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The use of the scintillation technique for monitoring seasonal water consumption of olive orchards in a semi-arid region

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ABSTRACT

To monitor seasonal water consumption of agricultural fields at large scale, spatially averaged surface fluxes of sensible heat (H) and latent heat (L_e) are required. The scintillation method is shown to be a promising device for obtaining the area-averaged sensible heat fluxes, on a scale of up to 10 km. These fluxes, when combined with a simple available energy model, can be used to derive area-averaged latent heat fluxes. For this purpose, a Large Aperture Scintillometer (LAS) was operated continuously for more than one year over a tall and sparse irrigated oliveyard located in south-central Marrakesh (Morocco). Due to the flood irrigation method used in the site, which induces irregular pattern of soil moisture both in space and time, the comparison between scintillometer-based estimates of daily sensible heat flux (H_{LAS}) and those measured by the classical eddy covariance (EC) method (H_{EC}) showed a large scatter during the irrigation events, while a good correspondence was found during homogenous conditions (dry conditions and days following the rain events). We found, that combining a simple available energy model and the LAS measurements, the latent heat can be reliably predicted at large scale in spite of the large scatter ($R^2 = 0.72$ and $RMSE = 18.25 \text{ W m}^{-2}$) that is obtained when comparing the LAS against the EC. This scatter is explained by different factors: the difference in terms of the source areas of the LAS and EC, the closure failure of the energy balance of the EC, and the error in available energy estimates. Additionally, the irrigation efficiency was investigated by comparing measured seasonal evapotranspiration values to those recommended by the FAO. It was found that the visual observation of the physical conditions of the plant is not sufficient to efficiently manage the irrigation, a large quantity of water is lost ($\approx 37\%$ of total irrigation). Consequently, the LAS can be considered as a potentially useful tool to monitor the water consumption in complex conditions.

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1. Introduction

The arid and semi-arid regions constitute roughly one third of the total earth surface. In these regions water scarcity is one of the main limiting factors for economic growth. The impact of such water scarcity is amplified by inefficient irrigation practices, especially since about 85% of available water is used for irrigation in these regions. In this context, several research programs have been designed to develop tools to support efficient management of irrigation water in arid and semi-arid zones. SUDMED (Chehbouni et al., 2003, 2004) and IRRIMED (<http://www.irrimed.org>) projects are amongst those programs taking place in the southern Mediterranean region. These projects focus on the assessment of temporal and spatial variability of water needs and consumption of irrigated agriculture under limited water resource conditions. The projects area is located in the Tensift river basin which includes the Haouz plain (near Marrakesh city, Morocco). In the Haouz plain the climate is semi arid and is characterized by low and irregular rainfall. The average amount of rainfall per year is about 240 mm, whereas the evaporative demand is very high – around 1600 mm per year – according to the FAO method (Allen et al., 1998). Cereals (wheat, barley), olive and citrus orchards are the dominating crops in the plain and use as much as 84% of the total available water.

Due to its high adaptability to semi-arid climate, olives make up the main component of the orchard in the Houaz plain. Flood irrigation is widely practiced by the majority of the farmers (more than 85%). Part of the water supplied to the orchard by rainfall and irrigation is effectively consumed by the crop, whereas the remaining is stored in the soil, percolates to deeper soil, or is lost through soil evaporation. In this regard, one can classify the loss in two categories: agronomical loss and hydrological loss. Agronomists consider that all the water which is not used by the plant is lost, while hydrologists judge only the soil evaporation to be lost since the infiltrated water is used to refill the ground water.

The present study focused on estimating seasonal water needs and consumption of a tall and sparse irrigated oliveyard (Agdal). Eddy covariance (EC) technique was used to monitor evapotranspiration, it is proven to be the most accurate method to measure evapotranspiration or latent heat flux: L_vE is a local measurement and therefore difficult to use in the case of heterogeneous surfaces, unless a network of EC systems is available which is very costly and require a well trained staff to operate and to maintain it. Moreover, over tall sparse vegetation such as an oliveyard, the variability of local fluxes appears to be large (e.g. Vogt et al., 2004), therefore, strictly speaking several EC systems are needed, whereas a scintillometer provides an area average. From the view point of the farmer, a scintillometer has the advantage that the receiver and detector are installed at the peripheral of the field and not in the centre. This seriously limits the applicability of such system at the scale of the irrigation district which is the relevant scale for water managers. For these practical reasons it is worth investigating the applicability of scintillometry over this tall sparse vegetating type. As far as we know such a study on scintillometer applicability to large scale water management has never been performed before.

In this context, the scintillation method which can provide either direct or indirect estimates of L_vE along a path length,

whose dimensions may range from a few hundred metres up to 10 km has been considered as an effective way to overcome this difficulty (Chehbouni et al., 1999). Three types of scintillometers are available: radio wave scintillometers (RWS), small aperture (laser) scintillometers (SAS), and large aperture scintillometers (LAS). The RWS, which operates at radio wavelength is the most sensitive to humidity fluctuations (Andreas, 1989) and is more suitable for directly obtaining L_vE over large areas. However, this type of scintillometer is not widely used since its system components are expensive and difficult to operate, moreover some interferences may occur especially close to cities (Meijninger et al., 2002a). Conversely, the LAS which operates in the visible and near-infrared wavelength region of the spectrum is relatively cheap and very robust which makes it suitable for operation in remote fields. This explains the fact that the LAS is regularly used nowadays in micrometeorological experiments (e.g. Chehbouni et al., 2000 (SALSA); Hoedjes et al., 2002 (Yaqui 2000); Hartogensis et al., 2002; Poulos et al., 2000 (CASES-99); Beyrich et al., 2000 (LITFASS-98), and 2006 (LITFASS-2003)).

However, the LAS only provides spatially averaged sensible heat flux (H_{LAS}). As it has been shown in Meijninger et al. (2002a), latent heat flux (L_vE_{LAS}) can then be obtained as the residual term of the energy balance equation providing estimates of available energy ($R_n - G$), where (R_n) is the net radiation and (G) is the soil heat flux.

In this study the potential of the LAS to derive L_vE_{LAS} over a complex field was investigated. The complexity is due to the fact that the vegetation is tall and sparse, which means that transfer processes are more complex than for short and dense crops, and this Monin-Obukhov similarity theory may not apply. Moreover, flood irrigation creates a large heterogeneity in soil humidity, and in some cases advection from the surrounding areas occurred.

