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Combining scintillometer measurements and an aggregation scheme to estimate area-averaged latent heat flux during the AMMA experiment

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S U M M A R Y
This paper deals with the issue of using scintillometry in conjunction with a simple aggregation scheme to derive area-averaged sensible and latent heat fluxes over a small watershed in Niamey, Niger (Wankama catchment). Data collected in the context of the African Monsoon Multidisciplinary Analysis (AMMA) program has been used to test the proposed approach. For this purpose, a Large Aperture Scintillometer (LAS) was set up over heterogeneous surface transect of about 3.2 km spanning three vegetation types.

The comparison between scintillometer-based estimates of area-averaged sensible heat fluxes and those measured by a network of the classical eddy covariance (EC) devices showed good agreement, with a relative error of about 20% (R² = 0.85, RMSD = 22 W m⁻², and SEE = 21.39 W m⁻²). This is a good result considering the contrast in vegetation cover and type—and/or by precipitation—generates a large spatial variability of surface fluxes. Thereby, estimating LE under such conditions is not an easy task.

Among the surface processes of prime importance in addressing the issue of the interaction of surface conditions and climate processes is the evapotranspiration or latent heat flux density (LE), which is essential in bringing together analyses of the physical, biological, and hydrological processes occurring at different space-time scales over continental surfaces. This same process describes the transport of water into the atmosphere from surfaces, through soil evaporation and plant transpiration.

Additionally, understanding the spatial distribution of LE is essential for many environmental applications including water resources management, agriculture efficiency, global vegetation analysis, climate dynamics, and ecological applications. Consequently, the AMMA program put a strong emphasis on the challenging task of modeling and measurement of LE at different ranges of the space-time scale. The surface heterogeneity caused by the contrast in vegetation cover and type—and/or by precipitation—generates a large spatial variability of surface fluxes. Therefore, estimating LE under such conditions is not an easy task.

Introduction
The West African region has been undergoing tremendous changes over the last 30 years. The Sahel is prone to extremes in climate variability, with persistent drought which causes recurrent famine and humanitarian crises. It is thus of crucial importance to develop a clear understanding and accurate methods for predicting the combined effect of both human- and nature-induced changes over the last 30 years. The Sahel is prone to extremes in

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In this context, several large-scale field experiments such as the Hydrologic and Atmospheric Pilot Experiment in the Sahel (Goutorbe et al., 1994) and the African Monsoon Multidisciplinary Analysis (AMMA: http://www.amma-international.org) were conducted over this region in recent years. These studies have substantially advanced the understanding of the interaction between regional climate and the hydrological cycle.

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Nomenclature

Abbreviations
AMMA African Monsoon Multidisciplinary Analysis
EC eddy covariance
IRTS-P ion Infrared temperature sensor
LNS Laser Scintillometer System
MOST Monin-Obukhov Similarity Theory
SVATs Soil–Vegetation–Atmosphere Transfer Schemes
WAM West African Monsoon

Greek Symbols

Bowen ratio \((=H/LE)\) [1]
Von Karman constant \((\kappa)\) [1]

\(\rho\) density \([\text{kg m}^{-3}]\)
\(\psi\) integrated surface function [1]
\(\tau\) irradiation [1]
\(\varepsilon\) emissivity [1]
\(\sigma\) Stefan–Boltzmann constant \(\left[\text{W m}^{-2}\text{K}^{-4}\right]\)
\(\alpha\) albedo [1]

\(\text{AE}\) available energy \([\text{W m}^{-2}]\)
\(C^2\) refractive parameter of air [1]

\(c_p\) heat capacity of air at constant pressure \([\text{J kg}^{-1} \text{K}^{-1}]\)
\(C_f\) roughness structure parameter \([\text{m}^2 \text{K}^{-1}]\)
\(d\) displacement height [m]
\(e_a\) vapor pressure [hPa]
\(G\) ground flux density \([\text{W m}^{-2}]\)
\(g\) gravitational acceleration \([\text{m s}^{-2}]\)
\(H\) le heat flux density \([\text{W} m^{-2}]\)
\(L\) Monin–Obukhov length [m]
\(LE\) latent heat flux (transpiration) \([\text{W m}^{-2}]\)
\(p\) pheic pressure [Pa]
\(R_{n}\) global radiation \([\text{W m}^{-2}]\)
\(R_s\) pheic radiation \([\text{W m}^{-2}]\)
\(R_T\) lal radiation \([\text{W m}^{-2}]\)
\(\text{RMSD}\) mean square deviation \([\text{W m}^{-2}]\)
\(T\) surface temperature \([\text{K}]\)
\(u\) speed \([\text{m s}^{-1}]\)
\(u'\) wind velocity \([\text{m s}^{-1}]\)
\(z_0\) roughness \([\text{m}]\)
\(z_{\text{LAS}}\) height \([\text{m}]\)

