Recent micrometeorological studies of sensible heat flux in the plant-atmosphere system

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Abstract

For many years scientists working in fields related to micrometeorology have used the “Eddy Covariance (EC)” technique to study the transfer of water vapour, carbon dioxide and other greenhouse gases between plants, soils, bodies of water and the atmosphere at the boundary layer. This complex statistical technique uses high frequency measurements of the movement of air in the three dimensions along with the analysis of an air sample taken from the same position at the same time to determine the net exchange, or flux, of carbon dioxide, water vapour and sensible heat. Monitoring stations are typically installed above a canopy, field of crop or grassland, where some of the prerequisites of meaningful readings such as homogeneity of terrain can be attained. Acquisition and maintenance of the instrumentation required are expensive. Therefore, alternative methods are of interest and, if proven reliable, they may also be implemented to overcome routinely problems in direct measurements obtained by EC, such as gap filling.

On the basis of recent literature, this paper reports the results of experiments carried out to evaluate the reliability of two alternative methods based on surface renewal analysis to estimate sensible heat flux.

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1. Introduction

The partitioning between ecosystem latent (LE) and sensible (H) heat fluxes is critical in determining the hydrological cycle, boundary layer development, weather and climate. Two important issues
concerning flux partitioning are the variability of partitioning across different climates and ecosystems and the mechanisms for this variability. Energy partitioning at the surface is a complex function of longer-term interactions between biogeochemical cycling, disturbance, and climate, and shorter-term interactions between plant physiology and the development of the atmospheric boundary layer [1].

Determination of surface-atmosphere scalar exchange constitutes a major challenge in micrometeorology, being it necessary for improving regional weather and global climate models. As a direct technique, the eddy-covariance, EC, method is currently a widely applied technique. Partly, because it evaluates different scalar fluxes (i.e., large weighing lysimeters and sap flows provide direct measurement of latent heat flux and transpiration, respectively), the required instrumentation is transportable, and software packages for data processing are available and free distributed. In spite of the method is particularly friendly for groups with other skills rather than micrometeorology, the EC system is expensive. Among indirect techniques, main attraction lies on methods that (i) avoid the use of the three dimensional sonic anemometer, (ii) require few semi-empirical relationships, such as those based on Monin – Obukov Similarity Theory, MOST, and (iii) require few surface or canopy parameters as input, such as the zero-plane displacement, leaf area index, etc. Thus, while the first item concerns about flow distortion, sensor positioning and alignment avoiding a number of corrections and shortcomings, the second and third items concern on minimizing uncertainties that are inherent in semi-empirical relationships and measurements. Over moderately tall vegetation it is often difficult to deploy instrumentation in the inertial sublayer. Thus, measurements are often taken in the roughness sublayer which compromises the reliability of many methods (i.e., including the EC method) relying on MOST [2; 3; 4].

The objective of this study was to derive and compare methods based on the Surface Renewal technique to estimate sensible heat fluxes (H), exchanged within the plant-atmosphere system, avoiding some shortcomings inherent on the EC.

The performance of the methods was tested over a moderately tall and heterogeneous canopy (orange orchard) taking measurements in the roughness sub-layer. A mature orange orchard offers the optimal conditions for our purpose because its morphology is fairly constant through the year. Thus, a long experiment carried out during 2010 and 2011 allowed testing the methods performance for different weather conditions. Because the fetch was large, the H used as a reference for comparison was determined through EC system deployed at a height slightly higher than twice the canopy top.

2. Methods

2.1. Theory

In the study, Surface Renewal (SR) analysis was adopted for estimating sensible heat fluxes (H). SR theory is performed in conjunction with the analysis of the air temperature trace to extract the mean ramp dimensions (amplitude A and period τ) of the ramp like (or asymmetric triangle shape) pattern observed in the air temperature (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 [5]. The SR method is based on a solution of the scalar conservation equation for an incompressible steady and planar homogeneous turbulent flow. In our study, SR theory was used to implement the following M1 and M2 methods.
The first method (M1) implemented in the study is based on the assumption that above the canopy the production term in the budget equation of the mean turbulent variance of a scalar concentration, \( C \), \( (\text{w}^* \text{C}') (\text{d}\text{C}/\text{d}z) \) (w denotes vertical wind speed and primes the turbulent deviation from the mean), scales with \( (A^2/\pi \tau) \) [6]. The latter implies that the flux of a scalar can be estimated without measurements of the wind speed. By using the M1, half-hourly \( H \) can be estimated as:

\[
H_{M1} = \rho C_p \frac{A^2}{\pi \tau} \left( \frac{\partial T}{\partial z} \right)^{-1} \tag{1}
\]

A and \( \tau \) are the mean amplitude and period of the ramp pattern observed in the temperature trace, respectively, and \( T \) the mean air temperature.