The main objective of this paper is two-fold: (1) to combine the LAS measurements with estimates of available energy to derive spatially averaged L_vE_{LAS} , and (2) to investigate the feasibility of using the LAS to monitor seasonal water consumption of olive orchards in the Haouz semi-arid plain and to document irrigation efficiency through the comparison between LAS-based estimates of evapotranspiration values to those recommended by the FAO method (FAO-56). This paper is organised as follows: a brief physical background of the scintillation method and the proposed models to estimate the available energy are first provided. Second, an overview of the experimental design follows with a presentation of the results before presenting comparisons between simulated and observed fluxes. Finally, a discussion about the potential of the LAS combined with the estimated available energy to calculate the L_vE over olive orchards, and the ability of this approach to monitor the water consumption over semi-arid land, is presented.

2. Theoretical background

2.1. Determining the sensible heat flux, H_{LAS} , with LAS

The LAS is a device that provides measurements of the variation in the refractive index of air caused by atmo-

spheric turbulence. This instrument consists of a transmitter and a receiver installed at a certain height z_{LAS} above the surface. The LAS used in this study has an aperture diameter D of 15 cm. The transmitter emits electromagnetic radiation at wavelength $\lambda = 940$ nm over a known path length (L). The fluctuations in the light intensity at the receiver are analysed to give the variation of C_n^2 along the path.

Hill et al. (1980) has related C_n^2 with the structure parameters of temperature (C_T^2), humidity (C_q^2) and the covariant term (C_{Tq}) as follows:

$$C_n^2 = \frac{A_T^2}{T^2} C_T^2 + \frac{A_T A_q}{Tq} C_{Tq} + \frac{A_q^2}{q^2} C_q^2 \quad (1)$$

where A_T and A_q are quantities that represent the relative contribution of each term to C_n^2 , which are both dependent on optical wavelength and the mean values of temperature (T), humidity (q), and atmospheric pressure (p). In the case of the LAS in this project, the values of A_T and A_q are given by Andreas (1989):

$$A_T = -0.78 \times 10^{-6} \frac{p}{T} \quad (2)$$

$$A_q = -57.22 \times 10^{-6} q \quad (3)$$

Generally, the first term, containing C_T^2 , is much larger than the other two terms, except in the case where the Bowen-ratio β ($=H_{LAS}/L_v E_{LAS}$) is much smaller than 1. Assuming that temperature and humidity fluctuations are perfectly correlated, Wesely (1976) showed that the temperature structure parameter C_T^2 can be derived from the refractive index structure parameter C_n^2 by:

$$C_T^2 = C_n^2 \left(\frac{T^2}{\gamma p} \right)^2 \left(1 + \frac{0.03}{\beta} \right)^{-2} \quad (4)$$

where γ is the refractive index coefficient for air ($7.8 \times 10^{-7} \text{ K Pa}^{-1}$). The final bracketed term is a correction for the effects of humidity. C_n^2 and C_T^2 are in ($\text{m}^{-2/3}$) and ($\text{K m}^{-2/3}$), respectively.

According to the Monin-Obukhov Similarity Theory (MOST), it is possible to link the temperature structure parameter C_T^2 and the temperature scale T^* for unstable conditions, i.e., $L_{MO} < 0$:

$$C_T^2 = T_*^2 (z_{LAS} - d)^{-2/3} h \left(\frac{z_{LAS} - d}{L_{MO}} \right) \quad (5)$$

where z and d are the measurement and displacement height, respectively, h is a universal function. Wyngaard et al. (1971) found the following relation for h under unstable conditions:

$$h \left(\frac{z_{LAS} - d}{L_{MO}} \right) = c_{T1} \left(1 - c_{T2} \frac{z_{LAS} - d}{L_{MO}} \right)^{-2/3} \quad (6)$$

where c_{T1} and c_{T2} are constants, given by De Bruin et al. (1993) as 4.9 and 9.

Under stable conditions, Thiermann and Grassl (1992) proposed:

$$h \left(\frac{z_{LAS} - d}{L_{MO}} \right) = 6.34 \left(1 + 7 \frac{z_{LAS} - d}{L_{MO}} + 20 \left(\frac{z_{LAS} - d}{L_{MO}} \right)^2 \right)^{1/3} \quad (7)$$

L_{MO} is the Monin-Obukhov length (m) given by:

$$L_{MO} = - \frac{T_a u_*^2}{k g T^*} \quad (8)$$

with $k = 0.41$ is the von Karman constant, $g = 9.81 \text{ m s}^{-2}$ (gravity) and u_* (m s^{-1}) is the friction velocity:

$$u_* = k u \left[\ln \left(\frac{z_{LAS} - d}{z_0} \right) - \psi \left(\frac{z_{LAS} - d}{L_{MO}} \right) \right]^{-1} \quad (9)$$

u is the wind speed and ψ is the integrated stability function defined for unstable conditions ($z/L_{MO} < 0$) as (Panofsky and Dutton, 1984)

$$\psi \left(\frac{z_{LAS} - d}{L_{MO}} \right) = 2 \ln \left[\frac{1+x}{2} \right] + \ln \left[\frac{1+x^2}{2} \right] - 2 \arctan(x) + \frac{\pi}{2} \quad (10)$$

with

$$x = \left(1 - 16 \frac{z_{LAS} - d}{L_{MO}} \right)^{1/4}$$

z_0 is the roughness length. Knowing u_* and T^* , the sensible heat flux H_{LAS} (W m^{-2}) can be calculated as:

$$H_{LAS} = \rho c_p u_* T^* \quad (11)$$

with ρ (kg m^{-3}) and c_p ($\text{J kg}^{-1} \text{K}^{-1}$) are the air density and heat capacity, respectively.

The latent heat flux from the LAS is obtained as the residual the energy balance as (Meijninger et al., 2002a):

$$L_v E_{LAS} = R_n - G - H_{LAS} \quad (12)$$

In this study, a footprint model proposed by Horst and Weil (1992, 1994) was applied to determine the source areas for turbulent fluxes from the EC and the LAS (see Appendix A). In the case of the LAS, one has to combine footprint function with the spatial weighting function $W(x)$ of the LAS in order to calculate the source area.