Numerous Soil–Vegetation–Atmosphere Transfer schemes (SVATs) have been developed with varying degrees of complexity, and many are designed to use remote sensing data to provide an area-averaged LE (Allen et al., 2007; Bastiaanssen et al., 1998; Caparrini et al., 2003, 2004; Cleugh et al., 2007; Crow and Kustas, 2005; French et al., 2005; Moran et al., 1994; Mu et al., 2007; Norman et al., 2003; Schmugge et al., 1998; Su, 2002; Timmermans et al., 2007; Zhan et al., 1996). However, one of the main difficulties faced in developing these regional heat fluxes concerns the evaluation of their outputs against ground observations. In most of the micrometeorological studies, a network of point-sampling devices—such as the EC system—is used. However, due to their high price and the requirement for the continuous availability of well-trained staff to operate and maintain them, these devices might not be the best choice for obtaining the area-average of LE, especially in remote areas. Such limitations lead the scientific community to look for alternative techniques to estimate the area-average of LE over heterogeneous surfaces.

Recent studies have shown that scintillometry offers a useful alternative method for routine measurements of area-average of the sensible heat flux density \((H)\) and thus LE (Chenbouni et al., 1999, 2000a, in press; Ezzaha et al., 2007a; Hemakumara et al., 2003; Meijninger et al., 2002). In most of these studies, large aperture scintillometers (LAS) were used, which allow measurements over path lengths of up to 5 km. Recently, this instrument has become very popular especially because, in contrast to the network of EC systems, it requires relatively little maintenance and is therefore cost effective. The LAS provides a measurement of the structure parameter for the refractive index \((\beta^2)\), which can be related to the structure parameter of temperature \((\kappa)\) in order to derive sensible heat flux \((H_{\text{LAS}})\) through the application of the Monin–Obukhov Similarity Theorem (MOST).

It should be mentioned that the use of the LAS over heterogeneous surfaces to estimate path-average \(H\) is subject to the applicability of MOST theory under such conditions. Fortunately, the study performed in Ezzahar et al. (2007b) showed that MOST scaling function also holds over heterogeneous surfaces (tall and sparse vegetation). This study—as well as that of Chehbouni and al. (in press)—also shows that there is a layer below the so-called “blending height” where MOST still holds true. This is of practical interest since it is not always feasible to install the LAS in stable conditions on high towers (e.g. on platforms above the blending height).

It is thus feasible to use the LAS for operationally estimating area-average LE as the residual term of the energy balance equation providing estimates of area-average available energy \((AE = R_{n} - G)\), where \((R_{n})\) is the net radiation and \((G)\) is the soil heat flux. Here again, area-averaged \(AE\) can be constructed by deploying a network of net radiometers \((R_{n})\) and soil heat plates \((G)\), which is also costly and really not particularly feasible. An aggregation scheme for estimating area-average \(AE\) from remotely sensed surface temperature, albedo, incoming radiation and other ancillary meteorological data is therefore needed in order to estimate area-average LE through the combination of the LAS measurements and the energy balance equation.

In this regard, substantial efforts have been made in the development of the aggregation scheme to estimate area-average surface fluxes over heterogeneous surfaces (Koster and Suarez, 1992; Sellers et al., 1997; Noilhan and Lacarrere, 1995; Arain et al., 1996; Noilhan et al., 1997; Raupach and Finngan, 1995; Lhomme et al., 1994; Chehbouni et al., 1995, 2000b, 2008). The aggregation scheme is conceived as a method which seeks to link the model parameters which control surface exchange with the scale of the area-average value of equivalent model parameters applicable at larger scale or grid scale, assuming that the same equations are used to describe surface fluxes at both scales.

The present study is specifically devoted to the investigation of whether the combination of the LAS and a simple aggregation scheme for estimating area-averaged available energy can provide reasonable estimates of area-average LE over a heterogeneous catchment. This has been undertaken in the framework of the international AMMA program, which aims to improve our knowledge and understanding of the West African Monsoon (WAM) and its variability.

