ESTIMATING SENSIBLE HEAT FLUX USING SURFACE RENEWAL ANALYSIS AND THE FLUX-VARIANCE METHOD. A CASE STUDY Case OVER OLIVE TREES AT SÁSTAGO (NE OF SPAIN)

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ABSTRACT

The Eeddy covariance technique for measuring surface fluxes is often not affordable outside experimental research institutes. Therefore, knowledge of the performance of alternative methods for determining surface fluxes is valuable. The performance of surface renewal (SR) analysis and the fflux-variance (FV) method for estimating sensible heat flux (H) has been evaluated inover an experiment carried out over a heterogeneous canopy (olive orchard, 50% ground cover) at a semiarid climate in a windy area. Measurements were made at a single level close to the canopy top. SR analysis was accurate either under both stable and unstable stability conditions. The FVflux-variance method also showed a good performance under unstable conditions, but it was uncertain near neutral conditions and was not applicableperformed poorly under stable conditions.

KEYWORDS

Sensible heat flux, Surface renewal analysis, Flux-variance method.

1. INTRODUCTION

A campaign for estimating sensible heat flux over a drip irrigated olive orchard in a semiarid area has been carried out. The experiment was conducted in a region where agriculture plays a key role for the economy and an accurate management of the available water resources is crucial. Accurate weighing lysimeters and the eddy covariance technique for measuring surface fluxes are often not affordable outside experimental research institutes. Therefore, there is a need to analyse the performance of alternative methods for determining surface fluxes. Based on the surface energy balance equation, knowledge of sensible heat flux obtained from inot expensive and robust sensors is crucial for estimating latent heat flux since measurement of the available net surface energy is actually affordable. The aim of this paper iswas therefore the evaluation of two methods for estimating sensible heat flux over such a heterogeneous canopy. For practical reasons, to avoid the need to set up tall micrometeorological towers and to use the minimum number of robust sensors, in order to minimize costs and maintenance that permits a denser spatial cover, it was assumed that measurements are only available at a single level close to the canopy top. The performance of the following two methods was tested:

1) Surface renewal (SR) analysis in conjunction with air temperature traces (Paw U et al., 1995) [Equation (1) below], using a recent expression for estimating parameter α proposed by Castellvi (2004). SR analysis for estimating sensible heat flux over vegetated surfaces was selected because it has been proved to perform well over a variety of canopies, though most studies have been carried out mainly under unstable conditions and over homogeneous canopies (Paw U et al., 1995; Katul et al., 1996; Snyder et al., 1996; Chen et al., 1997a, 1997b; Spano et al., 1997, 2000; Zapata and Martínez-Cob, 2001; Castellvi et al., 2002; Castellvi, 2004).

2) The Fflux-variance (FV) method because it has been extensively proved and recommended when the eddy covariance method is not affordable. Though the flux-variance method has been mainly analysed under unstable conditions and operating in the inertial sub-layer, good performance was also found in some experiments when operating in the roughness sub-layer over homogeneous canopies (Weaver, 1990; Lloyd et al., 1991; Padro, 1993; De Bruin et al., 1993; Albertson et al., 1995; Katul et al., 1995, 1996; Hsieh and Katul, 1996; Wesson et al., 2001).

In our experiment, the baseis on which SR analysis and the FV method are build are farwere not completely to be met (see next). HoweverNevertheless, reasonable sensible heat flux estimates may still be useful usefulfor some field applications. For instance, determination of accurate precise irrigation crop water requirements is desired for irrigation scheduling and design. However, so many other factors are involved (crop varieties, cycles and management, soil characteristics, water availability, irrigation system design, wind conditions during sprinkler irrigation, pressure in water delivery systems, age of irrigation systems, and so on) that such highly accurate crop water requirements may not always be accomplished but it is expensive and not always can be implemented. In such situations, estimates of latent heat flux, obtained Therefore, through a surface energy-balance from reasonable sensible heat flux estimates are useful., estimates of latent heat flux within the error of how water is applied may be suitable (MACOAN, mejora esto).

2. THEORY

2.1. Surface renewal analysis

SR analysis assumes that turbulent exchange on any scalar is driven by the regular replacement of the air parcel in contact with the surface where exchange occurs. An air parcel sweeps down to the surface and replaces another that ejects from the canopy once the latter has enriched or depleted the scalar. This process appears as ramp-like time series when high frequency measurements of the scalar are plotted versus time. An ideal and comprehensive scheme for this process was originally presented by Paw U et al. (1995) (Scheme 1, Figure 1) and Chen et al. (1997a) (Scheme 2, Figure 1). Sensible heat flux density from the surface at height z (within the canopy, the roughness or the inertial sub-layers) is determined by the following expression (Paw U et al., 1995; Snyder et al., 1996; Chen et al., 1997a):

$$H = (\alpha z)\, \rho C_p \frac{A_T}{\tau_T} \tag{1}$$

where ρ and C_p are the density and specific heat of air at constant pressure, respectively; A_T and τ_T are the mean ramp amplitude and the inverse ramp frequency of the air temperature trace over the averaging period (commonly half hour), respectively. Methods for determining ramp dimensions can be found in the works of Paw U et al. (1995), Katul et al. (1996), Snyder et al. (1996) and Paw U (2002) for the ramp-model of Scheme 1 (Figure 1), and in the work of Chen et al. (1997a) for the ramp-model of Scheme 2 (Figure 1). Ramp parameters ofinthe frame of Scheme 2 requires measurements of the scalar at very high frequencies because the sampling must be lower than the micro-front time period. A practical approach for estimating

ramp dimensions according to Scheme 2, useful for field applications, is described in Appendix A based on Chen et al. (1997b).

The variable (αz) is the volume of air, with height z, per unit ground area exchanged on average for each ramp in the sample period (Paw U et al., 1995). Equation (1), based on the energy conservation equation, assumes that advection is negligible and parameter α requires calibration. During the last decade, several studies have analysed the SR method giving valuable understanding of the performance of parameter α (Castellvi, 2004 and references therein). Calibration of parameter α can be avoided when the canopy is divided into sub-layers. For thin sub-layers, it may be assumed $\alpha \approx 1$ (Paw U et al., 1995) and the total flux density can be estimated as the sum of Equation (1) applied for different sub-layers (Spano et al., 2000). However, this requires measuring the traces of the scalar at various heights within the canopy. Castellvi et al. (2002) interpreted the variable (αz) as the mean eddy size responsible for the renewal process. Based on the understandingfact that temperature ramps in traces represent injections of sensible heat flux into the atmosphere that changes the local vertical gradient of temperature, Castellvi (2004) derived the following relationship for estimating the parameter α when measuring above the canopy.

$$\alpha = \begin{cases} \left[\dfrac{k}{\pi} \dfrac{(z-d)}{z^2} \dfrac{\tau_T u_*}{\phi_h(\zeta)} \right]^{1/2} & z > z^* \\ \left[\dfrac{k}{\pi} \dfrac{z^*}{z^2} \dfrac{\tau_T u_*}{\phi_h(\zeta)} \right]^{1/2} & h \le z \le z^* \end{cases} \tag{2}$$

where d is the zero-plane displacement; z^* is the roughness sub-layer depth; h is the canopy height; u_* is the friction velocity;□$_h$(□ is the stability function for heat transfer described below in Equation (4), ζ is an stability parameter defined as $(z-d)/L_O$, with L_O being the Obukov length, $\phi_h(\zeta)$ is the stability function for heat transfer valid in the inertial sub-layer that is described below in Equation (4), and k~0.4 35 is the Von Kármán constant which is in according to Equation (4). Equation (2) is based on the one-dimensional diffusion equation and, following Cellier and Brunet (1992),(2) it assumes that the stability function for heat valid in the roughness sub-layer is $(z-d)/z^*\phi_h(\zeta)$. The Obukov length iswhere defined as (Brutsaert, 1988):

$$L_0 = -\frac{u_*^3\,\rho}{k\,g\left(\frac{H}{T\,C_p}+0.61E\right)} \approx -\frac{u_*^3\,T}{k\,g\left(\frac{H}{\rho\,C_p}\right)} \tag{3}$$

where T is the mean absolute air temperature, E is the water vapour flux (traditionally omitted for dry climates) and g is the acceleration due to gravity. Equation (3) can be approximated to the right-hand expression when water vapour flux is small. A widely accepted formulation for $\phi_h(\zeta)$ (also valid for any flux scalar) is the following (Businger et al., 1971):

$$\phi_h(\zeta) = \begin{cases} 0.74/\sqrt{1-9\zeta} & \zeta<0 \\ 0.74 & \zeta=0 \\ 0.74+5\zeta & \zeta>0 \end{cases} \tag{4}$$

