Tethys, 4, 19–26, 2007
www.tethys.cat
ISSN-1697-1523
eISSN-1139-3394
DOI:10.3369/tethys.2007.4.03

Journal edited by **ACAM**
(Associació Catalana de Meteorologia)

The estimation of latent heat flux: A reflection for the future

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Received: 14/II/2007 – Accepted: 2/XI/2007 – **Translated version**

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Abstract

Currently, the cost of measuring turbulent fluxes is extremely high. Thus, the development of models and theories that use robust and low-cost equipment to estimate turbulent fluxes is becoming an increasingly interesting line of research. This paper describes the difficulties encountered throughout the study in estimating evapotranspiration. A set of experiments, (already published), were carried out to estimate average sensible and latent heat fluxes every 30 minutes. These experiments used different models based on the Surface Renewal Analysis (SR); the results are presented in this paper. Considering the fundamental importance of water in the agricultural industry, this article addresses the issue of implementing SR in the protocol for data acquisition-transfer in a network of agro-meteorological stations.

1 Introduction

With the high cost of measuring turbulent fluxes (sensible heat, H; latent heat or evapotranspiration, LE; carbon dioxide, and any scalar in general) in the agrarian field, knowledge of *LE* is vital (Jensen et al., 1990). Furthermore, the importance of hydrological management has been magnified by the growing concern of climate change. However, at present, very few institutions have the financial or managerial resources required to measure *LE*. This involves the continuous maintenance of equipment such as precision lysimeters, anemometers, and fast response hygrometers, which are used to apply the eddy correlation method (EC method) when measuring *LE*. Both the initial cost of a precision lysimeter and its maintenance is very expensive. Furthermore, they come with a disadvantage in that over time the plant located on the lysimeter stops being representative of the area.

The EC method, based on Reynolds decomposition, measures the covariance of turbulent fluctuations in the vertical component of air speed and humidity. It is a complicated method. Regardless of the type of instrumentation used there are technical issues that limit the precision of results. These include the difficulty in simultaneously measuring air speed and humidity, the selection of a stationary flow period, and problem of ensuring that average vertical speed is zero (Kristensen et al., 1997; Lee and Black, 1994; Laubach and Teichmann, 1999; Mauder et al., 2007).

There is no a well-defined protocol to correct the various deficiencies encountered in the EC method; in some cases, attempts to correct deficiencies introduce new deficiencies into the calculation of the covariance (Twine et al., 2000; Wilson et al., 2002; Mauder et al., 2007). However, unlike lysimeters, the instrumentation is portable making the EC method versatile and more attractive.

Consequently, the development of models and theories to estimate *LE* by using robust and low-cost instrumentation constitutes a very interesting line of research (Wang and Bras, 1998; Wesson et al., 2001; Castellví, 2004). This allows an increase in the number of experiments (to improve space density) and to carry out longer campaigns, as the required maintenance is minimum (Anderson et al., 2003). This is vital in agriculture due not only to the amount of land used for this purpose, but also because of the diversity in the use and management of the land.

The aim of this paper was to highlight the problems in estimating *LE* We propose the Surface Renewal Analysis (SR) method, which although is still in the experimental phase, theoretically offers many advantages over existing conventional methods.