This paper is organized as follows: “Theory” presents the theoretical background used to estimate the area-average LE; “Experimental site and measurements” describes the site and its surroundings; “Eddy and Las...


**Experimental setup**; “Results and discussion” presents the results of the comparison between the measured and estimated area-averaged surface fluxes; finally, “Conclusions and perspectives” provides a discussion and conclusions marks.

**Theory**

Determination of the turbulent heat fluxes with the LAS

The LAS is a device that provides measurements of the variation in the refractive index of air caused by atmospheric turbulence. This instrument consists of a transmitter and a receiver, both with an aperture diameter of 0.15 m, set up at a separation distance (or path length) ranging from 250 to 5000 m. The transmitter emits electromagnetic radiation, which is scattered by the turbulent atmosphere, and the resulting variations in signal intensity (scintillations) are recorded by a receiver comprising an identical mirror and a photodiode detector. The intensity fluctuations are related to the path-averaged structure parameter of the refractive index of air, $C_n^2$. For the scintillometers operating at near-infrared wavelength, Wesely (1976) and, more recently, Moene (2003) demonstrate that $C_n^2$ is related to $C_T$, the structure parameter of temperature, as

$$C_T^2 = C_n^2 \frac{T_a^2}{(0.78 \times 10^{-6} \rho)} \left(1 + 0.03 \beta \right)^{-2}$$

where $T_a$ is the air temperature, $\rho$ is atmospheric pressure and $\beta$ is the Bowyn ratio. The factor involving the Bowyn ratio is the correction term for the influence of humidity fluctuations. $C_n^2$ and $C_T^2$ are in $(m^{-2/3})$ and $(K^2 m^{-2/3})$, respectively.

Using the Monin–Obukhov Similarity Theory (MOST), the sensible heat flux can be obtained from a combination of $C_T$ and additional weed data through the following dimensionless relationship

$$C_T^2(\zeta_{LAS} - d)^{2/3} = f_{T} \left(\frac{\zeta_{LAS} - d}{L}\right) = C_T^2 \left(1 - c_T \frac{\zeta_{LAS} - d}{L}\right)^{-2/3}$$

where $L$ is the Obukhov length (m), $T_a$ is the temperature scale, $(T_a = \frac{\epsilon_n}{\kappa p e})$, and $u^*$ the friction velocity expressed as

$$u^* = \frac{k u_{10}(\zeta_{LAS} - d)/\lambda_T}{\lambda_T}$$

where $\zeta_{LAS}$ is the effective height of the LAS above the surface. Here, $\zeta_{LAS}$ was estimated following the procedure of Hartogensis et al. (2003), which takes into account the change in topography along the LAS transect between the transmitter and the receiver. $\psi$ is the integrated stability function (Panofsky and Dutton, 1984), $d$ is the displacement height, $\lambda_T$ is the roughness length, $k$ is the Von Karman constant, $\gamma$ is the gravitational acceleration, $\rho$ is the density of air and $c_T$ is the specific heat of air at constant pressure. During the iteration procedure, the Bowyn ratio is estimated using the $H_{\text{net}}$ soil net radiation ($R_n$), soil heat flux ($G$) and $H_{\text{LAS}}$. In this study, we will use the MOS relationships $f_{T} = \left(2 \zeta_{LAS} / L \right)$, respectively.

Available energy

Net radiation

The net radiation quantifies the energy available for crop evapotranspiration, photosynthesis, and soil heating (Monteith and Unsworth, 1990). It is the biggest or most important term of the surface energy balance equation. In the current study, the net radiation was expressed as follows:

$$R_n = (1 - \alpha)R_s + \alpha e_{LS} - R_t$$

where $\alpha$ is the surface albedo, $R_s$ is the solar global radiation [W m$^{-2}$], $e_{LS}$ is the surface emissivity which has an almost constant value (in practical work a value of 0.98, may be taken for crop canopies; Ortega Farías et al., 2000), $R_t$ the atmospheric radiation which is emitted by air molecules [W m$^{-2}$] and $R_r$ is the terrestrial radiation which is emitted by the surface [W m$^{-2}$]. By using the Stefan–Boltzmann equation (Monteith and Unsworth, 1990), $R_r$ and $R_t$ could be expressed as functions of air and surface temperature, respectively. Then Eq. (4) can be rewritten as

$$R_n = (1 - \alpha)R_s + \alpha e_{LS}(\epsilon_{LS} - 1)$$

with $\epsilon_{LS}$ as the emissivity of the atmosphere, $T_{LS}$ is the air temperature [K], $T_{surf}$ is the surface temperature [K], and $p$ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$).