Thus, combining Equations (1), (2), (3) and (A.5), Castellvi (2004) proposed the following expression for estimating sensible heat flux:

$$H = \begin{cases} \rho C_p \left(\frac{g}{T}\right)^{1/5} \frac{\left[k(z-d)^{4/5}\right]}{\pi^{3/5}} \left[-\gamma^3 \frac{S^3_{(rx)}}{r_x}\right]^{3/5} \frac{1}{A_T^{3/5}} \left[\frac{1}{-\zeta\,\phi_h^3(\zeta)}\right]^{1/5} & z > z^* \\ \rho C_p \left(\frac{g}{T}\right)^{1/5} k^{4/5} \left(\frac{z^*}{\pi}\right)^{3/5} z^{1/5} \left[-\gamma^3 \frac{S^3_{(rx)}}{r_x}\right]^{3/5} \frac{1}{A_T^{3/5}} \left[\frac{1}{-\zeta\,\phi_h^3(\zeta)}\right]^{1/5} & h \le z \le z^* \end{cases} \quad (5)$$

where $S^3_{(rx)}$, r_x and γ are, respectively, the third order of the structure function for temperature, the time lag and a rather conservative parameter, all of which are defined in Appendix A. Because Equation (5) depends on the stability parameter, wind speed measurements are also required as input. According to Equation (4), the free convection limit for Equation (5) holds for $\zeta \le$ -0.03 with a relative error of less than 8.5% and can be expressed as (Castellvi, 2004):

$$H = \begin{cases} 2.4\rho C_p \left(\frac{g}{T}\right)^{1/5} \frac{\left[k(z-d)^{4/5}\right]}{\pi^{3/5}} \left[-\gamma^3 \frac{S^3_{(rx)}}{r_x}\right]^{3/5} \frac{1}{A_T^{3/5}} & z > z^* \\ 2.4\rho C_p \left(\frac{g}{T}\right)^{1/5} k^{4/5} \left(\frac{z^*}{\pi}\right)^{3/5} z^{1/5} \left[-\gamma^3 \frac{S^3_{(rx)}}{r_x}\right]^{3/5} \frac{1}{A_T^{3/5}} & h \le z \le z^* \end{cases} \quad (6)$$

For a variety of short canopies, Equations (5) and (6) with a parameter γ=1.1 (Table A.1) performed well using measurements taken at different heights above the canopy. Therefore, Equations (5) and (6) could be considered, in practice, exempt from calibration (Castellvi, 2004). Despite eEquations (1) and (2) do not have to be valid when measuring above but close to a heterogeneous canopy, in Castellvi (2004) was showedn a case over grapevines (60% ground cover) where Equations (1) and (2) provided adid good performance.

2.2. Flux-variance method

The flux-variance methodFV method (Tillman, 1972) is based on Monin-Obukhov similarity theory (MOST). It is a well-established method that has been the subject of intensive research over the last three decades, though mainly under unstable conditions and for estimating sensible heat flux. Its good performance has been extensively proved and recommended when eddy covariance system is not affordable (Wesely, 1988; Kader and Yaglom, 1990; Weaver, 1990; Lloyd et al., 1991; Padro, 1993; Albertson et al., 1995; Katul et al., 1995, 1996; Hsieh and Katul, 1996; Wesson et al., 2001). For estimating sensible heat flux, Tillman (1972) proposed:

$$H = \begin{cases} \rho C_p \left(\dfrac{\sigma_T}{C_1}\right)^{3/2} \left[\dfrac{k\,g(z-d)}{T}\right]^{1/2} \left(\dfrac{0.05-\zeta}{-\zeta}\right)^{1/2} & \zeta < 0 \\ -\rho C_p \left(\dfrac{\sigma_T}{C_2}\right)^{3/2} \left[\dfrac{k\,g(z-d)}{T}\dfrac{1}{\zeta}\right]^{1/2} & \zeta \geq 0 \end{cases} \tag{7}$$

where σ_T is the air temperature standard deviation measured at high frequency. The free convection limit approach for Equation (7) has proven to operate under slightly unstable conditions and can be expressed as:

$$H = \rho C_p \left(\frac{\sigma_T}{C_1} \right)^{3/2} \left[\frac{k\, g(z-d)}{T} \right]^{1/2} \qquad \zeta \leq -0.04 \tag{8}$$

Equations (7) and (8) can be obtained combining Equation (3), the generalized expression for sensible heat flux, ($H = \rho C_p u_* T_*$, where, T_*, is the surface temperature scale) and the similarity function, $g(\zeta)$, that involves σ_T and T_* as follows:

$$g(\zeta) = \frac{T_*}{\sigma_T} = \begin{cases} (C_0 - \zeta)^{1/3} / C_1 & \zeta < 0 \\ 1 / C_2 & \zeta \geq 0 \end{cases} \tag{9}$$

where C_0, C_1 and C_2 are similarity constants that can be set to 0.05, 0.95 and -2.0, respectively (Tillman, 1972; Stull, 1991). However, C_2 is an ill-defined constant. Several studies have shown that it ranges from 1.8 to 3 and that site-specific calibration is recommended (Stull, 1991; De Bruin et al., 1993; Wesson et al., 2001; Pahlow et al., 2001). For stable atmospheric conditions, Pahlow et al. (2001) proposed continuity in Equation (9), and their experimental data showed that $g(\zeta)$ rapid converges to C_2 for ζ>0.0015 and resulted very uncertain within the interval $0 \leq \zeta \leq 0.0015$.

and C is an ill-defined constant. Several studies have shown that it ranges from 1.8 to 3 and that site-specific calibration is recommended (Stull, 1991; De Bruin et al., 1993; Wesson et al., 2001; Pahlow et al., 2001). Under stable conditions, the constant C was set to 2.0 (Stull, 1991; DeBruin et al., 1993). The free convection limit approach for the flux-variance method has proven to operate under slightly unstable conditions and can be expressed as:

$$H = \left\{ \rho C_p \left(\frac{\sigma_T}{C_1} \right)^{3/2} \left(\frac{k\, g\, (z-d)}{T} \right)^{1/2} \qquad \varsigma \leq -0.04 \right. \tag{8}$$

where C_1 is considered a universal similarity constant that can be set to 0.95.

In terms of input data requirements, Equations (5) and (6) are directly comparable to Equations (7) and (8), respectively.

MOST refers to the surface layer over and extensive flat and homogenous terrain. In practice this situation is difficult to find. Then, though Equations (7), (8) and (9) do not need to be valid in other field conditions, the performance, robustness or applicability of the FV method has also been investigated over surfaces that are far of being ideal including non-uniform terrain, advective conditions and measurements taken close to the canopy [Weaver, 1990; De Bruin et al., 1991; Katul et al., 1996; Wesson et al.[, (2001, see section 5)]Strictly speaking, equations (7) and (8) are valid when operating in the inertial sub-layer but they have also been applied in the roughness sub-layer. This was done to analyse performances when similarity requirements were not well accomplished at the site of interest.In such cases, calibration of constants is often recommended. However, here it will be assumed that this is not possible, in order to allow direct comparison with SR analysis. Consequently, the flux-

variance method was assumed valid when measuring close to the canopy top, and, in terms of input data requirements, Equations (5) and (6) are directly comparable to Equations (7) and (8), respectively

3. MATERIALS AND METHOD

3.1. Site description and experimental set up

The campaign was carried out from April 15 to July 26, 2004 (days of the year 106 to 208) over a 7 years old commercial olive orchard located at Sástago (Zaragoza) in the river Ebro basin (NE of Spain, 41°18'04'' N latitude, 0°21'51'' W longitude, 150 m elevation above sea level). The area is windy and dry. The most frequent wind direction is North-West (along the basin axis). Drip irrigation was applied each day using preinstalled emitters at 1 m spacing and a discharge of 3.8 L/hHa. The canopy top was 3.4 m tall. Trees were planted at a spacing of 6.0 m x 3.5 m, approximately. The soil canopy cover was 50%, approximately. Surface area of the orchard was about 64 hHa and a micrometeorological tower (6.0 m height) supporting different sensors was located at about 250 m, 650 m, 400 m and 320 m from the south, north, west and east edges of the plot, respectively. Two dataloggers (Campbell CR23X and CR10X) were used to record the micrometeorological data.

CR23X. A 3-D sonic anemometer (Campbell CSAT3) operating at 10 Hz was used to record 30-minute averages, standard deviations and the respective covariances, of the three-component wind velocities and the sonic temperature. The CSAT3 was set at 4.9 m above soil surface and facing towards NW. Likewise, a net radiometer (Q-7, Radiation and Energy Balance Systems) and a soil temperature probe (Campbell TCAV probe) operating at 0.05 Hz were used to record 130-minute averages of net radiation and soil temperature. The Nnet radiometer was installed at the same height above the soil asthan the CSAT3. The soil

temperature probes were buried at 0.02-0.06 cm depths, one between adjacent rows and the other between trees within the same row.

