. *Int. J. Remote Sens.*,
408 29(17-18): 5161-5181.
- 409 Cleugh, H.A., Leuning, R., Mu, Q.Z. and Running, S.W., 2007. Regional evaporation
410 estimates from flux tower and MODIS satellite data. *Remote Sens. Environ.*, 106(3):
411 285-304.
- 412 Colaizzi, P.D., Evett, S.R., Howell, T.A. and Tolk, J.A., 2004. Comparison of aerodynamic
413 and radiometric surface temperature using precision weighing lysimeters. In: W. Gao
414 and D.R. Shaw (Editors), *Remote Sensing and Modeling of Ecosystems for
415 Sustainability*. Proceedings of the Society of Photo-Optical Instrumentation Engineers
416 (Spie). Spie-Int Soc Optical Engineering, Bellingham, pp. 215-229.
- 417 Courault, D., Seguin, B., Olioso, A., 2005. Review on estimation of evapotranspiration from
418 remote sensing data: From empirical to numerical modeling approaches. *Irrig. Drain.
419 Syst.*, 19(3-4): 223-249.
- 420 Dolman, A.J., Noilhan, J., Durand, P., Sarrat, C., Brut, A., Pignatelli, B., Butet, A., Jarosz, N.,
421 Brunet, Y., Loustau, D., Lamaud, E., Tolk, L., Ronda, R., Miglietta, F., Gioli, B.,
422 Magliulo, V., Esposito, M., Gerbig, C., Korner, S., Glademard, R., Ramonet, M.,
423 Ciais, P., Neininger, B., Hutjes, R.W.A., Elbers, J.A., Macatangay, R., Schrems, O.,
424 Perez-Landa, G., Sanz, M.J., Scholz, Y., Facon, G., Ceschia, E. and Beziat, P., 2006.
425 The CarboEurope regional experiment strategy. *Bull. Am. Meteorol. Soc.*, 87(10):
426 1367-1379.
- 427 Duchemin, B., Hadria, R., Erraki, S., Boulet, G., Maisongrande, P., Chehbouni, A., Escadafal,
428 R., Ezzahar, J., Hoedjes, J.C.B., Kharrou, M.H., Khabba, S., Mougnot, B., Olioso,
429 A., Rodriguez, J.C., Simonneaux, V., 2006. Monitoring wheat phenology and
430 irrigation in Central Morocco: On the use of relationships between evapotranspiration,
431 crops coefficients, leaf area index and remotely-sensed vegetation indices.
432 *Agricultural Water Management*, 79(1): 1-27.

- 433 Gentine, P., Entekhabi, D., Chehbouni, A., Boulet, G. and Duchemin, B., 2007. Analysis of
434 evaporative fraction diurnal behaviour. *Agr. For. Met.*, 143(1-2): 13-29.
- 435 Gowda, P., Chavez, J., Colaizzi, P., Evett, S., Howell, T. and Tolk, J., 2008. ET mapping for
436 agricultural water management: present status and challenges. *Irrig. Sci.*, 26(3): 223-
437 237.
- 438 Jia, L., Li, Z.L., Menenti, M., Su, Z., Verhoef, W., Wan, Z., 2003. A practical algorithm to
439 infer soil and foliage component temperatures from bi-angular ATSR-2 data.
440 *International Journal of Remote Sensing*, 24(23): 4739-4760.
- 441 Kalma, J.D. and Jupp, D.L.B., 1990. Estimating evaporation from pasture using infrared
442 thermometry: evaluation of a one-layer resistance model. *Agr. For. Met.*, 51(3-4): 223-
443 246.
- 444 Kalma, J.D., McVicar, T.R. and McCabe, M.F., 2008. Estimating Land Surface Evaporation:
445 A Review of Methods Using Remotely Sensed Surface Temperature Data. *Surv.*
446 *Geophys.*, 29(4-5): 421-469.
- 447 Kustas, W. and Anderson, M., 2009. Advances in thermal infrared remote sensing for land
448 surface modeling. *Agr. For. Met.*, 149(12): 2071-2081.
- 449 Kustas, W.P., Anderson, M.C., Norman, J.M. and Li, F.Q., 2007. Utility of radiometric-
450 aerodynamic temperature relations for heat flux estimation. *Boundary-Layer*
451 *Meteorol.*, 122(1): 167-187.