2.2. Proposed models to estimate available energy

2.2.1. Net radiation

The net radiation quantifies the energy available for crop evapotranspiration, photosynthesis, and soil heating (Monteith and Unsworth, 1990). Several authors have related net radiation to solar radiation by means of empirical relationships (André and Viswanadham, 1983; Kowalik and Turner, 1983; Mermier and Seguin, 1976). Unfortunately, these relationships may be difficult to be generalized to all surface and atmospheric conditions. In this study, the following

method for estimating net radiation at half-hourly time step from classical meteorological data is used. The net radiation is expressed as follows (Ortega-farias et al., 2000):

$$R_n = (1 - \alpha)R_g + \varepsilon_s R_a - R_t \quad (13)$$

where α is the surface albedo, R_g is the solar global radiation ($W m^{-2}$), ε_s is the surface emissivity, R_a the atmospheric radiation which is emitted by air molecules ($W m^{-2}$) and R_t is the terrestrial radiation which is emitted by the surface ($W m^{-2}$). By using the Stefan–Boltzman equation (Monteith and Unsworth, 1990), R_a and R_t can be expressed as a function of air and surface temperatures, respectively. Then, Eq. (13) can be rewritten as:

$$R_n = (1 - \alpha)R_g + \varepsilon_s \sigma (\varepsilon_a T_a^4 - T_{surf}^4) \quad (14)$$

with ε_a is the emissivity of the atmosphere, T_a is the air temperature (K), T_{surf} is the surface temperature (K), and σ is the Stefan–Boltzman constant ($5.67 \times 10^{-8} W m^{-2} K^{-4}$). In this study, T_{surf} was estimated from measured soil and canopy temperatures weighted by the fractional area of vegetation (Norman et al., 1995):

$$T_{surf} \approx [f_c T_c^4 + (1 - f_c) T_s^4]^{1/4} \quad (15)$$

where f_c is the cover fraction of olive trees.

Many authors have proposed empirical relationships which relate the atmospheric emissivity to the air temperature (Angstrom, 1918; Brunt, 1932; Idso, 1981). In what follows, we used the expression proposed by Brutsaert (1975) where ε_a is computed from air temperature and vapour pressure as:

$$\varepsilon_a = 1.24 \left(\frac{e_a}{T_a} \right)^{1/7} \quad (16)$$

where e_a is the air vapour pressure (hPa). Brutsaert (1975) pointed out that the 1.24 value for the proportionality coefficient, which was derived on an atmospheric radiative transfer basis, should vary according to variations in the type of atmosphere. Hatfield et al. (1983) and Olioso (1992) found that the original coefficient in the Brutsaert formula (1.24) led to an underestimation in calculated atmospheric radiation by 5%.

2.2.2. Soil heat flux

Due to the complexity of surface cover and physical processes occurring in the soil, the soil heat flux is the most difficult scalar to measure accurately at the appropriate space-scale. Several authors have related this scalar to the net radiation (Stull, 1988; Villalobos et al., 2000). In this study, we used the simple formula proposed by Su et al. (2001):

$$G = R_n [\Gamma_c + (1 - f_c)(\Gamma_s - \Gamma_c)] \quad (W m^{-2}) \quad (17)$$

in which they assume the ratio of soil heat flux to net radiation is $\Gamma_c = 0.05$ for full vegetation canopy (Monteith, 1973) and $\Gamma_s = 0.315$ for bare soil (Kustas and Daughtry, 1989).

3. Experimental site and measurements

3.1. Site description

The experiment was carried out between day of year (DOY) 323 (2002) and DOY 323 (2003) at the 275 ha Agdal olive orchard which is located to the southeast of the city of Marrakech, Morocco ($31^{\circ}36'N$, $W007^{\circ}58'$). Fig. 1 displays the area of interest on a very high spatial resolution image acquired by the Quickbird satellite (0.62 and 2.4 m in panchromatic and multi-spectral, respectively). The climate is typically semi arid Mediterranean; precipitation falls mainly during winter and spring, from the beginning of November until the end of April, with an average ranging from 192 to 253 mm per year. The atmosphere is very dry with an average humidity of 56% and the evaporative demand is very high (1600 mm per year), greatly exceeding the annual rainfall.

The experiment was set up in the southern area of the Agdal orchard, of about 700 m \times 800 m, surrounded by fields of orange and olive trees (Fig. 1). The average height of the olive trees is 6 m with an average coverage that reaches approximately 55%. Two water basins are used for irrigation. Water is diverted manually to every tree through a network of ditches, each tree is surrounded by a small earthen levy that retains the irrigation water, allowing application of irrigation water to every tree. The amount of water used during each irrigation event was about 80 mm. Irrigation starts on the southern border of the field, and, depending on available manpower, progresses towards the northern border of the site in approximately 12 days.

3.2. Micrometeorological and flux measurements

The field was equipped with a set of standard meteorological instruments to measure wind speed and direction (with a

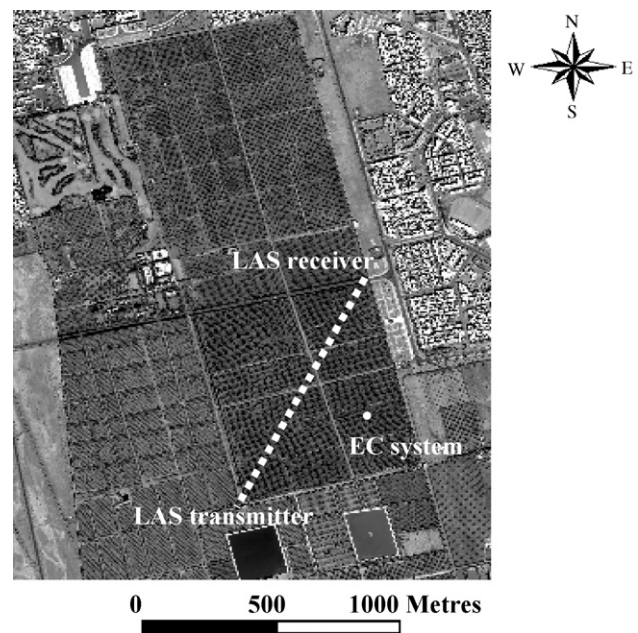
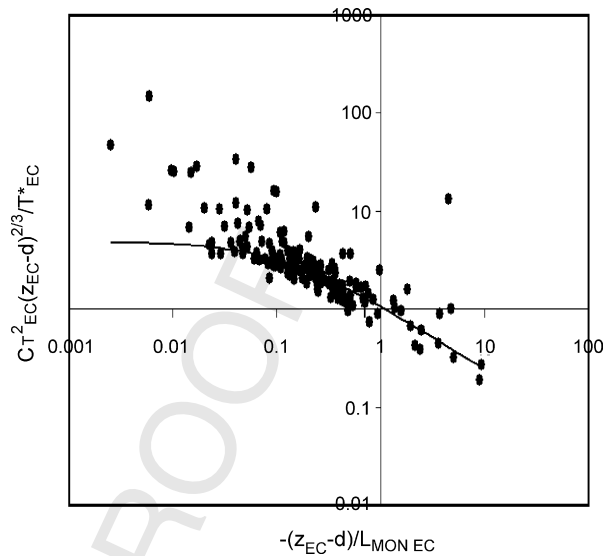


Fig. 1 – Overview of the study site (Quickbird image). The white dotted line represents the LAS path, and the location of EC system is also presented.