CR10X. Two fine wire thermocouples (76 μm diameter, Campbell Scientific, TCBR-3) operating at 4 Hz were used to record 1030-minute averages and standard deviation of air temperature and the 110-minute sums of the 2nd, 3rd and 5th moments of the differences between high-frequency air temperature for two time lags, 0.25 and 0.75 s. During post-processing, 30-min sums were obtained from the 10-min ones and the corresponding 2nd, 3rd and 5th order structure functions were obtained appling Equation (A.1). This procedure was done to avoid getting 30-min sums of the 2nd, 3rd and 5th moments of temperature differences above ±99999 which is the maximum value that a CR10 datalogger can store. These two fine wire thermocouples were set at 5.1 and 3.5 m above soil surface. Likewise, a HMP45AC (Vaisala) probe and four soil heat flux plates (Hukseflux HFP01) operating at 0.05 Hz were used to record 130-minute averages of air temperature and relative humidity, and soil heat flux, respectively. The HMP45AC probe was installed at 4.1 m above soil surface. Soil heat flux plates were buried at 0.08 m depth, at the same spots as than the TCAV probe. as, just below them. The recorded soil heat flux values were corrected as described by Allen et al. (1996) using the soil temperature records to get soil heat flux at soil surface. At each 130-minute period, the four soil heat flux values thus obtained were averaged.

A gap from days 188 to 190 (July 6-8) in the data set was due to power malfunction. Other minor gaps were due to farmer practices, maintenance of the equipment and rainy periods. A set of 3793 half-hour samples (1886 under stable and 1907 under unstable conditions) was thus obtained after averaging the corresponding 10-minute ones.

3.2. Method

It was assumed that measurements are available at one height above but close to the canopy top. Therefore, friction velocity can not be determined using traditional procedures based on the wind profile (Brutsaert,1988), and tThe following procedure was used for determining sensible heat flux using the SR analysis and the flux-variance methods from measurements of wind speed and air temperature taken at one height. The actual friction velocity was estimated through the horizontal wind speed standard deviation, σ_u, and using the mean horizontal wind speed, u, as follows (Kaimal and Finnigan, 1994):

$$u_* = a_1 \sigma_u \tag{10a}$$

$$u_* = a_2 u \tag{10b}$$

Wind profile was not available, hence, in Equations (7) and (8) the zero plane displacement in Equations (7) and (8) was assumed negligible as the canopy was open, without understories and the crown was not dense. The stability parameter was determined solving Equation (3) after implementing Equations (910a) or (10b) for friction velocity and the corresponding expression for sensible heat flux, Equations (5) or (7) for SR analysis or the flux-variance methodFV method, respectively. Simulated annealing procedure (Goffe et al., 1994) was used for optimizing the stability parameter. The optimization process requires bounds for the stability parameter and selection of the expression for $\phi_h(\zeta)$, Equation (4). This requires previous knowledge of the atmospheric surface layer stability condition to start the process. The sign of the ramp amplitude (Figure 1) can be used for distinguishingcriminating stable and unstable conditions. This method is straightforward because the stability parameter

and the third order temperature structure function (see Equation A.5) have the same sign and avoids the need of extra measurements. As a rule of thumb, the roughness sub-layer depth in Equation (5) was set to z^*=12 m. Following Cellier and Brunet (1992), it was estimated as 3.5 times the frontal stream-wise mean inter-row space (3.5 m). The parameter γ was set to 1.0 (tTable A1). Simulated annealing is a global optimization method that distinguishes between different local optima. Starting from an initial point, the algorithm takes a step and the function is evaluated. When minimizing a function, any downhill step is accepted and the process repeated from this new point. However, an uphill step may be accepted. Thus, it can escape from local optima. This uphill decision is made by the Metropolis criteria (Metropolis et al., 1953; Press et al., 1992). As the optimization process proceeds, the length of the steps decline and the algorithm closes in on the global optimum. Since the algorithm makes very few assumptions regarding the function to be optimized, simulated annealing is recommended as a local optimizer for difficult functions. Goffe et al. (1994) showed this procedure be superior to multiple restarts of conventional optimization routines for difficult optimization problems.

Therefore, and sSummarizsing, the following set of sensible heat flux estimates were determined: 1a) eddy covariance (H_{EC}): $H_{EC} = \rho\, C_p\, \overline{w'T'}$, where $\overline{w'T'}$ is the covariance between the fluctuations of vertical wind speed and sonic temperature; b) SR analysis with Equations (5) and (6) (free convection limit) at 5.1 m ($H_{SR\text{-}UP}$ and $H_{SR\text{-}FL\text{-}UP}$, respectively) and 3.4 m ($H_{SR\text{-}LOW}$ and $H_{SR\text{-}FL\text{-}LOW}$, respectively) above soil surface; c) sensible heat flux using the flux-variance methodFV method with Equations (7) and (8) (free convection limit) at 5.1 m ($H_{VA\text{-}UP}$ and $H_{VA\text{-}FL\text{-}UP}$, respectively) and 3.4 m ($H_{VA\text{-}LOW}$ and $H_{VA\text{-}FL\text{-}LOW}$, respectively) above soil surface.

4. RESULTS AND DISCUSSION

The sign of the ramp amplitude was used for distinguishingcriminating the stable and unstable conditions for each sample to start the optimization process. This procedure identifiedselected a set of 259 samples that were not in accordanceing with the sign of the sensible heat flux measured with the sonic anemometer. This set includes the mistakes made in both air temperature measurement levels and they were distributed along the day as follows: a) 0:00-5:00 Greenwich Meridian Time (GMT), 111 samples; b) 5:00-9:00 GMT, 61 samples; c) 9:00-18:00 GMT, 10 samples; d) 18:00-22:00 GMT, 52 samples; e) 22:00-24:00 GMT, 25 samples. This distribution corresponds to a total of 249 mistakes obtained under near neutral and stable conditions and 10 mistakes under slightly unstable conditions. The hourly intervals (bins) were selected to split the following periods: night, sunrise, daylight time including the typical capping inversion formation in the area at late afternoon, and sunset. It was found that during sunrise and sunset the lower level measurements (3.5 m) showed more mistakes (24 samples) than the upper level (5.1 m). For comparison, the performance of the method proposed by Wesson et al. (2001) for discriminating distinguishing atmospheric surface layer stability conditions was also analyzed; unstable conditions were assumed when the available net surface energy was positive and vice versa. It was assumed that the energy storage below the net radiometer could be neglected (the canopy was open, without understories and the crown was not very dense). Then, with the Wesson et al. (2001) method, unstable and stable conditions were assumed when net radiation minus soil heat flux (*Rn*-*G*) was positive and negative, respectively. This procedure led to 250 mistakes with similar hourly distribution to the previously mentioned. Therefore, in general, both procedures showed a similar performance. This set of 259 samples was discarded sofor as not to distorting the aim of this paper. Further analysis was therefore carried out on a set of 3534

samples; 1898 samples gathered under unstable conditions and 1636 under stable conditions.

Figures 2A and 2B shows the actual friction velocity versus the standard deviation of horizontal wind speed and the mean wind speed, respectively, for all the data. Figure 2 indicates that Equations (910a) and (10b) performed well in the roughness sub-layer for our heterogeneous canopy. In tTable 1 is shownlists the results obtained from simple linear fit regression analysis for Equations (10a) and (10b) for all the data,under unstable and stable conditions.The slope (b_1) of the linear regression fit forced trough the origin was 0.43, either for all the data, under unstable and stable conditions. That value was close to that (b_1=0.50)

The bias (coefficient b_0 in tTable 1*)* can, in practice, be neglected because the main influence of the friction velocity in estimating the sensible heat flux is under stable conditions. Whatever the expression used, the regression slopes obtained (coefficient b_1, Table 1) obtained appeared robust. For Equation (10a) the slope was close to a_1=0.50 found over homogeneous canopies (Kaimal and Finnigan, 1994). For Equation (10b) the results were also good, though the coefficient a_2 was lower than typical values obtained over uniform canopies (Kaimal and Finnigan, 1994; Raupach et al., 1996) indicating that less momentum is absorbed due to the free space between trees and because olives trees have not a such dense crown in comparison with other studied canopies.

$U_* = b_1 \square_u + b_0$	b_1	R^2	b_0
All data	*0.45*	*0.94*	*-0.02*
Unstable conditions	*0.45*	*0.93*	*-0.02*
Stable conditions	*0.45*	*0.96*	*-0.01*
$U_* = b_1 u + b_0$			

All data

Unstable conditions

Stable conditions

A sonic anemometer was the only type of anemometer available during the experiment. Then, a lower accuracy than that shown in fFigure 2 and tTable 1 for Equation (10a) will be obtained in practice because low-budget anemometers have lower time response to wind fluctuations. But, affordable anemometers measure the mean wind speed accurately. Therefore, Equation (10b) may then suit better our purposes than Equation (10a) because it allows to bypass the instrumental error associated to low time response of the anemometer.