The second method (M2) requires high frequency air temperature measurements taken at one level, 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:

\[
H_{M2} = \rho C_p \left( \alpha z \right) \frac{A}{\tau} \tag{2}
\]

with:

\[
\alpha = \left[ k \frac{(z^* - d)}{z^2} \tau u_* \phi_h^{-1}(\zeta) \right]^{1/2} \quad \text{and} \quad z^* = h_c + \left( \frac{h_c - h_u}{h_c - d} \right) \frac{I_u^2}{(c_d \text{LAI})} \tag{3}
\]

where \( z_c \) is the measurement height of the air temperature trace, the parameter \( \alpha \) is included to correct the volume for the unequal heating within the air parcel, \( k = 0.4 \) is the Von Kármán constant, \( u_* \) is the friction velocity, \( \phi_h(\zeta) \) is the flux-gradient stability function and \( \zeta \) is a stability parameter, \( z^* \) the roughness sub-layer, \( d \) the zero-plane displacement, \( h^* \) 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 \( I_u \) is the turbulent intensity where \( u \) is the horizontal mean wind speed at the canopy top. The friction velocity can be estimated as, \( u_c = 0.5 \sigma \) (where \( \sigma \) is the turbulent standard deviation of \( u \)). The zero-plane displacement can be estimated as a portion of the canopy height where an intermediate scaling is \( d = 0.75 h_c \) [7].

2.2. The field experiment

The trial was carried out over a 120 ha mature orange orchard in Sicily (37°16’ N, 14°53’ E) in 2010-2011 period. During the campaign, the weather was typical of the Catania plain, which is characterized by convective rain events, clear sky days and regional advection of sensible heat flux [8; 9]. The minimum fetch was 500 m. The trees were 3.75 m tall with a 4 m distance between trunks within a row and 5.5 m between rows, and they were drip-irrigated with a mean leaf area index (LAI) of approximately 4.25 m² m⁻². A three-dimensional sonic anemometer and a fine-wire thermocouple with a 76 μm diameter operating at 10 Hz were deployed at \( Z = 4 \) m and at \( Z = 8 \) m. The mean air temperature (HMP45C) was measured every 10 min at \( Z = 6.5 \) m and at \( Z = 9.5 \) m. Maintenance of the station was performed twice per month.
The H estimates were determined using time intervals of 30 minutes to derive the mean ramp dimensions $A_{30}$ and $\tau_{30}$ as described by [8], and the half-hourly gradient ($dT_{30}/dz$) was calculated after determining $T_{30}(z)$ as the average of the three, 10 min air temperatures at z:

$$H_{M1} = \rho C_p \frac{A_{30}^2}{\pi \tau_{30}} \left( \frac{dT_{30}}{dz} \right)^2 \tag{4}$$

In the same canopy, the M2 method performance was studied [8]. The ramp dimensions used as input were the turbulent standard deviation and the mean of the horizontal wind speed at $Z = 4$ m, and the LAI was set equal to 4.25 m$^2$ m$^{-2}$ and $d = 0.7$ h, where h is the canopy height. The $c_d$ values, obtained during 2010 experimental periods, were $c_d = 0.075$ for $Z/L > 0$ and $c_d = 0.2$ for $Z/L \leq 0$.

After excluding rainy days, the dataset used for comparison of M1 and M2 included samples that passed the Foken’s quality control test up to level 7 [10]. The test checks the assumptions of steady flow and developed turbulence invoked in the EC method.

The roughness sublayer depth above the ground ($Z^* = (z^*+d)$) may oscillate around the measurement heights of $Z = 6.5$ m and $Z = 9.5$ m. In particular, the samples gathered from the micrometeorological station were split into three sublayers. One sublayer had samples collected when all three measurement heights fell in the inertial sublayer (ISL), i.e. $Z^* < 6.5$ m; another sublayer had samples taken in the roughness sublayer (RSL), or $Z^* > 9.5$ m. In the third sublayer, $Z^*$ falls within the measurement heights of $6.5$ m $\leq Z^* \leq 9.5$ m, and the instrumentation was deployed in the transition sublayer (TSL).