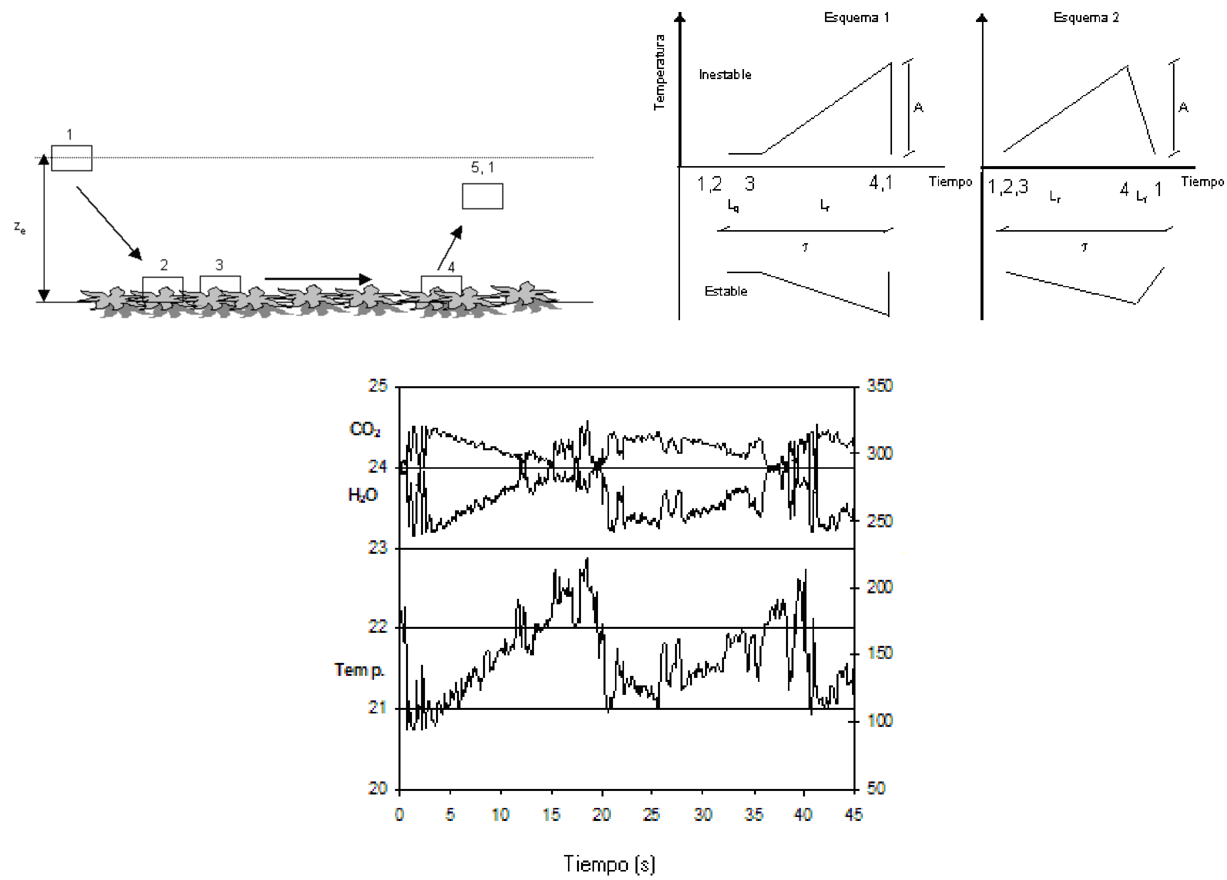

Figure 1. a)(Top left) Coherent movement of a particle. b)(Top right) Idealized time variation of the concentration of a scalar (temperature) for the different positions illustrated based on two models. c)(Below) Example of three 45 s time series for temperature (left Y axis in °C), and concentration of water vapor (right Y axis), H_2O (10^{-3} mol m^{-3}) and carbon dioxide, CO_2 (10^{-4} mol m^{-3}).

2 The estimation of latent heat flux; a short comment about conventional methods

The estimation of *LE* is difficult. *LE* measurement is expensive and lacks precision due to a number of disadvantages, some of which are known and others still unsolved. As a result, a number of methods used to estimate *LE* are based on insufficient theories and hypotheses. For instance, some of the commonly used methods include expressions based on the Monin-Obukhov Similarity Theory, MOST (aerodynamics method, variance method, etc.), and the Bowen Ratio-Energy Balance technique (BREB). These require measurements taken inside the inertial turbulent layer (Brutsaert, 1988; Kaimal and Finnigan, 1994) and consequently are difficult to apply on high vegetation or in areas with low vegetation cover (this is commonly named "lack of fetch").

The inertial turbulent layer is the atmosphere stratus which separates (transition in the vertical) the atmospheric layer in contact and influenced by rough elements of land surface (land and vegetation) and the atmospheric layer with a turbulence which is basically generated by the general flow and non influenced by the sort of surface where air movement takes place.

