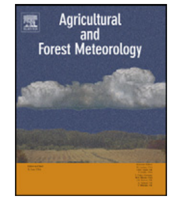
Agricultural and Forest Meteorology 152 (2012) 58–64

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Sensible heat flux estimates using two different methods based on surface renewal analysis. A study case over an orange orchard in Sicily

F. Castellví[a,*], S. Consoli[b], R. Papa[b]

[a] University of Lleida, Spain
[b] University of Catania, Dpt. di Gestione dei Sistemi Agroalimentari e Ambientali, Via S. Sofia, 100, Catania 95123, Italy

ARTICLE INFO

Article history:
Received 13 December 2010
Received in revised form 31 August 2011
Accepted 1 September 2011

Keywords:
Sensible heat flux
Eddy covariance
Surface renewal analysis
Orange tree

ABSTRACT

An experiment was carried out over a mature orange orchard to evaluate the reliability of two methods based on surface renewal, SR, analysis, SR1 and SR2, to estimate sensible heat flux, H. After calibration, the method SR1 only requires as input the air temperature measured at high frequency. However, method SR2 requires air temperature measurements taken at high frequency, the mean and turbulent standard deviation of the horizontal wind speed, the leaf area index, the canopy height and the vertical extent (m) of the foliage. Methods SR1 and SR2 operated at the canopy top, $z = 4$ m. The H measured using the eddy covariance, EC, method operating at height slightly higher than twice the canopy height, $z = 8$ m, was taken as a reference, $H_{EC\_8\,m}$. For completeness, because the method SR1 may also operate well above the canopy, its performance was also analyzed at $z = 8$ m, and another EC system was deployed close to the canopy top at $z = 4$ m, $H_{EC\_4\,m}$. For calibration, three periods of 15 days were selected. For method SR1, regardless the height at which operated, it is shown that calibration was dependent on weather conditions, including daily and seasonal patterns. Therefore, in contrast to other experiments that recommended application of method SR1, this study questions its reliability. For method SR2, calibration was the same for each calibration period. Validation was made for three periods of three months each. In relation to $H_{EC\_8\,m}$, regardless of the validation period SR2 was closer than SR1 and it was less biased than $H_{EC\_4\,m}$. Because reliability is mandatory for method selection SR2 is recommended over SR1 and it could be considered to fill gaps of the EC method for samples affected by flow distortion.

1. Introduction

Acquisition and maintenance of the instrumentation required to directly measure scalar surface fluxes (i.e., the eddy covariance, EC, system) are expensive. Therefore, alternative methods are of interest and, if proven reliable, they may also be implemented to overcome routinely problems in direct measurements, such as gap filling (Dias et al., 2009; Guo et al., 2009). Alternative methods are especially useful when they are affordable, and when operating simultaneously with direct methods they do not share shortcomings. The surface renewal, SR, analysis method to estimate the flux of a scalar (pioneered by Paw U et al., 1995) is appropriate because the theoretical grounds invoked are different from the EC method. As a consequence, to apply the SR method the three dimensional sonic anemometer is not required and it can operate either in the roughness and inertial sublayers. SR studies mostly centred on sensible heat flux, H, estimation, and the earlier SR method, SR1, has been recommended for more than a decade (Anandakumar, 1999; Anderson et al., 2003; Consoli et al., 2006; Drexler et al., 2004, 2008; Katul et al., 1996; Mengistu and Savage, 2010; Paw U et al., 2005; Snyder et al., 1996, 1997; Spano et al., 1997; Zapata and Martínez-Cob, 2001, 2002).

Method SR1 requires calibration of one parameter, the so-called parameter α (see Eq. (1)). However, the assumption to take α as a constant appeared stringent because earlier studies shown dependency on stability cases, canopy architecture and measurement height (Castellví, 2004). The parameter α has been a matter of research which may be summarized as follows. An expression to estimate α (half-hourly) was derived that was capable to explain the performance observed in previous experiments (Castellví, 2004). Therefore, the SR method using half-hourly α estimates, method SR2, became exempt of calibration, provided the input required is available.