317 Young Wp200 anemometer), air temperature and humidity
 318 (with a vaisala HMP45AC probe) at 9 m above the ground. The
 319 four components of the net radiation were measured using a
 320 CNR1 radiometer (Kipp & Zonen), i.e. independant estimates
 321 incoming and outgoing solar and far-infrared radiation. The
 322 CNR1 was located in a place (at 8.5 m) that is representative of
 323 the vegetation and soil. Radiative soil and vegetation temper-
 324 atures were measured using 2 IRTS-P's (Apogee). The soil
 325 heat flux density was measured using heat flux plates (HFT3-L,
 326 Campbell Scientific Ltd.) at three locations with contrasting
 327 amounts of radiation reaching the soil. The measurement
 328 depth was 1 cm. The plates were placed: one below the tree
 329 near the trunk in order not to be exposed to direct solar
 330 radiation; one was exposed directly to solar radiation, the last
 331 one in an intermediate position. An average of these three
 332 measurements was made to obtain a representative value. Soil
 333 temperature was recorded at two locations at a depth of 0.05 m
 334 (temperature probe 108). Soil moisture was measured at
 335 different depths (0.05, 0.1, 0.2, 0.3 and 0.4 m) using 5 CS616
 336 water content reflectometers (Campbell Scientific Ltd.). Mea-
 337 surements were sampled at 1 Hz, averaged, and then stored at
 338 30 min intervals on CR10X dataloggers.

340 An EC system was installed to provide continuous
 341 measurements of vertical fluxes of heat, water vapour and
 342 carbon dioxide (CO₂) at 9.2 m (see Fig. 1). During the first three
 343 months the EC system consisted of a 3D sonic anemometer
 344 (CSAT3, Campbell Scientific Ltd.) which measured the fluctua-
 345 tions in the wind velocity components and temperature, and
 346 an open-path infrared gas analyser (LICOR-7500, Campbell
 347 Scientific Ltd.) that measured concentration of water vapour
 348 and carbon dioxide. Raw data were sampled at a rate of 20 Hz
 349 and were recorded using a CR23X dataloggers (Campbell
 350 Scientific Ltd.) which were connected to portable computer to
 351 enable storage of large raw data files. After the first three
 352 months of the experiment, the LICOR-7500 IRGA was replaced
 353 by a Krypton hygrometer (KH20, Campbell Scientific Ltd.), and
 354 the datalogging system was replaced with a CR5000 datalogger
 355 (Campbell Scientific Ltd.), equipped with a 1 Gb PCMCIA-card
 356 for the storage of large raw data files. The half-hourly fluxes
 357 were later calculated off-line after performing planar fit
 358 corrections (Wilczak et al., 2001), correcting the sonic
 359 temperature for the presence of humidity (Schotanus et al.,
 360 1983), frequency response corrections for slow apparatus and
 361 path length integration (Moore, 1986), the inclusion of the
 362 mean vertical velocity according to Webb et al. (1980) and
 363 oxygen correction for the Krypton hygrometer, which is
 364 sensitive to O₂ (Van Dijk et al., 2003). For the data processing,
 365 use was made of the eddy covariance processing software
 366 'ECpack', developed by the Meteorology and Air Quality Group,
 367 Wageningen University. This software is available for down-
 368 load at <http://www.met.wau.nl/>.

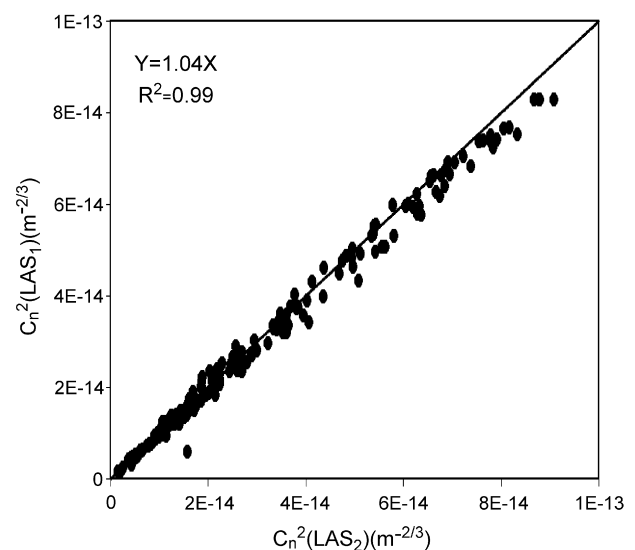
369 In order to ascertain that the height of the EC was adequate
 370 and fulfils the conditions required for turbulent fluxes
 371 measurements (i.e. the constant-flux layer), one can study
 372 the behaviour of the temperature structure parameter (C_{TEC}^2),
 373 the temperature scale (T_{EC}^*) and the Monin-Obhukov length
 374 $L_{MON EC}$ derived from the EC according to MOST. For this
 375 purpose, observed values of $C_{TEC}^2(z_{EC} - d)^{2/3}/T_{EC}^{*2}$ have been
 376 plotted against observed values of $(z_{EC} - d)/L_{MON EC}$ in Fig. 2,
 377 together with the scaling curve (Eq. (6)). The measurements



377 **Fig. 2 – Observed values of $C_{TEC}^2(z_{EC} - d)^{2/3}/T_{EC}^{*2}$ plotted**
 378 **against observed $(z_{EC} - d)/L_{MON EC}$, all data were derived from**
 379 **the EC system. Solid line represents the scaling giving by**
 380 **De Bruin et al. (1993): $4.9(1 - 9(z_{EC} - d)/L_{EC})^{-2/3}$.**

377 follow the shape of the theoretical scaling given by De Bruin
 378 et al. (1993). Therefore, it can be conclude that the measure-
 379 ments were taken in the constant-flux layer.

381 Additionally, two identical LAS were used in this experi-
 382 ment, the first one (denoted LAS₁) was operated from the
 383 beginning of the experiment until DOY 12 (2003) and was then
 384 replaced with the second one (denoted LAS₂). Both of them
 385 were built by the Meteorology and Air Quality Group
 386 (Wageningen Agriculture University, the Netherlands). These
 387 instruments were made according the basic design described
 388 in Ochs and Wilson (1993). They have an aperture size of
 389 0.15 m and the wavelength of the light beam emitted by the
 390 transmitter is 940 nm. At the receiver, C_n^2 was sampled at 1 Hz



391 **Fig. 3 – Inter-comparison between the two scintillometers**
 392 **referred as LAS₁ and LAS₂ used in the experiment.**

and averaged over 1 min time steps by a CR510 datalogger. The LAS were installed perpendicularly to the dominant wind direction with a path length of 1 km. The transmitter was mounted on a tripod installed on a roof, located on the southwest corner of the field, while the receiver was mounted on a 15 m high tower that was positioned next to the road (see Fig. 1). The path of the scintillometer was chosen so that the saturation effects are expected to be small (Kohsiek et al., 2006).