Therefore, the characteristics of the inertial layer are controlled by changes in the land surface; for instance, those changes encountered in the transition from bare soil to crop. However, it also depends on the distance of that transition following the horizontal direction of air movement. This is named the fetch.

On a vast and homogeneous surface, the basis of the inertial layer is estimated to be between 1.5 and 3 times the height of the vegetation (or the average height of rough elements). Thus, in order to measure the inertial layer of tree cover in an area (forests, fruit trees, etc.), large meteorological towers must be installed. In addition, a small fetch makes the inertial layer narrower; therefore, measurements are taken at heights that are close to one to another. However, the surrounding area may disturb the measurements; part of the measured scalar comes from sources of other surfaces, making the gradient measurements subject to error.

On average, for each 100 m fetch the thickness of the inertial layer is increased by one meter (a little higher or lower in unstable and stable cases, respectively). In practice, and especially in those cases of stable stratification, the lack of fetch is usually a common inconvenience and invalidates the estimation aforementioned techniques. To avoid this requires research into the spatial representativeness of the measurements. This is commonly known as a foot prints analysis. If the estimation of the *LE* is carried out using models or theories that require the measurement of the humidity variability of the ground, such problems can be avoided. However, when the necessary instrumentation is placed at different depths, the ground measurements can be altered or perturbed. Therefore, parameters that influence water mobility (porosity, compaction, root density, etc.) are not significant anymore. Moreover, the ground has a high spatial variability and thus local estimations of *LE* cannot be representative of the surrounding area.

Methods based on the measurement of sap flux are limited to wood species and have the inconvenience that the plant could be damaged if the installation is inaccurate. In general, too many probes are required to get a precise measurement and the cost of the measurement system is very high. Another disadvantage to this method is that it estimates the quantity of transpired water rather than the water evaporated from the ground. Further research into this area is required.

Regarding the stations of the meteorological networks, the measurements taken are rarely used to estimate *LE* through semi-empiric expressions such as those proposed by Hargreaves et al. (1985), Priestley and Taylor (1972), etc., as they are generally imprecise. Precision depends on the selected time scale (half-hourly, hourly, daily, fortnightly, etc.) to estimate *LE*. In shorter periods, errors are more likely to occur. Therefore, these expressions are usually used when meteorological information is limited, such as countries with poor infrastructure and in remote areas where station maintenance is very expensive.

In agriculture (mainly precision agriculture) there are agrometeorological station networks that estimate the reference evapotranspiration *ETo* of the reference crop. These estimations are based on the Penman-Monteith equation: PM (Allen et al., 1998). These station networks operate on a worldwide consensus (recommended by the United Nations Food and Agriculture Organization, FAO). The *ETo* is defined as the evapotranspiration rate calculated with the PM of the reference crop. This is defined as a hypothetical surface of grass with a height of 12 cm; it is well-watered; it casts a shadow over the entire ground surface; and has a stomatal resistance to water flux of 70 m s^{-1}. It has a roughness height of 0.015 and 0.0015, for the moment transfer and sensible heat flux, respectively.

Assuming the PM measurement for the vegetation cover of a relatively homogenous area (perhaps the most common type in Spain would be ryegrass), the *LE* value for other types is assumed to be proportional (through which a crop coefficient, *Kc* is denominated) to *ETo*; thus, *LE* = *Kc·ETo* (Jensen et al., 1990). We can then make the following assumptions: 1) *Kc* determination requires an accurate measurement of the *LE* for each crop, and 2) in order to assume that *LE* = *Kc·ETo* is valid in different agroclimatic conditions the possibility of a 'local' characteristic of the *Kc* must be ignored. Local characteristic would be any anomaly in the area that has the potential to alter the phonological state of the plant (diseases, lack of hours of cold, variability in ground salinity, drought, and crop management). Besides this, the up-to-date knowledge about *Kc* is limited to a few species or crops, and does not extend to specific climatic conditions. This technique cannot be applied to forests.