Figure 3 shows the performance of Equation (9) for all the data gathered from the sonic anemometer. It is interesting to outline the good performance obtained under unstable conditions for such heterogeneous canopy and with constants C_0=0.05 and C_1=0.95. After removing 16 samples that clearly were spurious data (see fFigure 3) we found the following coefficients were obtained for the simple linear regression agreement between $g(\zeta)$ and σ_T/T_*:; slope, = 0.99;, bias, =0.035; and R^2 = 0.94. Figure 7 (now 3) confirms that the assumption of negligible the good choice made for zero the plane displacement was appropriate. Under stable conditions the scatter was considerable for $0 < \zeta < 3$. A rapid convergence to the z-less relationship was not found indicating that MOST failed in such conditions. For this type of sparse tall vegetation, spatial temperature differences close to the canopy are expected to be large during night time. Cool air formed by radiative cooling at the top of the sparse vegetation would be mixed in a patchy way with underlying warmer air due to buoyancy. These local temperature variations do not contribute for the entire vertical flux of heat in the surface layer above the canopy. Therefore, when observations close to the canopy are used, one may expect a violation of the FV method. For this reason, this methodit was not used for

describing flux predictions under stable conditions.

Tables 2 and 3 listit is shown the simple regression analyses ($y = b_0 + b_1 x$) of estimated (dependent variable y) sensible heat flux (H) using the SR analysis and the FV methods versus that measured using the eddy covariance method (independent variable x). In table 2, estimates of H were determined using three different values for the friction velocity:; the a) actualmeasured by the sonic anemometer; b) estimated as, u_*=0.45 σ_u [Equation (10a)],; and c) estimated as u_*=0.18 u [Equation (10b)]. R^2, determination coefficient; b_0, intercept (bias); b_1, regression slope; RMSE, root mean square error. These comparisons were made for: all the data,; unstable conditions,; and stable conditions. In table 3 is shown the performance for the free convection limit approaches, Equations (6) and (8).

Under unstable conditions, Table 12 indicates that the performance obtained using SR analysis, Equation (5), and the flux-variance methodFV method, Equation (7), was good in general. SR analysis showed an excellent performance for the upper measurement height with a root mean square error (RMSE) value within a typical error for the eddy covariance. The mean air temperature during the campaign was 25 °C under unstable conditions. Mean vertical velocities of about 10^{-3} m/s are not detectable by eddy correlation systems (Mortensen, 1994). Therefore, assuming a mean vertical velocity of 10^{-3} m/s and air temperatures close to 25 20 °C, a missing convective transport for sensible heat flux ($H = \rho C_p \overline{w}\,\overline{T}$) close to 24 W/m^2 should be expected. This figure is a realistic measurement error when measuring sensible heat flux using the eddy covariance technique under unstable conditions.

Whatever the measurement height, Equation (5) led to lower bias and higher determination coefficient than Equation (7) mainly because the flux-variance methodFV method was not as accurate for low values of sensible heat flux as SR analysis. Such

performance is shown in Figure 43 for the upper measurement level. Figure 43 compares the estimates obtained from Equations (5) and (7) ($H_{SR\text{-}UP}$ and $H_{FVVA\text{-}UP}$, respectively) versus the measured using the eddy covariance under unstable conditions. Similar performance was obtained for the lower measurement level. For Equation (7), a lower RMSE value was obtained for the low measurement height than that for the upper measurement level (Table 21). This cannot be attributed to a better performance of the flux variance method when measuring at the canopy top. According to Högström (1990) this was as a consequence that the flux-variance methodFV method was uncertain near neutral conditions (Figure 34).Despite such uncertain performance, the RMSE obtained did not differ considerably respect to that for SR analysis because of the large amount of samples used for analyses.

ForRegarding to Equations (6) and (8), whatever the measurement level, Table 31 shows that SR analysis performed slightly better than the flux-variance methodFV method. Estimates of H obtained with these two equations showed a similarslightly lower bias and regression slopes of that obtainedslightly closer to 1.0 than estimates obtained with Equations (5) and (7). However, the R^2 and RMSE values were better for the estimates obtained with these last two equations. In general, estimates obtained with Equations (5) and (6) were closer among them than those obtained with Equations (7) and (8). Differences between (7) and (8) were higher for the lower than for the upper measurement height. Thus, RMSE value increased from fromabout 301.02 W/m^2 for $H_{FVVA\text{-}LOW}$ (Table 2) to 53.1 W/m^2 for $H_{VA\text{-}FL\text{-}LOW}$ (Table 31).

Under stable conditions, the flux-variance method, Equation (7), performed poorly. It was not able to explain the sensible heat flux variability. It was uncorrelated and biased (the averaged actual sensible heat flux was –23.3 W m^{-2}). Moreover, the RMSE values were close to twice the actual sensible heat flux standard deviation, 14.4 W m^{-2} (Table 1). In contrast, SR

analysis, Equation (5), showed a good performance. Though it overestimated the actual sensible heat flux about 11 % and 23 % for the upper and lower measurement heights, respectively, SR analysis was unbiased, well correlated and showed relatively low RMSE values (Table 12). Figure 45 shows the estimates obtained from EquationEquations (5) for the upper and (7)upper measurement level($H_{SR\text{-}UP}$ and $H_{VA\text{-}UP}$, respectively) versus the eddy covariance measured sensible heat flux under stable conditions. In accordance to Table 1, Figure 4 shows the good and poor performance, respectively, provided by the SR analysis and the flux-variance method. Though not shown, similar performance was obtained for the lower measurement height.

Table 1 shows that both methods provided good estimates of H fFor all the data set, In general, the best performance was obtained with the SR analysis did good performance.

If Whatever the method, determination coefficients were quite high but SR analysis was able to capture most variance. Regression slopes were closer to 1.0 for the flux-variance method than for the SR analysis; however, biases and RMSE values were higher for the flux-variance method. Nevertheless, the poor performance of the flux-variance method under stable conditions, the statistics shown for the whole data set resulted good because of its adequate performance under moderate to high unstable conditions.*H* estimates obtained using the actual friction velocity (Table 2) are taken as a reference for comparison, Table 2 shows that: a) whatever the procedure used for estimating the friction velocity, the SR analysis *H* estimates were comparable to the reference either for stable and unstable conditions; b) similar results were also obtained for the flux variance method under unstable conditions. Then, the possible different bias introduced by Equations (10a) or (10b), under determined atmospheric conditions, had a minor effect on the general performance. Consequently, since both Equations (10a) or (10b) provided good estimates, Equation (10b) fits better our

objectives than Equation (10a).

SR analysis provided accurate sensible heat flux estimates because of the general good performance of Equation (2) for estimating the α parameter, whatever the stability conditions. Figure 56 shows the α parameter estimates, Equation (2), versus the actual half hourly values (determined rearranging terms in Equation (1) using the sensible heat flux measured with the sonic anemometer) under unstable and stable conditions for the upper level as an example. Measurements taken at a single level were assumed, thus as mentioned above, the roughness sub-layer height was estimated as a rule of thumb to a fixed height. However, Figure 65 shows that, in general, the α parameter estimates were good for most of the samples. Then, a reliable representative value for the roughness sub-layer height was chosen. It is interesting to note the square root dependence of the roughness sub-layer height in Equation (2); the α parameter is therefore rather robust respect to moderate variations around a fixed roughness sub-layer height. For correcting the vertical temperature gradient from the bottom to the top of the volume of air parcel to be renewed, Paw U et al. (1995) proposed to fix the α parameter to 0.5 when measuring temperature traces at the top of homogeneous tall canopies. Katul et al. (1996) showed that α parameter over forest was close to 0.5 but clearly dependent on the stability conditions. Castellvi (2004) showed that Equation (2) was able to explain such performances. Figure 65 shows that the actual α parameter is far to be close to 0.5 when measuring near the canopy top. Note that the surface was heternot homogeneous, thereby, the ratio roughness sub-layer height over measurement height was considerable. Equation (2) indicates that parameter α depends on measurement height, stability conditions and wind speed but also the canopy structure plays an important role when measuring close to the canopy top.