In order to be more confident in the consistency in the measurements made by both LAS, an inter-comparison of the two LAS was performed between DOY 284 (2002) and 288 (2003). To avoid possible interference between the two signals, the transmitter and receiver were alternated. They were deployed at the same height. The linear regression forced through the origin yielded ($m^{-2/3}$): $C_n^2(LAS_1) = 1.04C_n^2(LAS_2)$, $R^2 = 0.99$. This means that the agreement is excellent with 4% difference (Fig. 3). This small difference lies within acceptable instrumental error.

4. Results and discussions

In this paragraph we first analysed the closure of the energy balance. Then the measured and simulated ($R_n - G$) components were compared, as well as the sensible heat flux measured by EC (H_{EC}) and that derived from the LAS (H_{LAS}). After that, the feasibility of deriving the latent heat flux from the LAS with the estimated values of the available energy ($R_n - G$) was checked, so that $L_v E$ can be derived at large scale with a minimum number of instruments in the fields.

4.1. Energy balance closure

The energy balance closure is an important indicator of the performance of an EC system. By ignoring the term of canopy

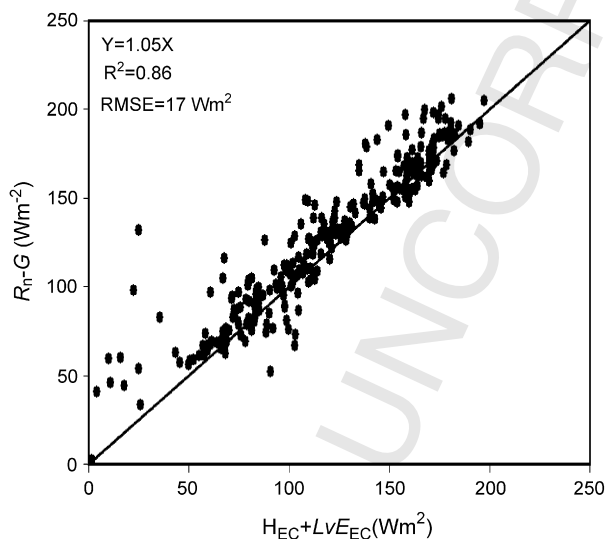


Fig. 4 – Assessment of energy balance closure. Daily average fluxes of net radiation (R_n) minus the soil heat flux (G) are compared against the sums of sensible (H_{EC}) and latent heat ($L_v E_{EC}$) measured by the eddy correlation system.

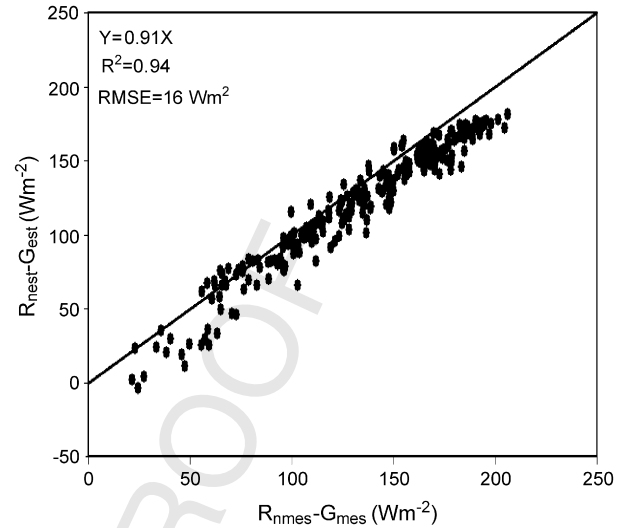


Fig. 5 – Comparison between daily estimated ($R_{nest} - G_{est}$) and observed ($R_{nmes} - G_{mes}$) available energy.

heat storage at daily time scale (Testi et al., 2004; Baldocchi et al., 2004) and assuming the principle of conservation of energy, the energy balance closure is defined as $R_n - H_{EC} - L_v E_{EC} - G$ and should be close to zero ($L_v E_{EC}$ is the latent heat flux derived from the EC). In this study all daily values were calculated by averaging up the half-hourly values. Fig. 4 presents a cross plot between measured ($R_n - G$) and the sum of the turbulent fluxes ($H_{EC} + L_v E_{EC}$) for daily time scale. A linear regression yields: $R_n - G = 1.05(H_{EC} + L_v E_{EC})$ and $R^2 = 0.86$, with $RMSE = 17 \text{ W m}^{-2}$ (the equation used to calculate RMSE is presented in Appendix B). The difference in terms of the sources areas of the different instruments has the biggest impact on the closure of the energy balance especially over sparsely vegetated surfaces. The source area sampled by eddy covariance is much larger than that of net radiation and soil heat flux and it can change rapidly depending on wind speed and direction and on surface conditions. However, comparatively to what has been reported in the literature (Testi et al., 2004; Baldocchi et al., 2004; Twine et al., 2000), the closure can be considered as fairly good.

4.2. Estimating available energy

The net radiation is derived from Eq. (14) using an albedo value of 0.11 (annual averaged measured with CNR1), a surface emissivity of 0.98 (Jones et al., 2003), and the atmospheric radiation is computed from air temperature and vapour pressure using Brutsaert's formula with a correction factor taking into account the 5% underestimation shown by different authors (Hatfield et al., 1983; Olioso, 1992; Ortega-farias et al., 2000). The soil heat flux was estimated using Eq. (17). Due to power supply problems at the beginning of the experiment, some data were missing, we therefore used 270 days of data.

The comparison between daily observed and estimated available energy is presented in Fig. 5. A regression analysis yields (W m^{-2}): $R_{nest} - G_{est} = 0.91(R_{nmes} - G_{mes})$, $R^2 = 0.94$, and $RMSE = 16 \text{ W m}^{-2}$. The subscripts est and mes referred to

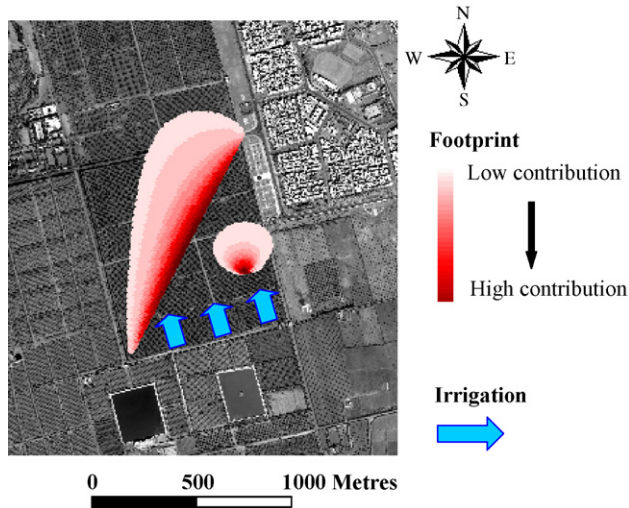


Fig. 6 – Footprints of the LAS and EC system (corresponding to approximately 95% of the sensible heat flux) are shown in red and the irrigation schedule in blue.