3 Surface Renewal Analysis (SR)

The measurement of net radiation (*Rn*) and heat flux on the ground (G) is currently affordable. As a result, the development of H estimation models using robust and low-cost sensors has become particularly interesting in agronomy. Also, within the agrarian field a simplified expression of the first law of thermodynamics (commonly designated Surface Energy Balance Equation, EB), $Rn - G = H + LE$, could be applied to a high number of crops. Thus, models based on SR are of interest (Paw U et al., 1995; Drexler et al., 2004). One model of surface renewal analysis is a Lagrangian method. This is based on the conservation of a scalar to estimate a scalar flux. A description of the model and its use up until 2002 (approx.) with the relevant bibliography can be found in Paw U et al. (2005). A description incorporating more recent modifications can be found in Castellví (2004) and Castellví et al. (2006a).

The basic idea is to interpret the time series of a scalar measured at high frequency and is described below. Figure 1a demonstrates that a particle of air situated on a certain level, z_e, that moves embedded in the general flow, will at some point (due to a transfer of moment in the direction of the surface) descend and make contact with the scalar in surface sources (sinks). If, during the contact time, the particle becomes enriched (impoverished) of scalar and we suppose that there is a negligible loss (i.e. there is no loss in the superior part of the particle volume), the rate of scalar enrichment is directly related to the source intensity.

Taking air temperature, T, as an example of a scalar, s (or the equivalent for sensible heat, $s = \rho\ C_p\ T$, where ρ and C_p indicate density and specific heat capacity at constant air pressure), Figure 1b shows the ideal time variation of the particle temperature, based on a Lagrangian concept, in the different positions as is shown in Figure 1a. Positions 1 and 2 should be an almost instantaneous, incursion phase. Positions 2 and 3 represent a transitory phase (period L_q), required by the particle to acquire the characteristics of the surface. Positions 3 and 4 represent a quasi steady phase of continuous enrichment of the scalar (period L_r), and positions 4 and 5 (1) represent a quasi instantaneous renovation phase (period L_f). Diagram 1 (Figure 1b) assumes an instantaneous renovation phase. Diagram 2 assumes that the transitory phase is negligible.

Both diagrams are characterized by amplitude, A, and a period τ. When A is positive, the surface behaves as a source of scalar; when A is negative, the surface behaves as a sink. Figure 1a shows a coherent motion; it is commonly said that what is seen in Figure 1b is the sign of a coherent structure.

Therefore, a coherent structure is, in a simplified way, identified by A and τ, which represent the amplitude and the period in the asymmetric triangular shape shown in Figure 1b. It is important to highlight that when temperature, positive amplitude indicates an unstable stratification and stable amplitude indicates a stable stratification (Figure 1b). Thus, an estimation (average height) of scalar source intensity (horizontally homogeneous) by unit of control volume, S, could be taken as, $S = A\ \tau^{-1}$ and therefore the scalar flux, $F_{(z)}$, is directly related to the following expression: $F_{(z)} \sim z\ A\ \tau^{-1}$, where z is the control volume per area unit. It is important to note that $S = A\ \tau^{-1}$ is a Lagrangian and not an Eulerian estimation, as required by the energy balance equation.

If the fluid is assumed to be incompressible, both sources coincide; however, being water vapor sources (as with carbon dioxide) they cannot be treated as incompressible. Implementation of this correction is not fully understood, even if the theories developed by Webb et al. (1980) and Paw U et al. (2000) are applied as an approximation. Since the scalar is measured at a fixed point, the measured time series differs from that shown in Figure 1b. Figure 1c shows a case of an unstable stratification with a short series for different scalars (temperature, water vapor concentration, and carbon dioxide). All scalars were measured at a 10 Hz frequency, a height of 2 m over natural grassland, which was 0.25 m high, and under unstable stratification. Figure 1c shows a sequential tendency of coherent structures or ramps, such as those shown in Figure 1b. Those shown in Figure 1b are superimposed to more random fluctuations of higher frequency, and are assumed to be locally isotropic.

Therefore, the extraction of the average quantities of the coherent structure embedded in a time series (commonly half an hour), using different mathematical techniques, allows the estimation of the half-hourly average flux. Even if there are various mathematical methods to filter and extract signals, the methods that are most commonly used to determine coherent structures might be the wavelet transform and the study of the structure functions. This is because these are objective techniques and use the information of all measurements (Atta, 1977; Chen et al., 1997a,b).