When measurements are taken in the inertial sublayer over a rather homogeneous surface, there is evidence that the method SR2 is superior to SR1 (Castellví, 2004), and that SR2 may be considered as an independent method for estimating scalar fluxes (Castellví, 2004, 2010; Castellví and Snyder, 2009a, 2010a; Castellví et al., 2008). When measurements are taken in the roughness

* Corresponding author at: Dpt. Medi Ambient i Cienciès del Sòl, E.T.S.E.A. C. Rovira Roure, 191, Lleida 25198, Spain. Tel.: +34 973 702620; fax: +34 973 702613.
E-mail address: f-castellvi@macs.udl.es (F. Castellví).

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doi:10.1016/j.agrformet.2011.09.001

sublayer, the performance of method SR2 only has been analyzed for H (according to our knowledge). Earlier studies consisting on short datasets mainly gathered under unstable cases (Castellví, 2004; Castellví et al., 2006) and at a windy site regardless of the stability case (Castellví and Martinez-Cob, 2005) shown that method SR2 performed close to the EC method using estimations of the roughness sublayer depth (from the ground), z^*, and the zero-plane displacement, d, as a portion of the canopy height, h_c. Over grapevines it was shown that portions of multiple pairs (z^*/h_c, d/h_c), can provide reliable H estimates (Castellví and Snyder, 2010b) and an objective method was derived to determine a reliable pair for near neutral cases over homogeneous and moderately heterogeneous canopies. For these experiments, relationships to account for the variability of z^* were not required because the H estimates were close to the determined using the EC method. However, over rice (Castellví and Snyder, 2009b) and peach orchard (Castellví and Snyder, 2009c), methods SR2 and EC were close when it was coupled with semi-empirical relationships to estimate z^* half-hourly. It was recommended to check these relationships and a set of equations were derived to facilitate this task (Castellví and Snyder, 2009b). Therefore, in the roughness sublayer there is a need to establish a general procedure for estimating α in SR2, valid for different surfaces and weather conditions. For field applications, the latter will state which is the input required to apply SR2.

For sensible heat flux, two earlier studies (133 and 43 half-hourly samples gathered under unstable cases over grapevines and wheat, respectively) shown that using reasonable scaling for (z^*/h_c, d/h_c) SR2 performed superior to SR1 (Castellví, 2004). Likely, because there is not a unique α-procedure to apply SR2 and methods SR1 and EC are highly correlated for unstable cases recent studies have recommended SR1 without analyzing the performance of SR2 (Drexler et al., 2008; Mengistu and Savage, 2010). This study was motivated in light to compare SR1 and SR2 using a procedure to estimate α that accounts for variability of z^* depending on weather conditions and canopy characteristics (Castellví and Snyder, 2009c). Therefore, differences in input requirements and performance between the SR methods can be compared. An experiment (from February to October 2010) was carried out to estimate H over a mature orange orchard. The experiment offers the optimal conditions for our purpose because the morphology of a mature orange tree is fairly constant through the year. Thus, calibration and validation depend on weather conditions.

2. Theory

SR analysis for estimating scalar surface fluxes uses SR theory (pioneered by Higbie, 1935) in conjunction with the analysis of the scalar trace to extract the mean ramp dimensions (amplitude and period) of the ramp like (or asymmetric triangle shape) pattern observed in the trace (typically, half-hourly). Ramp dimensions identify a coherent structure which can be defined as an eddy capable to provide organization within the turbulent motion and responsible for the main vertical turbulent mixing (Hongyan et al., 2004; Paw U et al., 1995). The SR method is based on a solution of the scalar conservation equation for an incompressible steady and planar homogeneous turbulent flow. For sensible heat flux, assuming that the air parcel renewed (i.e., the associated with the coherent structure) is uniformly heated (cooled) with no heat lost through the parcel top while it remains in contact with the sources (sinks), it can be estimated as (Paw U et al., 1995; Castellví, 2004):

$$H_{SR}=\rho C_p(\alpha z)\frac{A}{\tau}\begin{cases}\text{method SR1; } \alpha=\text{constant} & \text{for } h_c<z\\ \text{method SR2; } \alpha=\left[\dfrac{k}{\pi}\dfrac{(z^*-d)}{z^2}\tau u_*\,\phi_h^{-1}(\varsigma)\right]^{1/2} & \text{for } h_c<z\le z^*\end{cases} \tag{1}$$