The $e_{LS}$ is calculated using the expression proposed by Utsaert (1975) as

$$e_{LS} = 1.24(e_{LS}/T_a)^{1/7}$$

with $e_{LS}$ as the air vapor pressure (hPa).

Soil heat flux

The soil heat flux is the conduction of energy per unit area in response to a temperature gradient. It is the most difficult scalar to measure accurately at the appropriate space-scale, due to the complexity of surface cover and physical processes occurring in the soil. Therefore, in several micrometeorological studies $G$ is parameterized as a constant proportion of $R_n$. The ratio of the soil heat flux to net radiation was calculated according to Santanello and Friedli (2003) as follows:

$$G/R_n = A \cos(2\pi(t + 10800)/B)$$

where $t$ is the time of day in seconds, and $A$ and $B$ are adjusting factors which were set by Santanello and Friedli (2003) as 0.31 and 74000 s, respectively. Recently, Hoedjes et al. (2008), Chehbouni et al. (2008) have tested this relationship over a complex field of olive trees (Enisft Al Haouz basin, Morocco) and a semi-arid mixed agric land (Yaqvi Valley, Mexico), respectively. They found reasonably good results when comparing the measured and estimated values of $A$.

In this section, a simple aggregation scheme was used to estimate the area-average available energy. As reported in Chehbouni et al. (2008), this procedure is based on two assumptions. The first one is of formulating grid-scale surface fluxes using the same factors that govern patch-scale behavior, but whose arguments are the aggregate expressions of those at the patch-scale. The second one stipulates that “the effective area-averaged value of a land surface parameter is defined as a weighted average over the component land types in each grid, through that function involving the parameter which most succinctly expresses its relationship with the associated surface flux” (Shuttleworth et al., 1997). Applying this...
simple aggregation rule to area-averaged (denoted by angle brackets) net radiation and soil heat flux leads to:

\[
\left( R_n \right) = \left( 1 - \langle \alpha \rangle \right) R_n + \langle \epsilon_s \rangle \sigma (\langle T_0 \rangle - \langle T'_0 \rangle)
\]

(8)

\[
\left( \frac{G}{R_n} \right) = A \cos \left[ 2 \pi (t + 10800) / B \right]
\]

(9)

Similarly, the application of the second assumption leads to the following set of relationships between local (subscript \( i \)) and effective (in brackets) radiative temperature, surface emissivity, surface albedo, displacement height, and roughness length (Chehbouni et al., 2008):

\[
\left( T_{surf} \right) = \sum_{i=1}^{3} f_i \left( T_{surf} \right)^{\alpha_i}
\]

(10)

\[
\langle \alpha \rangle = \sum_{i=1}^{3} f_i \alpha_i
\]

(11)

\[
\langle \zeta \rangle = \sum_{i=1}^{3} f_i \zeta_i
\]

(12)

\[
(d) = \sum_{i=1}^{3} f_i d_i
\]

(13)

\[
\ln(\zeta_0) = \sum_{i=1}^{3} f_i \ln(\zeta_0)
\]

(14)

where \( f_i \) is the fraction of the surface covered by the patch \( i \) with, obviously, \( \sum_{i=1}^{3} f_i = 1 \).

The area-average estimates of available energy \( (AE) = \left( R_n \right) \) and flux \( (G) \) were combined with the estimates of sensible heat \( (\epsilon_s) \) and latent heat \( (\zeta_0) \) in the LAS to obtain the area-average latent heat flux. \( \langle LE \rangle \) represents the lateral contribution in the surface energy balance equation, i.e.

\[
\langle LE_{LAS} \rangle = \langle AE \rangle - \langle H_{LAS} \rangle
\]

(15)

### Experimental site and measurements

The study took place in Wankama catchment, between Day of Year (DOY) 204 and 225 (July 23rd–August 13th) in 2006. This catchment is located near the city of N’jamé, Niger. In this section, site description and experimental setup are briefly summarized; the reader is referred to Cappelaere et al. (this issue) for a complete description. The climate is typically Sahelian with a short rainy season from June to September and high temperatures throughout the year. Potential evapotranspiration is about 2500 mm per year. The catchment is intensively cultivated: 54% planted fields (mainly millet), and 26% of the field lands fallow (Peugeot et al., 2003); the remaining area is classified as degraded shrubs.