The main idea of this study is that, through SR, the information required to estimate the half-hourly flux of a scalar is the high frequency measurement (generally, frequencies higher than 10 Hz are not necessary in agrarian surfaces) of the corresponding scalar (air temperature for H, humidity for *LE*, etc.). Depending on the model of SR used, it is important to know the average value (every 30 minutes) of the wind on a reference level. Therefore, SR offers some advantages at times when *LE* can be estimated as a residual of EB with the expression $LE = Rn - G - H$. This is due to the simple fact that, at most, only a thermocouple, a net radiation meter, a geothermal flux plate (in case the surface is not homogeneous, as in fruit tree plantations, vineyard, etc., several measurements of G are necessary), and a simple anemometer are required.

Consequently, the instrumentation needed to estimate *LE* is affordable, robust, transportable, and easy to maintain. When it is not possible to apply the expression $LE = Rn - G - H$, the latent heat flux could be estimated through the high frequency measurement of air humidity. It is important to highlight that, as SR is based on the conservation of a scalar, the measurement of the scalar could be done under the inertial layer (rough layer). This reduces the inconvenience resulting from the lack of fetch and that in cases of tall vegetation, high meteorological masts are not necessary.

It is obvious that in SR the formation of well-defined ramps in the time series is required. Therefore, the flux estimation will be less reliable when atmospheric situations favor ramp malformation. For instance, *in principle*, SR would be less reliable when the sources (sinks) are less intense. More specifically, H estimation is difficult in periods near neutral stability. According to the author's experience, the term *in principle* emphasizes the fact that in these situations the fluxes taken as a reference for comparison are either in or near to the error in measurement techniques. Because of this, evaluating the results is very difficult.

In terms of temperature (sensible heat flux), the sign of the ramp amplitude allows for the discrimination between stable and unstable cases (Figure 1b). Therefore, the transition periods and establishment of filtering criteria as quality control can be detected. Although in theory the amplitude tends to be zero when the sources (sinks) are less active, sometimes this does not happen due to the sporadic apparition of high fluctuations that are not always noticeable (Vickers and Mahrt, 1997). In fact, it is impossible for the sign of the determined amplitude to correspond to the type of atmospheric stability. In principle, these deficiencies should be corrected by taking longer series, and/or increasing the measurement frequency. According to the author's knowledge, there are no references or studies regarding such differences, even though, in terms of *LE* estimation during these periods (normally during sunrise and sunset), $LE \approx Rn - G$ is obtained. Therefore in practice, these deficiencies, even if they are difficult to study, do not represent any relevant inconvenience for agrarian finalities.

4 Experimentation and discussion

Table 1 shows a brief summary of several experiments in which H and/or *LE* (every 30 min) were estimated using various recently developed SR models. There are three aspects to be highlighted: 1) the variety of the kind of cover (some are far off being homogeneous and therefore the hy-

Table 1. Summary of the experiments showing the results of a linear regression analysis (slope, a, ordinate at the origin, b, and correlation coefficient, R^2) for all data and mean square error, *MSE*. The results correspond to the estimation of H using the estimated flow by the eddy covariance technique as a reference (independent variable). Results do not represent rice. The results shown correspond to estimations of (H + LE) taking the measurements of (Rn - G) as reference. The fetch is expressed in meters, and the origin ordinate and *MSE* are expressed in W m^{-2}.

Cover and height (m)		Measurements taken[a]	Fetch (m)	Number of data inputs[b] and place		a	b	R^2	*MSE*
Ryegrass	0.15	Above inertial	50	578	Davis (CA, USA)	1.01	-2	0.91	7.5
Wheat	0.4	Roughness	>400	43	Davis (CA, USA)	1.02	-1	0.72	49
Vineyard	2.5	Roughness	400	133	Oakville (CA, USA)	1.06	-3	0.93	24
Pradera	0.25	Inertial	>200	6013	Ione (CA, USA)	1.00	-1	0.95	20
Nectarine tree	3.2	Roughness	60	126	Lisboa (Portugal)	1.00	10	0.94	22
Olive tree	3.4	Roughness	>400	3796	Zaragoza (Spain)	1.11	0	0.87	10
Rice	0.4	Above inertial	70	160	Zaragoza (Spain)	1.05	3	0.96	44.5