457
458 estimated and measured values, respectively. It can be seen
459 that the simple model used to estimate the available energy
460 works fairly well over tall and sparse vegetation (an under-
461 estimation of 9%). It must be noted that the use of the
462 Brutsaert's formula which was established for clear sky
463 conditions only, may create an important scatter for low
464 radiation values. To overcome this difficulty, a comparison
465 between the R_{nmes} and R_{nest} using the measured and the
466 estimated atmospheric radiation was made (not shown). A
467 regression analysis for both comparisons yields almost the
468 same slope (≈ 0.96), but the R^2 and RMSE differed. The R^2 and
469 RMSE were 1 and 5 W m^{-2} , and 0.95 and 12 W m^{-2} for
470 measured and estimated atmospheric radiation, respectively.

4.3. Sensible and latent heat fluxes

471
472 To assess the accuracy of the LAS, a comparison of the daily
473 sensible heat fluxes derived from the LAS and those measured
474 from the EC system was made. The days with missing data in
475 LAS and EC measurements were not taken into account.
476 Missing data was mostly due to rainfall and very strong wind
477 associated with storms which disturbed the alignment of the
478 LAS (about 12% of the data).

479 During this study, the site changes from being almost
480 homogeneous under dry conditions or following rain events to
481 very heterogeneous during the irrigation. The irrigation
482 method creates a large difference in terms of soil moisture
483 which leads to a large difference in the characteristics of the
484 source area sampled by the LAS and by EC, respectively. In
485 Fig. 6, the footprints of the LAS and EC (corresponding to
486 approximately 95% of the sensible heat flux) for the prevailing
487 wind direction are presented, together with the orientation of
488 irrigation. It can be seen that during the irrigation the small
489 source area of the EC will be irrigated much sooner than the
490 large area of the LAS. Consequently, the EC source area started
491 to dry out before the entire source area of the LAS is irrigated.
492 Fig. 7a and b, present comparisons between H_{LAS} and H_{EC} over

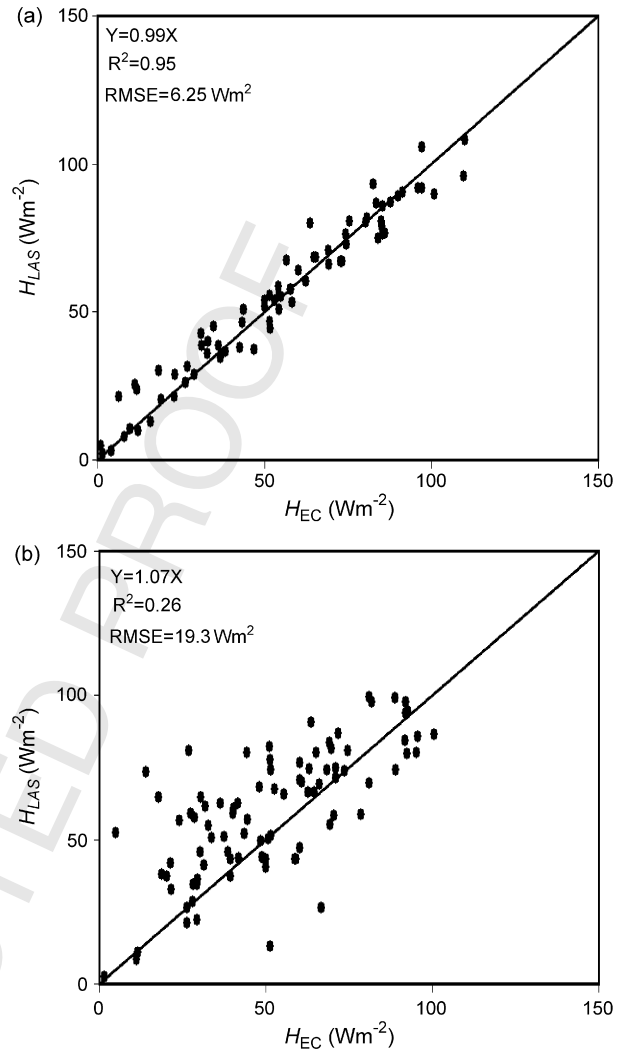


Fig. 7 – (a) Comparison between the daily averaged LAS and EC sensible heat fluxes, H_{LAS} and H_{EC} , respectively, during homogenous conditions (dry conditions and days following the rain events). (b) Comparison between the daily averaged LAS and EC sensible heat fluxes, H_{LAS} and H_{EC} , respectively, during heterogeneous conditions (periods of irrigation events).

492 homogeneous and heterogeneous conditions, respectively.
493 The correlation between H_{LAS} and H_{EC} during the irrigation
494 was very poor ($R^2 = 0.26$, $RMSE = 19.3 \text{ W m}^{-2}$), this disagree-
495 ment was expected due to the irrigation method used, which
496 causes a large heterogeneity in soil humidity of the sources
497 area of the LAS and EC, which in turn affects the sensible heat
498 flux. In contrast, the correlation was very good ($R^2 = 0.95$,
499 $RMSE = 6.25 \text{ W m}^{-2}$) during homogenous conditions (dry con-
500 ditions and days following the rain events). Examining the
501 comparison during the entire year (Fig. 8), yields a satisfactory
502 agreement ($R^2 = 0.72$, $RMSE = 13.3 \text{ W m}^{-2}$). It can be therefore
503 concluded that the effect induced by the irrigation method is
504 compensated when comparison is made during the entire
505 season. This result is of great interest since it indicates that the
506 LAS can be effectively used to accurately estimate spatially
507

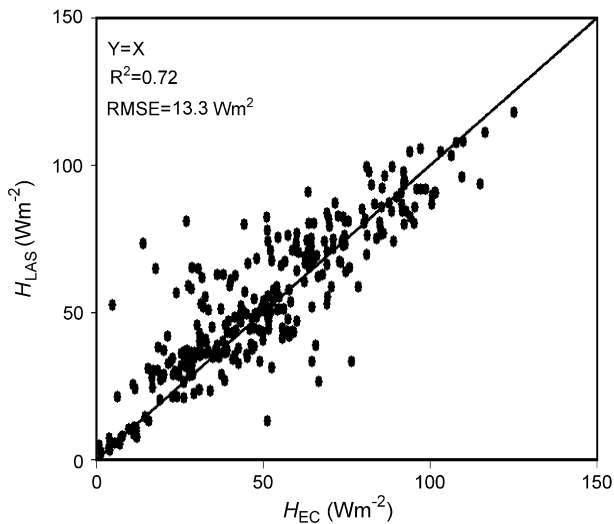


Fig. 8 – Comparison between the daily averaged LAS and EC sensible heat fluxes, H_{LAS} and H_{EC} , respectively, during the entire year.