- 452 Kutsch, W.L., Aubinet, M., Buchmann, N., Smith, P., Osborne, B., Eugster, W., Wattenbach,
453 M., Schrumpf, M., Schulze, E.D., Tomelleri, E., Ceschia, E., Bernhofer, C., Beziat, P.,
454 Carrara, A., Di Tommasi, P., Grunwald, T., Jones, M., Magliulo, V., Marloie, O.,
455 Moureaux, C., Olioso, A., Sanz, M.J., Saunders, M., Sogaard, H. and Ziegler, W.,
456 2010. The net biome production of full crop rotations in Europe. *Agriculture*
457 *Ecosystems & Environment*, 139(3): 336-345.
- 458 Lhomme, J.P., Chehbouni, A. and Monteny, B., 2000. Sensible heat flux-radiometric surface
459 temperature relationship over sparse vegetation: Parameterizing B-1. *Boundary-Layer*
460 *Meteorol.*, 97(3): 431-457.
- 461 Lhomme, J.P., Troufleau, D., Monteny, B., Chehbouni, A. and Bauduin, S., 1997. Sensible
462 heat flux and radiometric surface temperature over sparse Sahelian vegetation .2.
463 Model for the kB(-1) parameter. *J. Hydrol.*, 189(1-4): 839-854.
- 464 Massman, W.J., 1999. A model study of kB(H)(-1) for vegetated surfaces using 'localized
465 near-field' Lagrangian theory. *J. Hydrol.*, 223(1-2): 27-43.
- 466 Matsushima, D., 2005. Relations between aerodynamic parameters of heat transfer and
467 thermal-infrared thermometry in the bulk surface formulation. *J. Meteorol. Soc. Japan*,
468 83(3): 373-389.

- 469 Myneni, R.B., Ross, J., Asrar, G., 1989. A review on the theory of photon transport in leaf
470 canopies. *Agricultural and Forest Meteorology*, 45(1-2): 1-153.
- 471 Norman, J.M. and Becker, F., 1995. Terminology in thermal infrared remote-sensing of
472 natural surfaces. *Agr. For. Met.*, 77(3-4): 153-166.
- 473 Olioso, A., Inoue, Y., Ortega-Farias, S., Demarty, J., Wigneron, J.P., Braud, I., Jacob, F.,
474 Lecharpentier, P., Otlé, C., Calvet, J.C. and Brisson, N., 2005. Future directions for
475 advanced evapotranspiration modeling: Assimilation of remote sensing data into crop
476 simulation models and SVAT models. *Irrig. Drain. Sys.*, 19(3): 377-412.
- 477 Paulson, C.A., 1970. The Mathematical Representation of Wind Speed and Temperature
478 Profiles in the Unstable Atmospheric Surface Layer. *J. Appl. Meteorol.*, 9(6): 857-861.
- 479 Pereira, L.S., Perrier, A., Allen, R.G. and Alves, I., 1999. Evapotranspiration: Concepts and
480 future trends. *Irrig. Drain. Syst.*, 125(2): 45-51.
- 481 Shuttleworth, W.J., and Wallace, J.S., 1985. Evaporation from sparse crops - an energy
482 combination theory. *Q. J. R. Meteorol. Soc.*, 111: 839-855.
- 483 Stewart, J.B., Kustas, W.P., Humes, K.S., Nichols, W.D., Moran, M.S. and Debruin, H.A.R.,
484 1994. Sensible heat-flux radiometric surface-temperature relationship for 8 semiarid
485 areas. *J. Appl. Meteorol.*, 33(9): 1110-1117.
- 486 Su, Z., Schmugge, T., Kustas, W.P. and Massman, W.J., 2001. An evaluation of two models
487 for estimation of the roughness height for heat transfer between the land surface and
488 the atmosphere. *J. Appl. Meteorol.*, 40(11): 1933-1951.
- 489 Venturini, V., Islam, S. and Rodriguez, L., 2008. Estimation of evaporative fraction and
490 evapotranspiration from MODIS products using a complementary based model.
491 *Remote Sens. Environ.*, 112(1): 132-141.
- 492 Verhoef, A., de Bruin, H. A. R., and van den Hurk, B. J. J. M., 1997. Some Practical Notes on
493 the Parameter kB^{-1} for Sparse Vegetation. *J. Appl. Meteorol.*, 36: 560-572.
- 494 Yang, K., Koike, T., Ishikawa, H., Kim, J., Li, X., Liu, H.Z., Liu, S.M., Ma, Y.M. and Wang,
495 J.M., 2008. Turbulent flux transfer over bare-soil surfaces: Characteristics and
496 parameterization. *J. Appl. Meteorol. Climatol.*, 47(1): 276-290.