Linear regression analysis with a slope and intercept, coefficient of determination ($R^2$) and the root mean square error (RMSE) were used to compare estimates versus the measured $H$ at $z = 8$m ($H_{EC}$). Because regression analysis assumes that $H_{EC}$, which is the reference, is free of random sampling errors, the coefficient

$$D = \Sigma H_{M1(\text{or}M2)}/\Sigma H_{EC} \tag{5}$$

was also determined as an integrated evaluation by averaging out errors in the half-hourly estimates.

3. Results and conclusion

Table 1 shows the number of data ($N$) available for methods comparison, the results of the linear fitting ($R^2$), the RMSE and D, which compares the H estimates from methods M1 and M2 versus $H_{EC}$ from Eddy Covariance.

Sensible heat fluxes obtained from M1 and $H_{EC}$ were highly correlated (i.e. considering all the three sublayers), with $0.87 \leq R^2 \leq 0.90$, the RMSE was moderate at $42$ W m$^{-2} \leq \text{RMSE} \leq 52$ W m$^{-2}$, and deviation of D with respect to one was within 7%.

Fig. 1 (a, b) shows the performance of methods M1 and M2 versus $H_{EC}$ for all the analyzed data during 2011.
Table 1 shows that the M2 method’s performance was excellent. It was closer to the EC method than M1, which indicates that the $c_d$ calibration performed in 2010 against $H_{EC}$ still applied. This issue corroborates that the M2 method is robust [8]. A crucial difference between M1 and the M2 method is that M1 is free from calibration, because, in principle, $c_d$ is site, i.e. climate, and canopy specific, i.e. it depends on the Reynolds number and the type of leaves [7].

The measurements taken have shown that for unstable conditions with wind speed data at 8 meter $u_{8m} \geq 2$ m/s, the $H$ estimates from M1 and $H_{EC}$ were close. Because M1 was biased for stable cases (data not shown) under the influence of regional advection of sensible heat flux, further studies are required to check its performance for stable cases.

Table 1. Sensible heat flux estimates: Eq. (2) and Eq. (4) versus $H_{EC}$ determined using Eddy Covariance.

<table>
<thead>
<tr>
<th>Case*</th>
<th>N</th>
<th>Intercept</th>
<th>Slope</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1757</td>
<td>-13</td>
<td>1.13</td>
<td>0.89</td>
<td>48</td>
<td>1.04</td>
</tr>
<tr>
<td>M2</td>
<td>1757</td>
<td>10</td>
<td>0.97</td>
<td>0.94</td>
<td>28</td>
<td>1.06</td>
</tr>
</tbody>
</table>

* the slope and the intercept showed in Table 1 (Intercept, in W m⁻²) are determined from a linear regression analysis. $R^2$ is the coefficient of determination, RMSE is the root mean square error in W m⁻², and D is the integrated $H$ estimates over the integrated $H_{EC}$.

Fig. 1. (a) Sensible heat fluxes estimated using M1 versus the fluxes measured with the Eddy Covariance technique; (b) Sensible heat fluxes estimated using M2 versus the fluxes measured with the Eddy Covariance technique.

Preliminary results obtained from the study confirm that the main advantage of method M1 over M2 and the Eddy Covariance technique is that it is exempt of calibration and does not require measurements of the wind speed and knowledge of canopy parameters as input. Sensible heat fluxes ($H$) can be thus calculated from low/high frequency measurements of air temperature taken at three heights. Furthermore, M1 avoids shortcomings and corrections related to coordinate rotation, sensor separation, frequency response, alignment problems, and interference from tower or instrument-mounting structures that are inherent in the EC method. Additionally, there is no need to measure and/or estimate the canopy parameters or the empirical relationships or coefficients that are inherent in other methods based on MOST and Surface Renewal.

For unstable cases in particular, this study concludes that to estimate sensible heat flux by taking measurements at approximately two times the canopy height, the proposed method M1 is an alternative to other methods (EC) because it is reliable, affordable, simple to apply, and exempt from calibration.
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References