[a] Turbulent layer.
[b] Total number of data inputs, which includes different measurement levels.

pothesis of homogeneous turbulence cannot be applied); 2) the variety of available fetch in each particular case (in some cases this was very restricted); and 3) the heights at which measurements were taken on the same cover (generally outside the inertial turbulence layer). Table 1 shows cases when traditional methods based on MOST, BREB, and the method based on the balance between production and dissipation of a scalar variance, could not be strictly applied (Brutsaert, 1988; Kaimal and Finnigan, 1994; Högström, 1996; Edson and Fairfall, 1998).

Figure 2 shows examples of H estimation using different SR models with regard to those measured with the EC method for the surfaces listed in Table 1. Details about the experiments (location, climate, vegetation characteristics, instrumentation and measurement processing, analysis of the spatial representativeness, and quality control), and a detailed description of the comparison of the results obtained using different conventional methods of H and LE estimation. They are described in the following studies: for ryegrass, wheat, and vineyards, Castellví et al. (2002) and Castellví (2004); for grassland, nectarine tree, and olive tree, Castellví and Martinez-Cob (2005); Castellví et al. (2006a, 2008); for rice, Castellví et al. (2006b). To determine H_{SR}, the temperature was measured at a frequency of 8 Hz, while H_{EC} was measured at 10 Hz. For ryegrass, wheat, and vineyards, measurements on different heights were taken simultaneously, either below, inside, and over the inertial layer.

Below are some relevant characteristics about the architecture of the vegetation cover, type of land and climate where the experiments were carried out. On vineyards, the vines were bushy and the distance between plants was 2.5 m. On grassland, the research was carried out in a region influenced by regional advection where the similarity theory for the scalars temperature, water vapor, and carbon dioxide could not be applied (Castellví et al., 2008). In this case, the land was undulated with savanna vegetation, and the closer trees were located at 400 m and were 18 m high. In the summer the ground was bare due to the arid conditions. During this time, the nectarine trees had a dense top and were 5.5 m meters apart. In contrast, the tops of the olive trees were not dense and the distance between trunks was 6.0 m. In both cases, measurements were taken near the top.

Figure 2 shows the results of H estimation; measurements with the EC method were taken as a reference (precise estimation). It is important to highlight that there are only a few studies regarding LE. This is partly explained by the lack of a reliable comparison reference, which could lead to irrefutable conclusions about the behavior of the estimation model. The only references found have been the following: a case study about forests (Katul et al., 1996), about rice (Castellví et al., 2006b) and about grassland (Castellví et al., 2008).

In all experiments shown in Table 1, except that of wheat, differences between estimation and measurement for the during day period (the period of highest LE demand) are within the disparity rank found using different sets of EC equipment (commercial brands) (Mauder et al., 2007). A higher sampling rate might have been required in the atmospheric conditions in which the experiment with wheat was carried out. The measurements were taken during a front passage that generated small and dense cumuli. Those cumuli frequently caused significant decreases in the net radiation and therefore half-hourly samples correspond to a non stationary flow.

Based on the author's experience, it seems that in cases of stability the precision of the estimations depends on the turbulent intensity. Therefore, if the friction velocity is low (generally under 0.15 m s^{-1}), the SR does not explain the temporal variability of the flow measured by the EC method. However, in cases of strong stability, the EC method does not represent a reliable reference (Foken and Wichura, 1996). The difficulties in obtaining good estimations when H is negative may not be well illustrated in Figures 2d and 2e. The reason is that in the experiment over grassland (Figure 2d) a very exhaustive quality control of the measurements and foot prints was carried out and therefore many samples were filtered (Baldocchi et al., 2004). It is important to highlight that this kind of control cannot be carried out using the mini-