Those samples where Equation (2) showed poor performance (Figure 65) were mostly

gathered near neutral conditions. As an example, to better illustrate the performance of Equation (2), Figure 67 shows the time evolution corresponding to half hourly samples of (*Rn*-*G*), the estimated and the actual α parameter during three typical days of the campaign (17-19 May). Despite thehigh large differences between the estimated and the actual α parameter for some samples when (*Rn*-*G*) is close to 0, Figure 43 shows that they had a minor effect for estimating sensible heat flux because near neutral conditions ramps have low amplitudes and frequencies. This issue is crucial for explaining the better performance of SR analysis than the flux-variance methodFV method under unstable conditions shown in Table 12. Similarly, t

Similarly, the flux-variance methodFV method provided in general accurate sensible heat flux estimates under unstable conditions because of the good performance of Equation (9). in this experiment, of the similarity function, g(ζ), that involves the air temperature standard deviation and the surface temperature scale, T_*, defined as, $T_* = H/(\rho C_p u_*)$. Traditionally, g(ζ) is expressed as follows:

$$g(\varsigma) = \frac{T_*}{\sigma_T} = \begin{cases} (C_0 - \varsigma)^{1/3} / C_1 & \varsigma < 0 \\ 1/C_2 & \varsigma \geq 0 \end{cases} \quad (10)$$

where C_0, C_1 and C_2 are constants set to 0.05, 0.95 and -2.0, respectively, for obtaining Equation (7) (Stull, 1991). Pahlow et al. (2001) proposed continuity in Equation (10), but experimental data showed that g(ζ) rapid converges to C_2 (for ζ>0.0015) and resulted very uncertain within the interval 0≤ ζ ≤ 0.0015. Figure 7 shows the performance of Equation (10) for all the data gathered from the sonic anemometer. It is interesting to note the good performance under unstable conditions of Equation (10) for such heterogeneous canopy, which in principle is valid in the inertial sub-layer. Figure 7 confirms the good choice made for the

plane displacement. Under stable conditions the scatter was considerable for $0 < \zeta < 3$. Any stability relationship can reasonably fit the experimental data and the best value for the constant C_2 was considerably different than that for the inertial sub-layer, $C_2 = -5$ (Figure 7). Sensible heat flux estimates under stable conditions implementing $C_2 = -5$ in Equation (7) performed poorly (Table 1). Therefore, even assuming that calibration was possible, the flux-variance method did not suit in this experimental site under stable conditions.

Figure 3(B) shows that the FV method tends to overestimate the sensible heat flux when exceeds, let say, about 150 W/m^2. Because Equation (9) did good performance, the trend found in Figure 3(B) may be attributed to other factors. Following Weaver (1990) and Vogt et al. (2003), Equation (9) likely requires to be adjusted at different levels when measuring close to the canopy.

One may expect horizontal variation of flux measurements taken above but close of a heterogeneous canopy. This was confirmed by Vogt et al. (2003) for an olive orchard including measurements within the canopy. This indicates the need to average different local sensible heat flux measurements to provide a better assessment in *H*, such as we did for *G*, if one would escape fetch constrains and to set up a tall tower. Consequently, SR analysis in conjunction with Equation (10b) suits the aim of this paper since it did good performance for different stability conditions and can be implemented using affordable instruments that permits a dense spatial cover.

5. SUMMARY AND CONCLUDING REMARKS

This paper presents a long term monitoring experiment for estimating sensible heat flux over a heterogeneous canopy where the total sensible heat flux comes from the canopy and the ground (olive orchard, 50% ground cover). For convenience, it was assumed that measurements of wind speed and air temperature were only available at a single level close to the canopy top. The performance for SR analysis and the flux-variance methodFV method was evaluated. The SR analysis was found to be accurate, whatever the stability conditions. It was shown that a considerable dependence of the actual α parameter was on the stability conditions and canopy structure (Figures 6 and 7). Thus, SR analysis performed well because Equation (2) provided, in general, good half-hourly estimates of the actual α parameter. The performance of the flux-variance methodFV method was good under unstable conditions and, somehow uncertain near neutral conditions. , and poor uUnder stable conditions MOST failed. It is concluded that SR analysis was a robustvery reliable method that was able to provide reliable sensible heat flux estimates over a heterogeneous canopy.

5. APPENDIX A. DETERMINATION OF THE RAMP PARAMETERS

The two ramp models shown in Figure 1 provide similar results when determining ramp amplitude (Chen et al., 1997a). Then, structure functions [Equation (A.1)] and the analysis technique [Equations (A.2) to (A.4)] from Van Atta (1977) were applied:

$$S^n(r) = \frac{1}{m-j} \sum_{i=1+j}^{m} \left(T_i - T_{i-j}\right)^n \tag{A.1}$$

where m is the number of data points in the 30-minute interval measured at frequency (f) in Hz, n is the power of the function, j is a sample lag between data points corresponding to a time lag ($r=j/f$), and T_i is the ith temperature sample. An estimate of the mean value for the mean ramp amplitude A_T is determined by solving Equation (A.2) for the real roots:

$$A_T^3 + pA_T + q = 0 \tag{A.2}$$

where:

$$p = 10\,S^2(r) - \frac{S^5(r)}{S^3(r)} \tag{A.3}$$

and

$$q = 10\,S^3(r) \tag{A.4}$$

According to Chen et al. (1997a), the relationship between the inverse ramp frequency (τ_T) and ramp amplitude is:

$$\frac{A_T}{\tau_T^{1/3}} = -\gamma\left[\frac{S^3(r_x)}{r_x}\right]^{1/3} \tag{A.5}$$

where r_x is the time lag r that maximizes $S^3(r)/r$ and γ is a parameter that corrects for the difference between $A_T / \tau_T^{1/3}$ and the maximum value of $\left[S^3(r)/r\right]^{1/3}$. Parameter γ varies by less than 25% with respect to unity (0.9-1.2) for a range of canopies (Table A.1). For bare soil and straw mulch, parameter γ mainly varies between 1.0 and 1.2, while for Douglas-fir Forest it mainly varies between 0.9 and 1.1. Table A.1 shows mean values for parameters γ and r_x, and suitable measurement frequencies (in Hz) for different canopies required to solve Equation (A.5), i.e. to find the appropriate solution for Equation (A.5) for the majority of samples (Chen et al., 1997a, b).

Table A.1. Recommended mean values for γ, r_x (in seconds) and samplig frequencies (in Hz) for different canopies.

Canopy and height	γ	Frequency (Hz)	r_x (s)
Fir forest (16.7 m)	1.001	5	0.833
Straw mulch (0.06 m)	1.175	11	0.111
Bare soil	1.104	26	0.066

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TABLES

Table 1. Simple linear fit regression analysis for Equations (10a) and (10b). R^2, coefficient of determination; b_0, intercept (bias); b_1, regression slope.

Data set	Equation (10a): $u^* = b_1 \sigma_u + b_0$			Equation (10b): $u^* = b_1 u + b_0$		
	R^2	b_0 (m/s)	b_1	R^2	b_0 (m/s)	b_1
All data	0.94	-0.02	0.45	0.95	0.01	0.18
Unstable conditions	0.93	-0.02	0.45	0.94	0.04	0.175
Stable conditions	0.96	-0.01	0.45	0.96	-0.01	0.18

Table 2. Linear fit regression and root mean square errors (RMSE) of sensible heat flux (H) estimated using the SR analysis and the FV methods (dependent variables y) versus that measured using the eddy covariance method (independent variable x). Estimates of H obtained using three different friction velocity values: a) measured (u_{*m}); b) determined from Equation (10a) (u_{*10a}); and c) determined from Equation (10b) (u_{*10b}). R^2, coefficient of determination; b_0, intercept (bias); b_1, regression slope.

Data set	Variable y[a]	R^2			b_0 (W/m^2)			b_1			RMSE (W/m^2)		
		u_{*m}	u_{*10a}	u_{*10b}	u_{*m}	u_{*10a}	u_{*10b}	u_{*m}	u_{*10a}	u_{*10b}	u_{*m}	u_{*10a}	u_{*10b}
All data[b]	$H_{SR\text{-}UP}$	0.98	0.97	0.97	0.1	-0.8	-1.8	0.95	0.94	0.95	17.4	18.9	19.1
	$H_{SR\text{-}LOW}$	0.98	0.97	0.97	0.3	1.3	0.0	1.15	1.14	1.14	19.3	28.6	28.7
Stable conditions[b]	$H_{SR\text{-}UP}$	0.83	0.82	0.71	2.1	1.8	-2.2	1.08	1.11	1.00	7.0	7.7	9.2
	$H_{SR\text{-}LOW}$	0.85	0.84	0.71	1.1	0.7	-3.8	1.10	1.23	1.10	8.9	9.8	10.4
Unstable conditions	$H_{SR\text{-}UP}$	0.93	0.92	0.92	5.0	5.7	5.1	0.92	0.91	0.91	23.4	24.7	24.5
	$H_{SR\text{-}LOW}$	0.93	0.91	0.91	10.1	13.3	11.2	1.04	1.08	1.08	35.2	38.0	37.4
	$H_{FV\text{-}UP}$	0.90	0.86	0.84	25.7	29.6	29.3	1.02	1.00	0.98	39.7	45.2	43.8
	$H_{FV\text{-}LOW}$	0.90	0.87	0.74	25.1	28.6	28.5	0.90	0.86	0.82	26.4	31.2	32.7

[a] Sub-indices refer to: SR, surface renewal analysis; FV, flux-variance method; UP, upper measurement height; LOW, lower measurement height.