The LAS used in this study was developed and built by the Meteorology and Air Quality Group at Wageningen University, the Netherlands. This instrument has been constructed according to the basic design specified in Ochs and Wilson (1993). It has an aperture size of 0.15 m, and the transmitter operates at a wavelength of 0.94 µm. At the receiver, \( C_3 \) is sampled at 1 Hz and averaged over 1-min intervals by a CR510 data logger (Meijninger et al., 2000). The transmitter and the receiver were mounted on 10-m-high towers at an altitude difference of approximately 46 m. The receiver was installed at the highest part of the basin (ploughed), while the transmitter was installed at the lowest part of the basin (Fig. 1). The LAS was set up over a 3.2 km transect spanning three vegetation types—fields of millet, fallow fields, and areas of degraded shrub. The direction of the LAS path was 250° from North. Analysis of the wind direction pattern during the study period showed that the dominant (70%) wind direction is situated within an interval ranging from 157.5° to 247.5° (see Fig. 2).

Along the LAS transect, three vegetation types have been instrumented with eddy covariance (EC) systems. Two fields—millet (denoted “site A”) and fallow (denoted “site B”)—were instrumented since 2005 (Ramier et al., this issue). In order to measure representative fluxes along the transect of the LAS, in 2006 we installed a third EC system over the degraded shrubs site (denoted “site C”); see Fig. 1. The EC systems, installed at the A and B sites, consisted of a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd.) and an open-path infrared gas analyzer (LI7500, Licor Inc.). At the third site—i.e. “site C” —the EC system consisted of a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd.) and a Krypton hygrometer (KH2Q, Campbell Scientific Ltd.). Raw data were sampled at a rate of 20 Hz and were recorded using CR5000 data loggers (Campbell Scientific Ltd.). The half-hourly fluxes were later calculated off-line using two post-processing software packages: ECpack and EdiRe, which are developed, respectively, by the Meteorology and Air Quality Group at Wageningen University and by

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**Fig. 1.** Overview of the Wankama basin and the experimental setup, locations of LAS (T and R stand for transmitter and receiver, respectively) and EC systems are shown (Sites A, B, and C).
Edinburgh University. The ECpack and EdiRe are available for download from http://www.met.wau.nl/ and http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/Downloads.html, respectively. For the ECpack software, the fluxes were calculated after performing planar fit corrections (Wilczak et al., 2001), correcting the sonic temperature for the presence of humidity (Schatonius et al., 1983), frequency response corrections for slow apparatus and path length integration (Moore, 1986), the inclusion of the mean vertical velocity according to Webb et al. (1980), and oxygen correction for the Krypton hygrometer, which is sensitive to O2 (Van Dijk et al., 2003). For the EdiRe software, the fluxes were calculated after despiking, double rotation, Webb correction and the cross-correlation for derivation of time lag between the sonic anemometer and the gas analyzer (Cappelaere et al., this issue). It is certainly unfortunate that two groups and we did not have access to raw data for “site A” and “site B”. Nevertheless, we did perform a comparison of the two post-processing programs using one week of data over “site C”. The correspondence in terms of sensible heat flux estimates was very good ($R^2 = 0.99$ and RMSE = 6.7 W m$^{-2}$). It can be thus concluded that the difference between the two programs is not very significant, at least under the prevailing conditions within the considered study.

In the vicinity of each EC tower, a set of standard meteorological instruments were installed to measure net radiation using the Q7 net radiometer (REBS Inc., WA, USA) over “site C” and the CNR1 (Kipp and Zonen, the Netherlands) over “site A” and “site B”, air temperature and humidity using a Vaisala (HMP45AC temperature and humidity probe), soil heat flux at different depths using the soil heat flux plates (HFT3-L, Campbell Scientific Ltd.), and surface temperature using the Precision infrared temperature sensor (IRTS-P) over “site C”. Over “site A” and “site B,” the surface temperature was inverted from the CNR1 measurements. In addition, two CM3 pyranometers were installed over “site C” to measure incoming and outgoing shortwave (CM3, Campbell Scientific Ltd.).