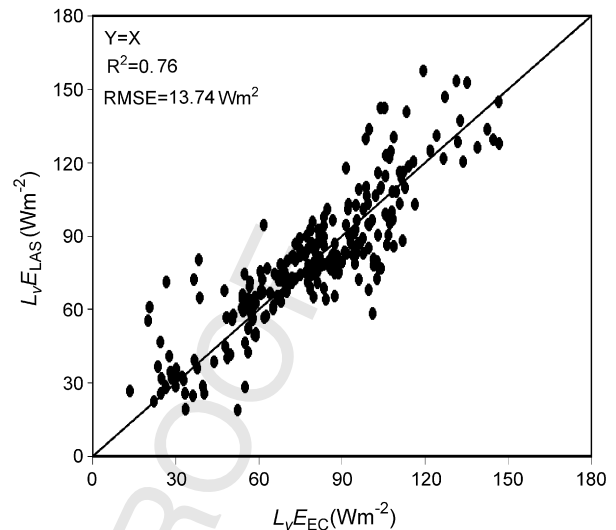


Fig. 10 – Comparison between daily observed (derived from EC system $L_{vE_{EC}}$) and simulated evapotranspiration (derived from the LAS using the measured available energy, $L_{vE_{LAS}}$).

507 averaged sensible heat flux despite the heterogeneity induced
508 by the irrigation method.

509
510 A comparison between the daily latent heat flux from the
511 LAS ($L_{vE_{LAS}}$) calculated as $L_{vE_{LAS}} = R_{nest} - G_{est} - H_{LAS}$ and the
512 latent heat flux from EC ($L_{vE_{EC}}$) is shown in Fig. 9. The
513 regression analysis gives: $L_{vE_{LAS}} = 0.86L_{vE_{EC}}$, $R^2 = 0.72$ and
514 $RMSE = 18.25 W m^{-2}$. Such discrepancy can be explained by
515 the combination of several factors. First, the error asso-
516 ciated with the closure of the measured energy balance is
517 translated into an error in the simulated $L_{vE_{LAS}}$. Second,
518 since the scintillometer-based $L_{vE_{LAS}}$ is obtained as the
519 residual term of the energy balance, any difference between
520 measured and simulated available energy is directly

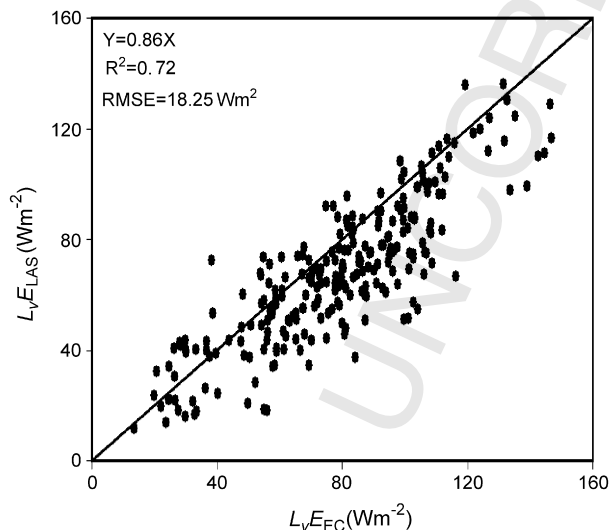


Fig. 9 – Comparison between daily observed (derived from EC system $L_{vE_{EC}}$) and simulated evapotranspiration (derived from the LAS using the estimated available energy, $L_{vE_{LAS}}$).

521 translated into error in the simulated $L_{vE_{LAS}}$. In this regard,
522 comparison between the $L_{vE_{LAS}}$ simulated using the mea-
523 sured available energy values (Fig. 10) and the $L_{vE_{EC}}$ yields to
524 $L_{vE_{LAS}} = 0.96L_{vE_{EC}}$, $R^2 = 0.74$ with $RMSE = 14 W m^{-2}$. More
525 importantly, the impact of the difference in the footprint
526 of the LAS and EC which was very important during the
527 irrigation events greatly influences the correspondence
528 between observed and simulated fluxes. Although a mod-
529 erate discrepancy is observed, the correspondence between
530 measured and simulated L_{vE} is deemed acceptable. There-
531 fore, one can conclude that combining LAS measurements
532 with estimates of available energy is a very effective and
533 operational tool for seasonal crop water consumption
534 assessment at a scale relevant to the managers (i.e. the
535 irrigation district).

4.4. Irrigation efficiency assessment

536
537 In this paragraph, we investigate the efficiency of the irrigation
538 practices over the study site which is representative of the
539 practices in the region. To achieve this, crop water require-
540 ments deduced from the FAO-56 method (FAO-56 paper, Allen
541 et al., 1998) were compared to the LAS-based estimates of
542 ET_{LAS} and the sum of the rainfall and irrigation.

543 During the experiment, the total irrigation applied by the
544 farmer was about 800 mm over 10 irrigation cycles. Total
545 precipitation (P) during the experiment reached 354 mm,
546 which is much higher than the annual average of 240 mm.
547 The yearly estimated evapotranspiration (ET_{LAS}) derived from
548 the LAS was calculated by summing up the daily values. The
549 result in terms of yearly estimates of ET using our approach
550 (ET_{LAS}) was about 860 mm.

551 In order to compare this value against that suggested by the
552 FAO, the crop water requirement (ET_c) was calculated
553 following the standard procedure of the FAO (FAO-56 paper;
554 Allen et al., 1998). ET_c is computed by multiplying reference

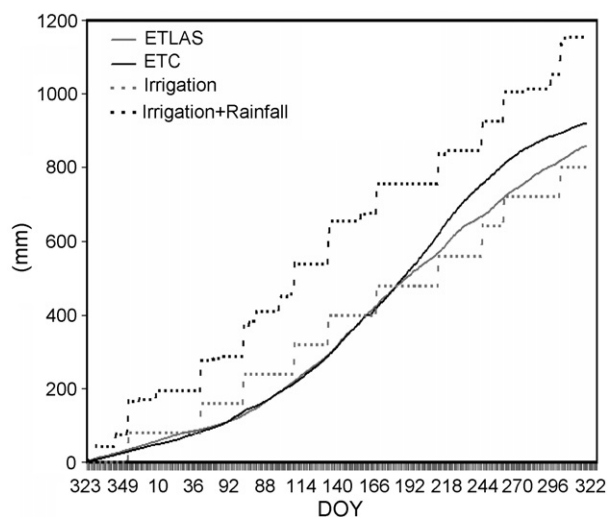


Fig. 11 – Accumulated crop evapotranspiration derived from FOA-56 (ET_c), Evapotranspiration derived from the LAS (ET_{LAS}), irrigation applied by the farmer and sum of irrigation and rainfall.