[b] Stable cases for the flux-variance method are not included, see text.

Table 3. Linear fit regression and root mean square errors (RMSE) of sensible heat flux (H) estimated using the SR analysis and the FV methods (dependent variables y) for the free convection limit case [Equations (6) and (8)] versus that measured using the eddy covariance method (independent variable x). R^2, coefficient of determination; b_0, intercept (bias); b_1, regression slope.

Variable y[(a)]	R^2	b_0 (W/m^2)	b_1	RMSE
$H_{SR\text{-}FL\text{-}UP}$	0.87	2.9	0.92	31.0
$H_{SR\text{-}FL\text{-}LOW}$	0.85	10.8	1.04	39.8
$H_{FV\text{-}FL\text{-}UP}$	0.73	11.1	0.90	46.6
$H_{FV\text{-}FL\text{-}LOW}$	0.73	9.0	0.73	53.1

[(a)] Sub-indices refer to: SR, surface renewal analysis; FV, flux-variance method; UP, upper measurement height; LOW, lower measurement height; FL, free convection limit.

FIGURE CAPTIONS

Table1. Estimate versus actual sensible heat flux. Slope, intercept (bias) and determination coefficient, R^2, determined from linear regression analysis, and root mean square error, Rmse (W m^{-2}).

FIGURE 1. Surface renewal analysis ramp models: a) Scheme 1, assuming a sharp instantaneous drop in air temperature; and b) Scheme 2, assuming a finite micro-front. L_r, L_q and L_f are the warming, quiescent and micro-front periods, respectively. A_T is the ramp amplitude and τ_T is the total ramp duration.

FIGURE 2. Actual friction velocity (u_*) versus: A) the horizontal wind speed standard deviation [dashed line represents the 1:2 line introduced for comparing with the coefficient a_1 = 0.50 found over homogeneous canopies (Kaimal and Finnigan, 1994)]; and B) the horizontal wind speed. In both cases, solid line represents the regression line.Performance of Equation (9). Friction velocity versus the standard deviation of the horizontal wind speed.

FIGURE 3. Performance of Equation (9). Stability function [$g(\zeta)$] versus the stability parameter (ζ) corresponding to 1.4 m above the canopy top.

FIGURE 4. Performance of Equations (5) and (7) under unstable conditions at the upper measurement height. Sensible heat flux (H) estimates obtained by (A) SR analysis ($H_{SR\text{-}UP}$), and (B) the flux variance method ($H_{VA\text{-}UP}$) versus measured (eddy covariance, H_{EC}) sensible heat flux.at the upper measurement height (5.1 m) from SR analysis, $H_{SR\text{-}UP}$, and Flux-variance method, $H_{VA\text{-}UP}$, versus the measured using the sonic anemometer, H_{EC}, at 4.9 m height. a) Under unstable conditions, and b) Under stable conditions.

FIGURE 5. Performance of Equation (5) under stable conditions at the upper measurement height.

FIGURE 6. Performance of Equation (2). Estimateding versus the actual α parameter at the upper measurement height. ; aA) Under unstable conditions; , and bB) Under stable conditions. Solid line represents the 1:1 line.

FIGURE 7. Three days tTime evolution of half hour (*Rn*-*G*) samplesfor; (solid line) in W m^{-2}, dashed line for the secondary axis; and the estimated [Equation (2), -●-] and actual (-■-) α parameter values corresponding to the upper measurement height from May 17 to 19., Equation (2), diamonds; and the actual α parameter, circles.

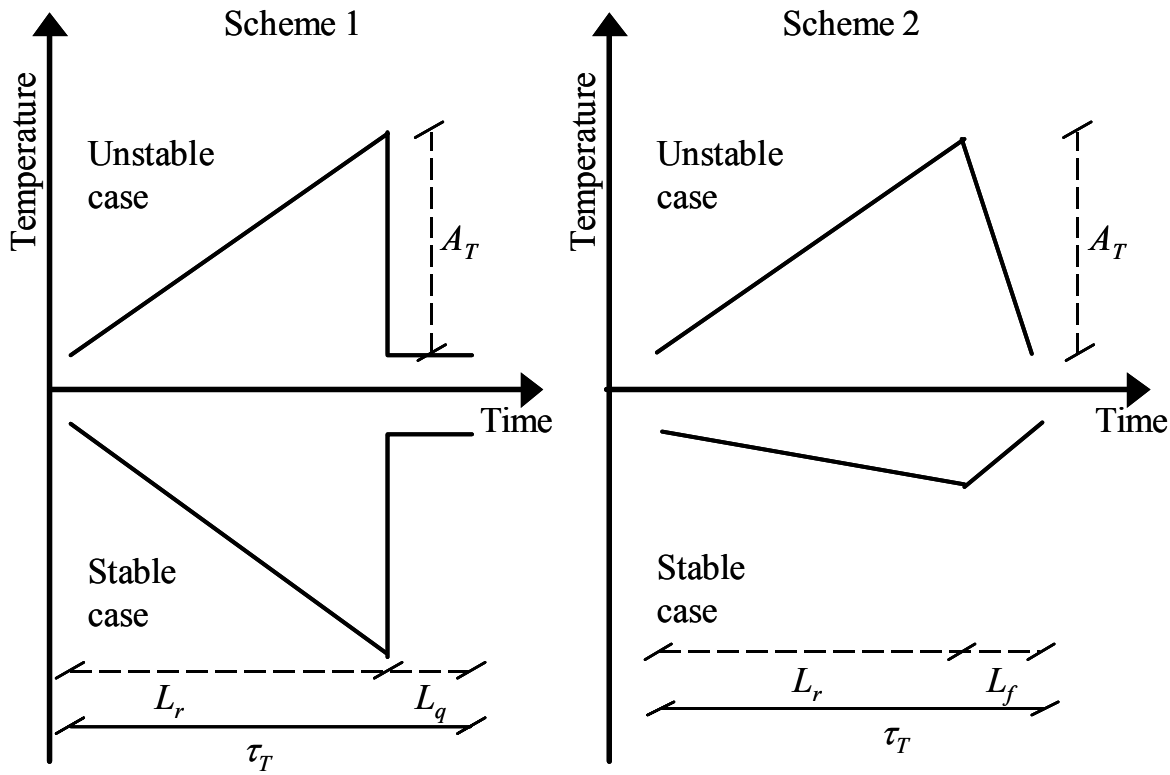

FIGURE 1. Surface renewal analysis ramp models: a) Scheme 1, assuming a sharp instantaneous drop in air temperature; and b) Scheme 2, assuming a finite micro-front. L_r, L_q and L_f are the warming, quiescent and micro-front periods, respectively. A_T is the ramp amplitude and τ_T is the total ramp duration.