Results and discussion

In this section, we first compare the LAS-based estimates of area-average sensible heat flux values to those constructed as area-average from measured values of sensible heat flux using the three EC systems (from here on, the constructed fluxes will be called measured). Second, the estimated and measured area-average AE were compared. Thereafter, we evaluate the applicability of the LAS to estimate the evapotranspiration flux over the Wankama catchment through the comparison of measured and estimated values. In this study, we will only consider daytime observations with half-hourly time scale, from 07:30 UTC until 18:00 UTC, since the behavior of the temperature structure parameter is not well known for stable conditions which can create greater uncertainty in the fluxes, especially over heterogeneous surfaces.

It should be noted that during this study, about 9% of LAS data was lost due to rainfall and very strong wind associated with storms which disturbed the alignment of the LAS. However, knowing that this study was undertaken during the rainy season, this quantity can be considered as being very small: during the rainy season, most rain falls during the night, which minimizes the loss of daytime data.

Sensible heat flux estimated by LAS

In this study, the EC data were used for assessing the accuracy of the LAS. Therefore, an analysis of the energy balance flux components was performed first. The comparison between the available energy ($R_{\text{net}} = \text{G}$) and the sum of the latent and sensible heat fluxes ($H_{\text{EC}} + L_{\text{EC}}$) measured independently by the EC systems, showed a high degree of agreement ($R^2 = 0.91$) and the agreement was good, with deviations not exceeding 5% for the A, B, and C sites, respectively. The problem of the energy balance no doubt can be entirely explained by the mismatch of the area representative for the convective fluxes and available energy measurements nor by uncertainties associated with measurement of soil heat flux and net radiation (Twine et al., 2000; Hoedjes et al., 2002, 2008; Chehbouni et al., in press). In this study, we chose to follow the approach suggested by Hoedjes et al. (2000), which consists of considering that, although the EC system underestimates sensible and latent heat fluxes, their ratio (the Bowen ratio) is correctly measured. Based on this assumption, we recalculated sensible and latent heat fluxes—over each, individual site—using measured Bowen ratio and available energy, thus forcing the closure of the energy balance. This correction is important in the case of comparison with the LAS, since LAS calculations of $H$ and $LE$ are made using an iterative procedure involving $R_{\text{net}}$, $G$, and $C$, and thus based on the principle of conservation of energy (Hoedjes et al., 2002).

Before evaluating the accuracy of the LAS, a footprint analysis was made. In this study, we used the analytical footprint model proposed by Horst and Weil (1992, 1994). The theoretical background of this model is briefly given in Appendix A. Fig. 3a and b shows the footprints of the LAS and EC (corresponding to approximately 95% of the sensible heat flux) for two wind intervals, 70° to 150° and 250° to 300°, respectively. It can be seen that within the wind cone, from the interval 70° to 250°, the footprint covers the area where the EC systems are installed (Fig. 3a), thus the LAS fluxes are more comparable with those measured by the EC systems. On the contrary, when the wind comes from the 250° to 300° interval, the footprint of the LAS (which spans more of the 1 fields) and the EC systems differed strongly (Fig. 3b), showing large differences between LAS fluxes and those measured by the EC. Consequently, we will only consider the fluxes associated with wind from the 70° to 250° wind interval.

Fig. 4 displays a comparison between area-average sensible heat fluxes derived from the LAS and those obtained by weighting the values measured at the EC systems ($L_{\text{LAS}}$ and $L_{\text{EC}}$). The area-average fluxes of $H_{\text{LAS}}$ and $L_{\text{EC}}$ were calculated that the local values obtained by each EC system are representative for the sites where those systems are installed along the basin. Sites A, B, and C represented about 54%, 26%, and 20%
of the Wankama catchment. The statistical results—including the slope, correlation coefficient ($R^2$), the root mean square difference (RMSD), standard error of the estimate (SEE), and mean bias error (MBE)—are shown in Table 1. It can be seen that the LAS sensible heat fluxes agree quite well with those derived from the EC systems. The $h_{LAS}^H$ is 3% higher than $h_{EC}^H$ with a relative error of about 20% ($R^2 = 0.85$, RMSD = 21.59 W m$^{-2}$, and SEE = 21 W m$^{-2}$). These results are similar to those reported in Chehbouni et al. (1999, 2000a, b, in press) and Meijninger et al. (2006) over heterogeneous surfaces. Although the correspondence between $h_{LAS}^H$ and $h_{EC}^H$ is good, some scatter is still seen. This can be explained by several factors: the contrast in the footprint scale (see Fig. 3a) with is amplified by the strong heterogeneity along the LAS path due to the changes in vegetation type and cover, as well as to topography; and the uncertainties of the similarity stability functions.