554 evapotranspiration (ET_0) by a crop coefficient K_c . The mean
 555 value of K_c for olive orchard under environmental conditions is
 556 0.68 (Er-Raki et al., 2006). The yearly simulated ET_c during our
 557 experiment was 920 mm. The accumulated ET_{LAS} and ET_c for
 558 olive season are shown in Fig. 11. By analyzing this figure, the
 559 accumulated ET_{LAS} and ET_c curves are close over the period
 560 DOY 323 to DOY 190. For the remaining days, ET_c was higher
 561 than ET_{LAS} . This is due to the stress induced by irrigation delay.
 562 It can be noticed also in this figure, that although the sum of
 563 irrigation and rainfall was greater than ET_c , one stress event
 564 occurred (from DOY 190). Such behaviour can be explained by
 565 inadequate distribution of irrigation. In fact, the farmer
 566 irrigated just after the recorded rainfall (four irrigations were
 567 applied in this case: DOY 353 (2002), 109 (2003), 169 (2003) and
 568 303 (2003)). Some of those irrigations should have been
 569 delayed (169 (2003), 309 (2003), 109 (2003)) and the first
 570 irrigation (353 (2002)) was unnecessary because it had rained
 571 for a long period beforehand. In addition, an important
 572 amount of water was lost by the flood irrigation technique.
 573 This quantity was lost by deep percolation and runoff and is
 574 noted ΔP . In order to quantify this term, the water balance
 575 equation of the FAO method on a yearly basis (Allen et al.,
 576 1998) was applied. In this study we ignored the variation in the
 577 water storage in the study area, because the initial conditions
 578 were similar to the conditions at the end of the experiment. So
 579 ΔP approached the sum of the total precipitation and irrigation
 580 minus the cumulative of the ET_{LAS} . The yearly ΔP obtained was
 581 around 295 mm considering the irrigation's quantity applied
 582 by the farmer, so it represents about 37% of the total applied
 583 irrigation. Another study was done over the same field by
 584 Williams et al. (2003) and showed that after the irrigation the
 585 soil evaporation represents about 14–28% of the total
 586 evapotranspiration. The result revealed that the farmer
 587 applied a large amount of water and the irrigation system
 588 was not appropriate for the orchard in the Haouz plain
 589 conditions.
 590

5. Conclusion

590 The purpose of this investigation was to identify whether the
 591 large aperture scintillometer combined with a simple available
 592 energy model could be used to monitor the water consumption
 593 in difficult environment conditions (tall vegetation,
 594 irrigation method which has an irregular pattern in space
 595 and time, and variable soil characteristics). An experiment
 596 was conducted over the irrigated oliveyard of Agdal which is
 597 located in Marrakech (Morocco). An eddy covariance (local
 598 scale measurements) and LAS (large scale measurements)
 599 were installed above the olive trees.
 600

601 The daily sensible heat fluxes derived from the LAS agreed
 602 reasonably well with those derived from the EC during
 603 homogenous conditions (dry conditions and days following
 604 the rain events). This result confirms that the LAS works well
 605 over tall and sparse vegetation. During the irrigation events
 606 (flooding irrigation), the comparison showed a large scatter
 607 between the two methods due to the large difference in the
 608 sources area of the LAS and EC created by the irrigation
 609 method.
 610

611 Consequently, the comparison between the latent heat flux
 612 derived from the LAS and that measured by EC yields an
 613 acceptable agreement with an underestimation of 14% and a
 614 large scatter ($R^2 = 0.72$ and $RMSE = 18.25 \text{ W m}^{-2}$). This differ-
 615 ence was related to the poor closure of the energy balance
 616 based on EC turbulent fluxes estimates, the different char-
 617 acteristics between the source areas of the LAS and EC (due to
 618 the irrigation method which created a large heterogeneity in
 619 soil moisture), and the use of Brutsaert's formula to compute
 620 downward longwave radiation. It is concluded that the use of
 621 estimate available energy which can be derived from the
 622 satellite image, the scintillometer is a potentially useful tool to
 623 obtain the latent heat flux at large scale even over complex
 624 surfaces. Therefore, this device provides a great potential for
 625 practical application of remote sensing approaches to basin
 626 scale water balance studies.
 627

628 In addition, the study revealed that the method of irrigation
 629 applied by the farmer was not appropriate for the orchard
 630 conditions, because a large quantity of water is ($\approx 295 \text{ mm}$) lost
 631 by deep percolation and overflow ($\approx 37\%$ of total irrigation).
 632 One can therefore conclude that the irrigation is not efficient,
 633 because the irrigation monitoring is done by visually observing
 634 the physical conditions of the plant which is not sufficient to
 635 manage the irrigation. As a result, it would be advisable to
 636 improve the irrigation management and to recommend to the
 637 farmer to follow a more technical irrigation scheduling criteria
 638 such as, that is by taking into account the actual soil type,
 639 slope, length of water run, flow rates, and weather forecast.
 640

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 645 Hoedjes) was employed by Wageningen University on STW
 646

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Appendix A

The contributing surface to scalar flux measurement from the EC and 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 of the upwind surface area to a measured vertical flux, relates to the vertical flux measured at height z_m , $F(x, y, z_m)$, to the spatial distribution of surface fluxes, $F(x, y, z = 0) \equiv F_0(x, y)$, i.e.,

$$F(x, y, z_m) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F_0(x', y') f(x - x', y - y', z_m) dx' dy' \quad (\text{A.1})$$

(Horst and Weil, 1994). Where x and y , respectively, are the upwind and crosswind distances (m) from the point where the measurements are taken. The source area arises from the integration of the footprint function. In this study we calculated the crosswind-integrated footprint function using the model of Horst and Weil (1994):

$$\bar{f}^y(x, z_m) \cong \frac{dz}{dx} \frac{z_m}{z^2} \frac{\bar{u}(z_m)}{\bar{u}(cz)} A \exp\left[-\left(\frac{z_m}{bz}\right)^r\right] \quad (\text{A.2})$$

where z is the mean plume height for diffusion from a surface source and $u(z)$ the mean wind speed profile. The variables A , b and c are gamma functions of shape parameter r . We have assumed that the violation 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.

Appendix B

The root mean square error (RMSE), which measures the variation of predicted values around observed ones, is calculated as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_{i\text{sim}} - y_{i\text{obs}})^2}$$

where $y_{i\text{sim}}$ and $y_{i\text{obs}}$ are the values of simulated and observed variables, respectively, and n is the number of observations.

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