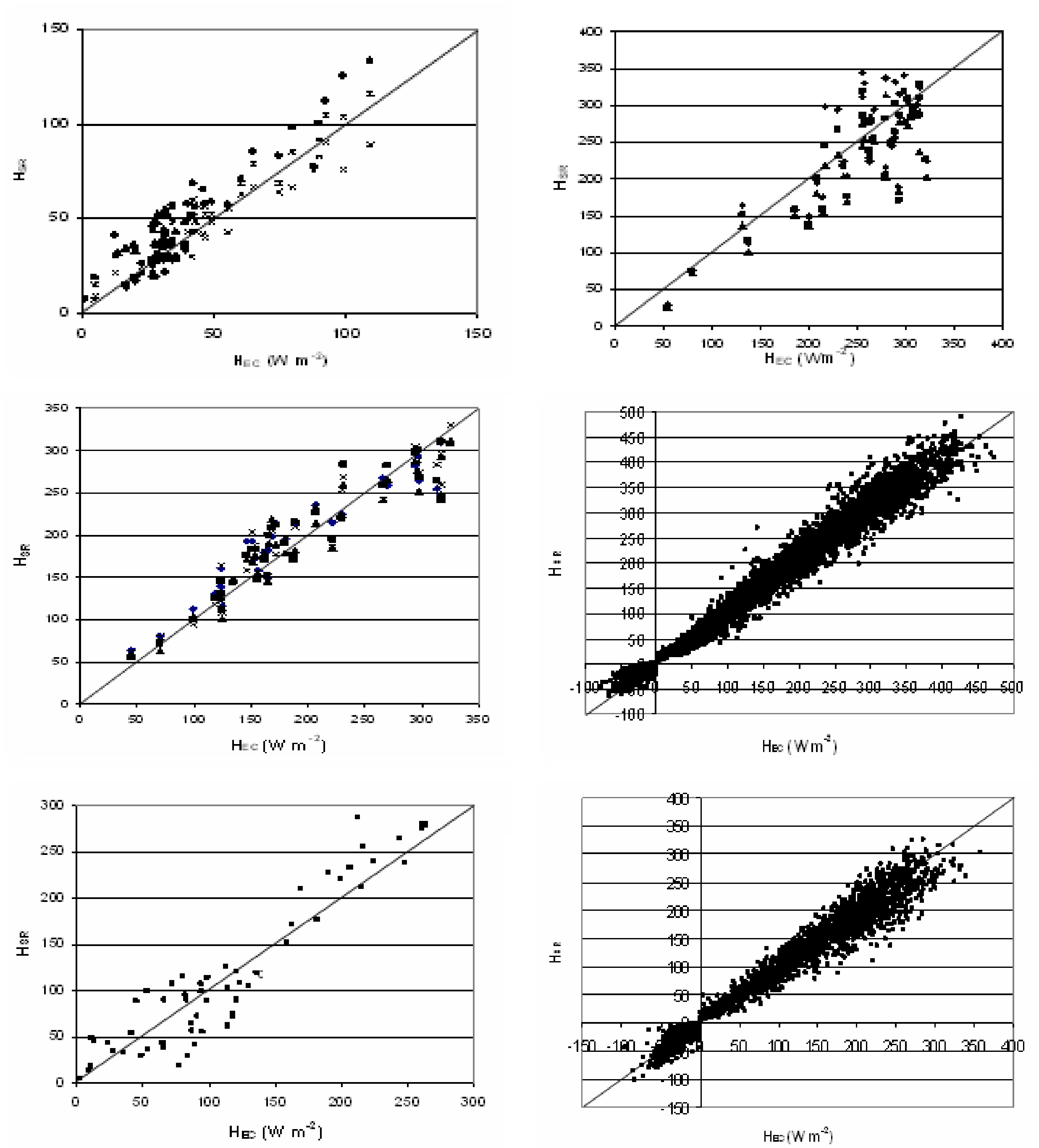

Figure 2. Estimated sensible heat flux, H_{SR}, compared with the one measured using the eddy covariance method, H_{EC}, for different kinds of vegetation cover. In some experiments (ryegrass, wheat and vineyards), measurements were taken at different heights, $z(m)$. a) Ryegrass (first row on the left), the heights (m) were the following: 0.6 (×), 0.7 (◇), 0.9 (∗) , 1.0 (□), 1.2 (◯) and 1.3 (△) m. b) Wheat (first row on the right), the heights (m) were the following: 0.7 (◇), 0.9 (□) and 1.3 (△) m. c) Vineyard (second row on the left), the heights (m) were the following: 2 (◇), 2.3 (□), 2.6 (△) and 2.9 (×) m. d) Grassland (second row on the right), z = 2.0 m. e) Nectarine trees (third row on the left), z = 3.5 m. f) Olive trees (third row on the right), z = 3.9 m.