To illustrate this heterogeneity, the daytime evaporation rates measured over each site, which is defined as the ratio of the latent heat flux and the sum of the sensible and latent heat fluxes, were plotted in Fig. 5. Here, it can be seen that the curves of the evaporation rate for “site A” and “site C” are close, with a difference of only about 4%. For “site B,” the evaporation rate was very high.

![Fig. 3. Footprint of the LAS and EC systems, calculated using the footprint model of Horst and Weil (1994) for the wind coming from the intervals 70° to 250° (a) and 250° to 70° (b).](image1)

![Fig. 4. Comparison between measured—derived from the EC systems, $h_{EC}^H$—and estimated—derived from the LAS, $h_{LAS}^H$—area-averaged sensible heat fluxes during the study period (DOYs 204–225). The error bars represent the average uncertainty of the fluxes for each 50 W m$^{-2}$ interval.](image2)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Statistical results of the linear regression (forced to the origin) between measured and estimated surfaces fluxes, area-average of sensible and latent heat fluxes and available energy. The slope, the correlation coefficient, the root mean square difference (RMSD), the mean bias error (MBE), the standard error of the estimate (SEE), and the number of samples are presented.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Sensible Heat flux, $H$</td>
<td>1.03</td>
</tr>
<tr>
<td>Available energy, AE</td>
<td>0.93</td>
</tr>
<tr>
<td>Latent heat flux, LE (using the estimated AE)</td>
<td>0.83</td>
</tr>
</tbody>
</table>

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compared with that of the other sites. This was expected, however, owing to the type of vegetation encountered at “site B” (savannah with a height of 3 m).

Estimating available energy

In many practical applications, area-average observations of net radiation and soil heat flux are not available, especially at the scintillometer footprint scale. However, providing a spatial distribution of surface temperature, albedo, and solar radiation from the satellite images (i.e. MODIS, ASTER), one can estimate the available energy at the catchment scale, using the proposed aggregation approach Eqs. (8)–(12). In the current study, the local measurements of the surface temperature, the albedo, and the incoming solar radiation have been used to estimate the area-averaged available energy \( \langle AE_{\text{est}} \rangle \), assuming that these local measurements are representative of the individual site. The albedo and the incoming solar radiation were calculated as area-weighted averages of those measured over the three sites. The effective surface temperature was obtained by combining Eqs. (10) and (11). In order to quantify the error related to the application of the aggregation rules to the flux estimation, the estimated \( \langle AE_{\text{est}} \rangle \) was compared against the measured values—\( \langle AE_{\text{meas}} \rangle \)—obtained as area-weighted averages of those measured over the three sites. The linear regression shows that \( \langle AE_{\text{est}} \rangle \) is 7% lower than \( \langle AE_{\text{meas}} \rangle \), with a relative error of about 34% \( (R^2 = 0.83, \text{RMSD} = 59.53 \text{ W m}^{-2} \text{ and SEE} = 55.44 \text{ W m}^{-2}; \text{Table 1}) \). This result indicates that the aggregation scheme is not exact and errors are associated with some of the assumptions used to derive them. Additionally, it is important to mention that the use of the Brutsaert’s formula for estimating the atmospheric radiation—which was established for clear sky conditions only—may create an extra scatter between measured and estimated values.

Fig. 5. Daily evaporation rate estimated at the three EC sites during the study period (DOYs 204–225). The rainfall is shown in the same figure.

Fig. 6. Comparison between the estimated—\( \langle AE_{\text{est}} \rangle \)—obtained using the aggregation approach—and measured—\( \langle AE_{\text{meas}} \rangle \)—obtained as area-weighted averages of those measured over the three sites—area-averaged available energy during the study period (DOYs 204–225). The error bars represent the average uncertainty of the fluxes for each 50 W m\(^{-2}\) interval.
and estimated net radiation (Ezzahar et al., 2007a). Therefore, this scatter can be translated to the soil heat flux, since the latter was estimated as a fraction of net radiation. Overall, these results showed that, at least under the prevailing conditions of this study, the proposed approach leads to accurate estimates of instantaneous area-averaged available energy over heterogeneous and contrasted surfaces.