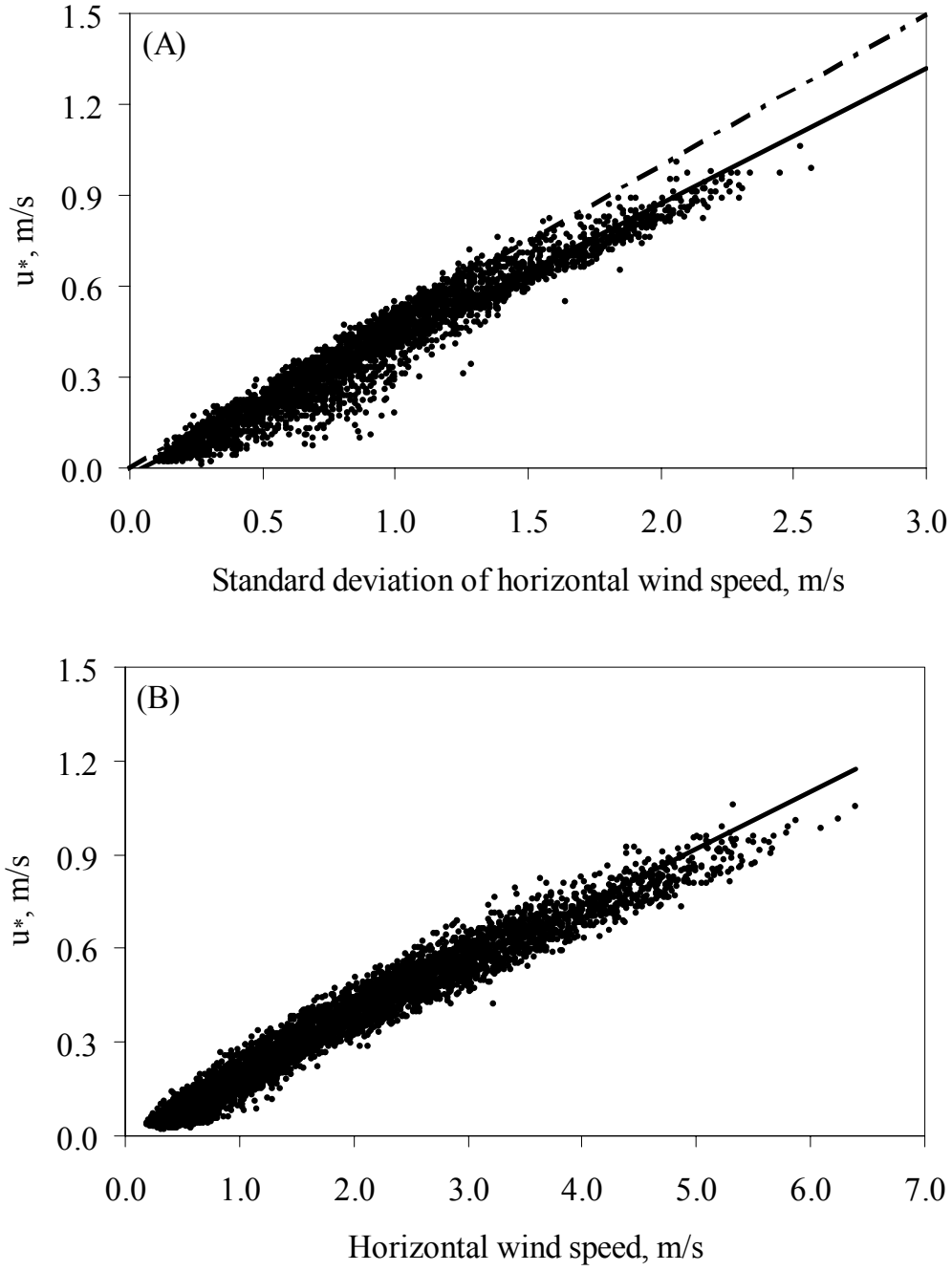

FIGURE 2. Actual friction velocity (u_*) versus: A) the standard deviation of horizontal wind speed [dashed line represents the 1:2 line introduced for comparing with the coefficient a_1 = 0.50 found over homogeneous canopies (Kaimal and Finnigan, 1994)]; and B) the horizontal wind speed. In both cases, solid line represents the regression line.Performance

of Equation (9). Friction velocity versus the standard deviation of the horizontal wind speed.

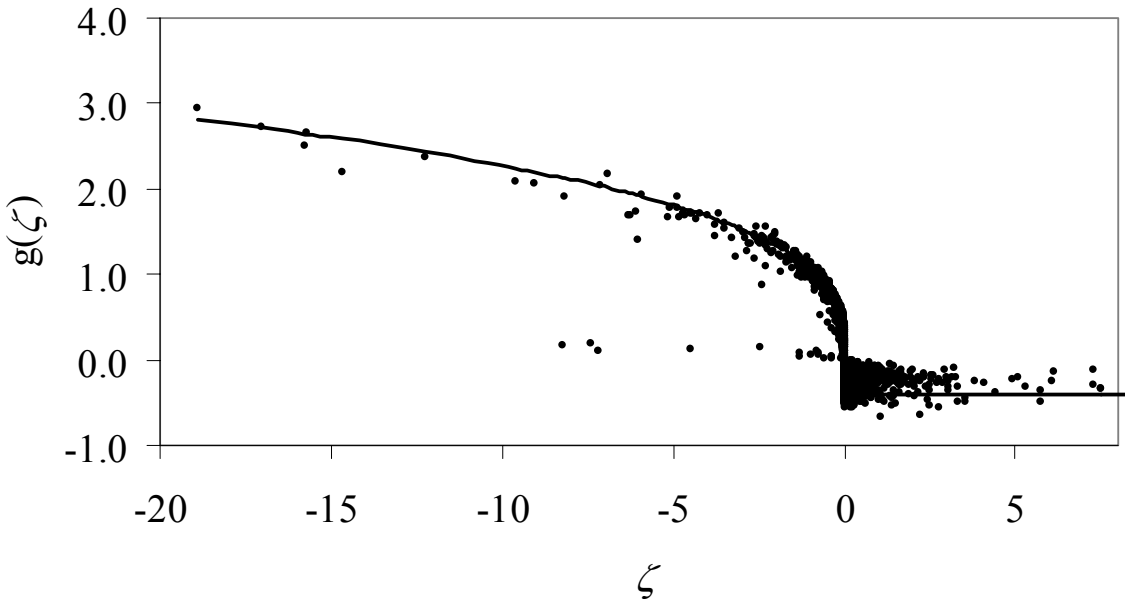

FIGURE 3. Performance of Equation (9). Stability function [$g(\zeta)$] versus the stability parameter (ζ) corresponding to 1.4 m above the canopy top.

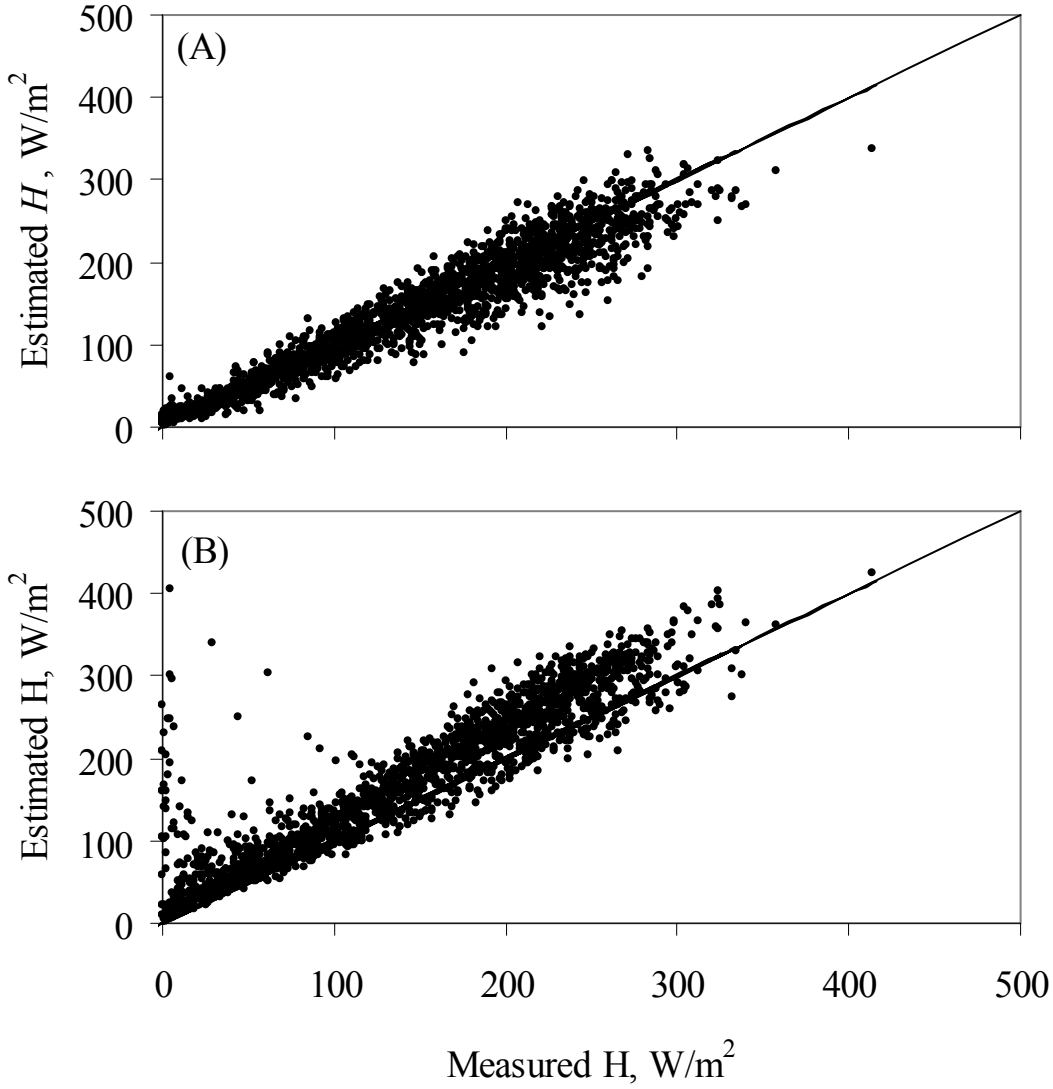

FIGURE 4. Performance of Equations (5) and (7) under unstable conditions at the upper measurement height. Sensible heat flux (*H*) estimates obtained by (A) SR analysis ($H_{SR\text{-}UP}$), and (B) the flux variance method ($H_{VA\text{-}UP}$) versus measured (eddy covariance, H_{EC}) sensible heat flux.at the upper measurement height (5.1 m) from SR analysis, $H_{SR\text{-}UP}$, and Flux-variance method, $H_{VA\text{-}UP}$, versus the measured using the sonic anemometer, H_{EC}, at 4.9 m height. a) Under unstable conditions, and b) Under stable conditions.