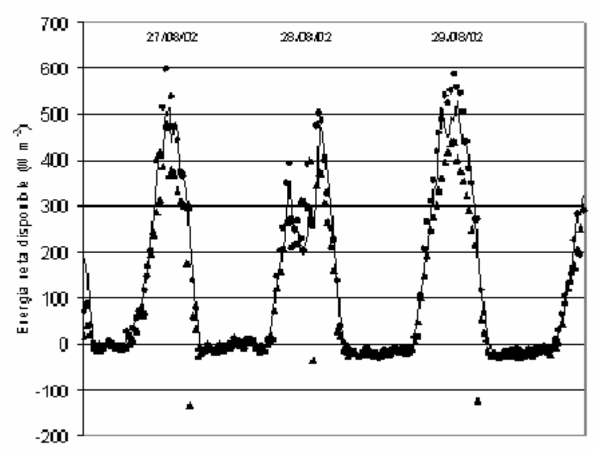

Figure 3. Results for a temporal study (three days) of the energy budget equation in a rice cover. The values every 30 minutes of $(Rn - G)$ measured (continuous line), $(H + LE)$ measured (EC, △) and estimated (SR, ◯) are shown.

mum instrumentation required to carry out a SR. With regard to the olive trees, as the research was carried out in a windy region, H, estimations were excellent regardless of the kind of stability (Figure 2f).

In Figure 3, the results of the experiment over rice (height of 0.4 m) are shown. It is important to highlight that the experiment was carried out in an experimental plot of rice watered by sprinklers and was roughly square-shaped with a surface area of 100 m^2; it was surrounded by experimental plots, which varied in type and the soil was bare. The measurements were taken in the center of the plot at a height of 1.5 m. The sensible and latent heat fluxes were of the same order (i.e. net energy available in equally partitioned surface). The SR equipment closed the energy balance equation better than the EC equipment (which is a thermocouple) of 76 μm of diameter connected to a three-dimensional (Csi) and a Kripton hygrometer (Kh20, Csi). The half-hourly values of (H + LE) estimated and measured (EC) and (Rn-G) are shown for the three-day study period.

SR appeared to perform equally or better, regardless of type of vegetation cover or atmospheric conditions compared to other conventional methods of flow estimation based on the variance of a scalar and the parameter of a scalar structure (Högström, 1996; Bruin et al., 1993).

5 Conclusions

According to Drexler et al. (2004), SR is currently the micro meteorological method with the lowest cost and offers the most advantages; although its full potential has still not been proved.

Nevertheless, SR is a relatively new method in comparison with other micro meteorological methods. The first SR model is still very new. This method allows an independent flux measurement (with no need of previous calibration) and measures at a reasonable frequency (4-10 Hz) (Castellví, 2004). This explains why the number of experiments carried out to study the reliability and theoretical potential offered by the SR method is smaller than that of other methods. However, several experiments have shown that H estimations are very close to those measured by the reference method (EC). As net radiation and heat flux on ground can be reliably measured, the conclusion is that good LE estimations could be obtained every 30 minutes.

This study evaluates how the implementation of SR could be useful in the estimation of the sensible and latent heat flux in the current protocol of data acquisition-transfer of an automated network of agrometeorological stations. This could improve the assistance to irrigator communities or simply adjust other semi-empiric estimation methods such as those that require data from satellite images. This is possible since SR increases the spatial density of flow measurements due to its reduced cost.

Acknowledgements. The authors would like to thank Asun, Carla, Tània, J. M. Villar, F. Fonseca, J. Cuxart and two anonymous reviewers for their collaboration in the reviewing process.

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