**Latent heat flux**

The estimated area-average latent heat flux from the LAS (denoted \(\text{LE}_{\text{LAS}}(\text{AE}_{\text{est}})\)) was obtained as the residual term of the energy balance (Eqs. (1)–(15)). Fig. 7 displays a comparison between measured and estimated area-average latent heat fluxes measured over the three sites using EC systems. The legend shows that \(\text{LE}_{\text{EC}}(\text{AE}_{\text{EC}})\) is 17% lower than \(\text{LE}_{\text{LAS}}(\text{AE}_{\text{est}})\), with a relative error of about \(\text{R}^2 = 0.72\), RMSD = 64 W m\(^{-2}\), and SEE = 50 W m\(^{-2}\). This shows that the LAS can be effectively used to estimate spatially-averaged sensible heat flux over complex terrains.

Additionally, the area-average latent heat flux was derived as the residual term of the energy balance equation through the combination of an aggregation scheme to derive area-average available energy and the LAS measurements. The comparison of the estimated latent heat flux (obtained using the aggregated available energy) against the area-average EC measurements yielded an acceptable agreement with an underestimation of 17% and a relative error of 34% \(\text{R}^2 = 0.72\) and RMSD = 64 W m\(^{-2}\), SEE = 50 W m\(^{-2}\). This difference was related basically to the error in the estimation of the area-average available energy, especially for low values. In spite of this scatter, the results demonstrate the potential of the proposed model (a combination of the LAS together with the aggregation scheme) to estimate latent heat flux over large and heterogeneous areas.

The proposed model to aggregate the available energy used local measurements of surface temperature, albedo, and solar radiation, and assumed that these local measurements are representative of the individual sites. This assumption can certainly lead to some errors because the heterogeneity is also encountered at the field or patch scale. To overcome this problem, a forthcoming investigation will address the possibility of using MODIS data to derive spatially-distributed available energy before aggregating it according to the LAS footprint, in order to assure spatial matching of the \(H\) and \(\text{AE}\) scales.

Finally, despite the limitations mentioned above, one can safely conclude that the proposed approach is reasonably adequate for routinely quantifying the values of LE at a catchment scale. The

![Fig. 7. Comparison between measured—derived from the EC systems, \(\text{LE}_{\text{EC}}\)—and estimated—derived from the LAS using the estimated available energy, \(\text{LE}_{\text{LAS}}, \text{AE}_{\text{est}}\)—area-averaged latent heat fluxes during the study period (DOYs 204–225). The error bars represent the average uncertainty of the fluxes for each 50 W m\(^{-2}\) interval.](image-url)
implication of this result is of great importance for improving the parameterization of land surface fluxes in meso-scale models. This result is also of great interest for hydrological modeling and, therefore, for water resources management. Indeed, accurate basin scale estimates of LE will significantly help in assessing the overall performance of hydrological models. In this regard, Chapronière et al. (2007) have shown that the fact that a hydrological model correctly simulates the observed runoff does not mean that intermediate processes such as the interaction between ground water and surface water or basin evapotranspiration are well reproduced.

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Appendix A

The contributing surface-to-scaler flux measurement from the LAS, called the source area (SA), was calculated using the analytical footprint model proposed by Horst and Weil (1992, 1994). The footprint function \( f \), or the contribution per unit surface flux of each unit element \( u \) upwind surface area to a measured vertical flux, relates to \( t \), the local flux measured at height \( z_0 \), to the spatial distribution of surface fluxes, \( R(x, y, z) \), i.e.

\[
\int_0^x \int_0^y f(x', y') f(x - x', y - y') \, dx' \, dy' \, R(x, y, z) \, dz_0 = \int_0^a \int_0^b f(x, y) f(x - x, y - y) \, dx \, dy \, R(x, y, z) \tag{A.1}
\]

where \( x \) and \( y \), respectively, are the upwind and crosswind distances; \( m \) the friction velocity, \( \frac{z}{u^*} \); point where the measurements are taken. In this study, we calculated the crosswind-integrated footprint function using the model of Horst and Weil (1994):

\[
\Phi(x, y, z_0) = \frac{\partial^2 \Phi}{\partial x \partial y} \frac{\partial \Phi}{\partial (z_0)} \exp \left( -\frac{z_0}{\delta^2} \right) \tag{A.2}
\]

where \( \delta \) is the mean plume height for diffusion from a surface area \( A \) and \( u(z) \) the mean wind speed profile. The variables \( A, \delta \), and \( u(z) \) are known functions of shape parameter \( r \). We have assumed that the value of the MOST is small (Meijninger et al., 2002b).

In the case of the LAS, one has to combine \( f \) with the spatial weighting function \( W(x) \) of the LAS in order to calculate the source area.

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