where ρ and C_p are the density and specific heat at constant pressure of air, respectively, z, is the measurement height of the air temperature trace which represents the volume, V, per unit area, S, of the parcel (i.e., $z = V/S$), the parameter α is included to correct the volume for the unequal heating within the air parcel, and A and τ are the mean amplitude and period of the ramp pattern observed in the temperature trace. Because method SR1 assumed parameter α as a constant to be calibrated against the EC method, the implication was sound because the only input required is the measurement of the air temperature trace at one height above the source. Method SR2 estimates α (half-hourly) and in Eq. (1) $k = 0.4$ is the Von Kármán constant, u_* is the friction velocity which can be estimated as, $u_* = 0.5\sigma_u$ where σ_u is the turbulent standard deviation of the horizontal wind speed measured at the canopy top (Kaimal and Finningan, 1994), $\phi_h(\zeta)$ is the flux-gradient stability function and ζ is a stability parameter, $\zeta = (z - d)/L_o$, where L_o is the Obukhov length, $L_o = -(u_*{}^3/k\,g(\overline{w'T_v'}))T_v$ [T_v and g are the air temperature (virtual) and acceleration due to gravity, respectively, and $\overline{w'T_v'}$ is the kinematic buoyant sensible heat flux]. In practice, when T_v is not available it is replaced by the air temperature. Regardless, a widely accepted formulation for $\phi_h(\zeta)$ is (Foken, 2006; Högström, 1988):

$$\phi_h(\zeta)=\begin{cases}(0.95+7.8\zeta) & 0\le\zeta\le 1\\ 0.95(1-11.6\zeta)^{-1/2} & -2\le\zeta\le 0\end{cases} \tag{2}$$

Castellví and Snyder (2009c) combined a model based on a mixing-length theory for momentum (Harman and Finnigan, 2007), mixing-layer analogy (Raupach et al., 1996), semi-empirical canopy-relationships (Graefe, 2004) and the relationship $u_* \approx 0.5\sigma_u$ to estimate z^* half-hourly:

$$z^* = h_c + \frac{(h_c-h_*)^2}{(h_c-d)}\frac{I_u^2}{(c_d LAI)} \tag{3}$$

where h_* is the height from the ground to the bottom of the canopy, c_d is the leaf drag coefficient, LAI is the leaf area index, and $I_u = (\sigma_u/u)$ is the turbulent intensity where u is the horizontal mean wind speed at the canopy top.

The zero-plane displacement can be estimated as a portion of the canopy height where an intermediate scaling is $d = 0.75\,h_c$ (Brutsaert, 1988). Estimation of the mean drag coefficient at the leaf scale is a compromise. It depends on the shape and orientation of the leaves and, in principle, it may depend on the velocity field within the canopy through the Reynolds number, Re, though such relationship is not still clear (Brutsaert, 1988; Pingtong and Takahashi, 2000). Models of transfer of momentum of different order support that c_d can be taken as a constant, that is not depending on Re (Pingtong and Takahashi, 2000).

Ramp dimensions. They were determined as described in Van Atta (1977) using structure functions, $S^n_{(r)}$ [r denotes time lag] of order, $n = 2$, 3 and 5. For solving the ramp period, several time lags were used to linearize the following relationship that holds for r much smaller than the warming (cooling) period, L_r, while the air parcel to be renewed remains in contact with the surface; $A^3 = -(S^3_{(r)}/r)\tau$. According to Chen et al. (1997), the shortest time lag to be used for linearization, r_{1G}, is that which produces the first global maximum of $S^3{}_{(r)}/r$. To estimate the maximum time lag, r_{end} to be used for linearization so that $r \ll L_r$, the second global maximum of $S^3{}_{(r)}/r$ was determined. The second global maximum occurs at a time lag, r_{2G}, giving $r_{2G} \approx ¾\tau$. Based on Qiu et al. (1995) that showed $(\tau - L_r) \approx 0.25\tau$, it follows that $r_{2G} \approx L_r$. Accordingly, the last time lag used for linearization was determined as 1% of r_{2G} to insure $r_{\text{end}} \ll L_r$.

The H estimates. For method SR1, once α is known, determination of H is immediate from measurements taken with a fine-wire thermocouple. For method SR2, provided c_d, d, h_* and LAI are known (or estimated), z^* is determined half-hourly and H can be iterated. Starting at neutral case, $\phi_h(\zeta) = 0.95$, α is determined which