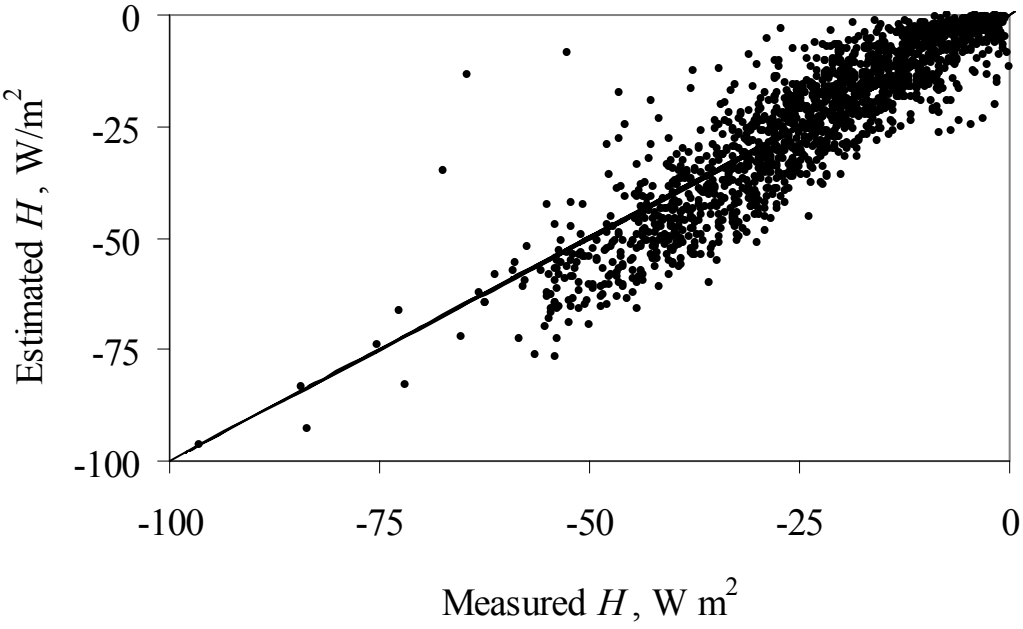

FIGURE 5. Performance of Equation (5) under stable conditions at the upper measurement height.

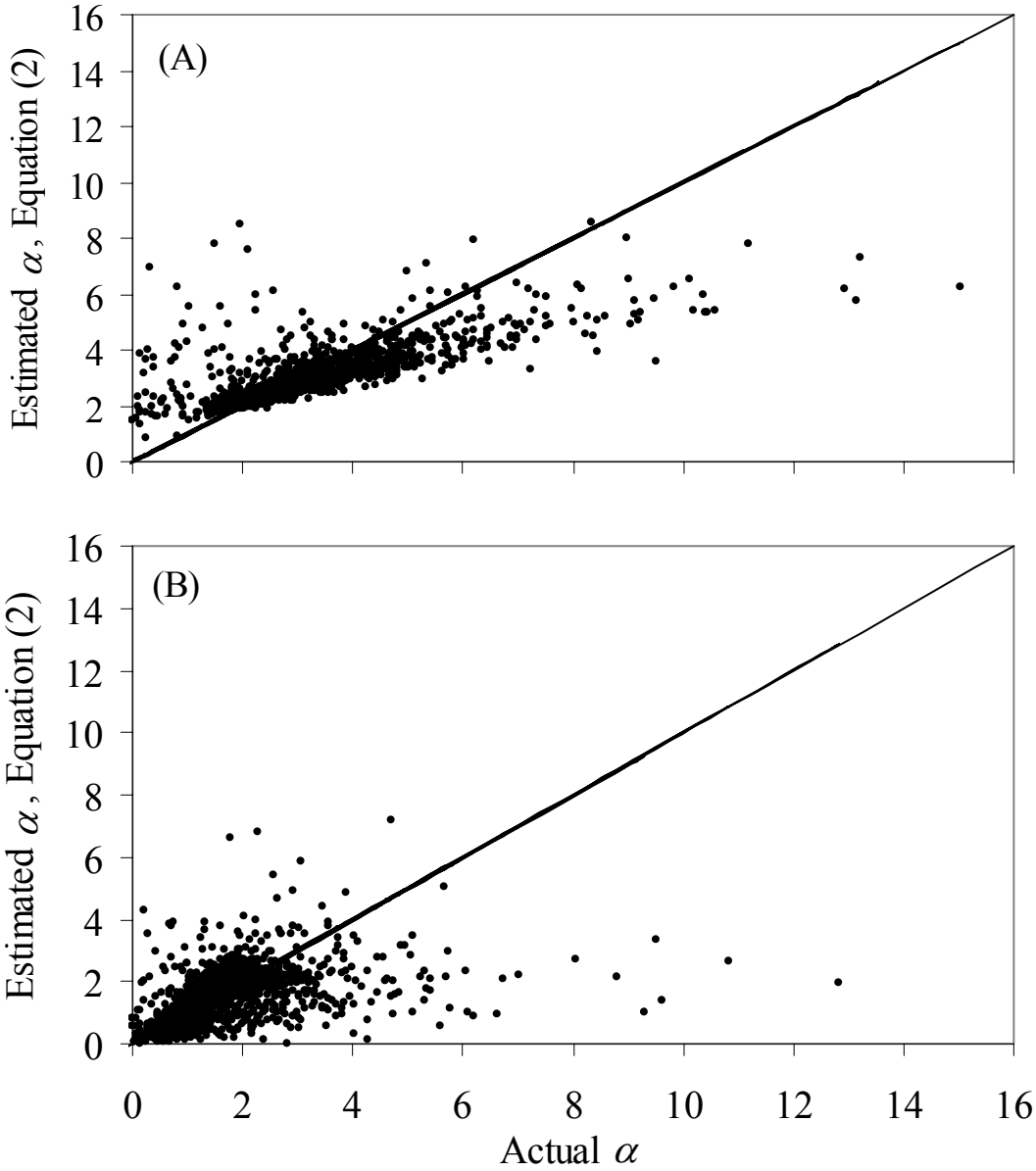

FIGURE 6. Performance of Equation (2). Estimateding versus the actual α parameter at the upper measurement height. ; aA) Under unstable conditions; , and bB) Under stable conditions. Solid line represents the 1:1 line.

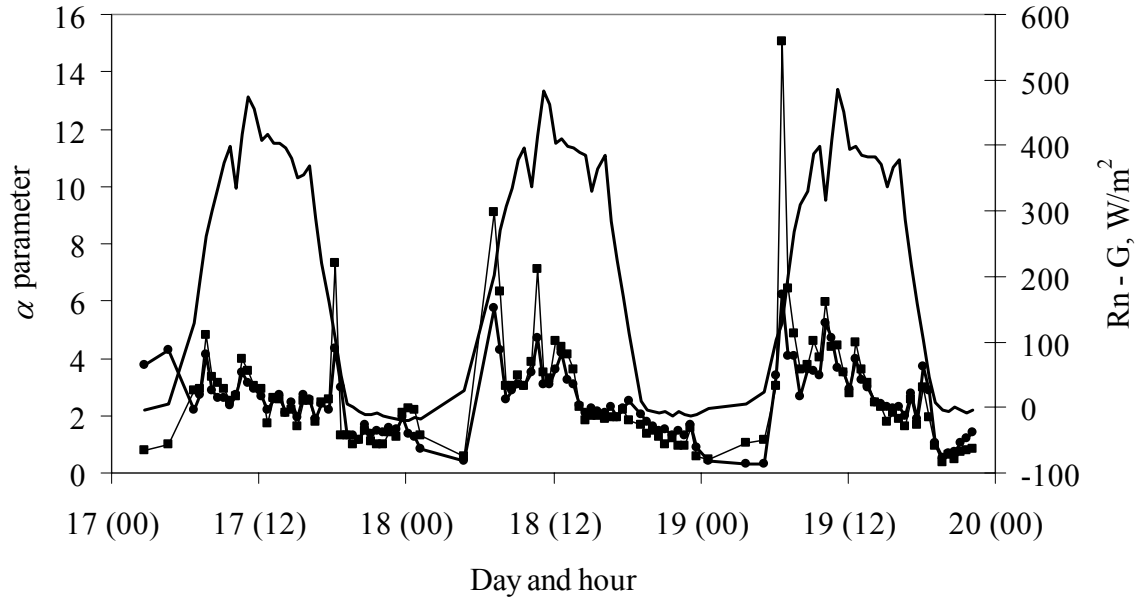

FIGURE 7. Three days tTime evolution of half hour (*Rn-G*) samplesfor; (solid line) in W m^{-2}, dashed line for the secondary axis; and the estimated [Equation (2), -●-] and actual (-■-) α parameter values corresponding to the upper measurement height from May 17 to 19., Equation (2), diamonds; and the actual α parameter, circles.