A New Procedure Based on Surface Renewal Analysis to Estimate Sensible Heat Flux:
A Case Study over Grapevines

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ABSTRACT

Grapevines are grown on a range of soils and in different climates. Depending on the desired final product and method of harvesting, the trellis system, and hence vineyard architecture, varies dramatically. Consequently, the crop coefficients used to estimate vineyard evapotranspiration from reference evapotranspiration are less universal than for other crops. Evapotranspiration measurements are often limited because of a lack of fetch and unavailability of vine parameters required as input. In this paper, a new procedure based on surface renewal (SR) analysis was derived to estimate sensible heat flux over the grapevines. A two-dimensional sonic anemometer operating close to the canopy can provide the inputs required to estimate the sensible heat flux and the work of expansion of the air parcels under constant pressure. Regardless of the stability conditions, the SR estimates were comparable to those determined using the eddy covariance (EC) method providing a root-mean-square error of 14 W m\(^{-2}\) for all data. Thus, the procedure is low cost and makes SR a simpler method than EC to estimate latent heat flux as the residual of the energy balance equation in moderately tall and heterogeneous crops. The experiment was carried out at a site influenced by regional advection of sensible heat flux.

1. Introduction

The ability to estimate grapevine water use is important for worldwide production (Mullins et al. 1992) in climates where water resources are limited. Vineyard architecture is variable because the trellis systems utilized to produce the grapes depend both on the final product desired (wine, raisins, or table grapes) and the method of harvest (by hand or machine). The spacing between rows and vines is adjustable, with canopy cover as low as 10% (Jacobs et al. 1996) or as high as 100%, depending on the trellising. Consequently, using crop coefficients and reference evapotranspiration to estimate crop evapotranspiration is not as straightforward as for other crops (Williams and Ayars 2005). Large lysimeters, which are capable of accurately measuring evapotranspiration on an hourly basis, are extremely expensive (Scott et al. 2005), so it is hard to justify their use by farmers.

A large variation in seasonal water use of mature grapevines has been reported, and it is unknown how much of the variability results from production practices or the measurement method (Williams et al. 2003a). Paraphrasing Williams et al. (2003b), the main limitations to determining evapotranspiration from vineyards are that “(1) soil and water balance techniques require difficult assessments of various soil and/or water parameters, (2) reliability of sap flow sensors is questionable; especially on large vines, and (3) micrometeorological techniques require expensive instrumentation and large areas of uniform fetch, which are uncommon in many grape production areas.” Because the surface renewal (SR) method may operate close to the canopy (Paw U et al. 1995, 2005), fetch requirements may be minimized, which makes it a useful micrometeorological method for small grape vineyards where fetch requirements limit the application of other methods. Spano et al. (2000), Castellví et al. (2002), and Castellví (2004) have used the SR method to estimate sensible heat flux $H$ over grape vineyards.
The methodology used in Spano et al. (2000) included high-frequency temperature measurements at several heights within the canopy. In their method, thermocouple damage was a possible limitation. The Castellví et al. (2002) and Castellví (2004) methods require temperature measurements only at a single level. The main difference between methods is that Castellví (2004) is a half-order closure model (i.e., scalar flux depends on the square root of the eddy diffusivity), whereas Castellví et al. (2002) is a semiemiprinc first-order closure model. The Castellví (2004) procedure gave a better match to sonic anemometer H data than Castellví et al. (2002). When measurements are taken within the roughness sublayer, however, the Castellví (2004) method requires \( z^* - d \) as an input, where \( z^* \) is the roughness sublayer depth and \( d \) is the zero-plane displacement.

This paper reports on a new SR procedure based on Castellví (2004) that is used to estimate sensible heat flux over a mature vineyard. An experiment was conducted during the summer of 2007 at the University of California in the Kearney Agricultural Research and Extension Center (KAC) near Parlier, California. The local climate is characterized by light winds and regional advection of sensible heat flux. The new procedure overcomes limitations derived from 1) fetch requirement restrictions, because it operates close to the canopy, 2) potential thermocouple damage and data acquisition system limitations, because required measurements are taken at a single level, and 3) the need to measure the zero-plane displacement, the roughness length for momentum, the plant area index (PAI), etc. It is indirectly shown that it is difficult to a priori guess realistic \( z^* \) and \( d \) values based on observed weather conditions.

In grape vineyards, negligible heat storage may be assumed in the canopy. Based on Wilson et al. (2002), storage was considered insignificant for woody canopies with height less than 8 m. In Meyers and Hollinger (2004) storage in maize and soybean was less than 5% of the net radiation when the canopy was fully developed. Eddy covariance (EC) measurements of sensible and latent heat fluxes over pear and mango orchards with PAIs that are considerable greater than those of grapevines showed a lack of energy balance closure of 10%–12% (Conceição et al. 2008; Teixeira et al. 2008). Therefore, the lack of closure observed was similar to that of other canopies with negligible storage, such as grasses (Twine et al. 2000; Wilson et al. 2002; Castellví et al. 2008). For irrigation assessment and routinely hydrological applications, it is generally assumed that the simplified surface energy balance equation applies and closure is forced (Brutsaert 1988). At sites influenced by regional advection of sensible heat flux, however, closure forced via the Bowen ratio using similarity theory should be discarded (Motha et al. 1979; Todd et al. 2000; Lee et al. 2004). To use robust, easy to maintain, and affordable instrumentation in regional advection conditions, forcing closure to estimate latent heat flux as the residual of the simplified surface energy balance equation is an alternative if reasonable sensible heat flux estimates can be determined. In this paper, it is shown that the inputs required for estimating the sensible heat flux and the work of the expansion of air parcel under constant pressure can be provided by a two-dimensional sonic anemometer.

2. Theory

a. Surface renewal analysis for estimating sensible heat flux densities

Consider an air parcel, with some scalar concentration, traveling at a given height above the surface. SR analysis assumes that at some instant the parcel suddenly moves down to the surface and remains connected with the sources (sinks) for a period of time during which it is horizontally traveling along the sources. By continuity, the parcel is ejected upward and is replaced by another parcel sweeping in from aloft. During the connection time with the surface, the scalar transfers either to or from the sources to the air parcel. Thus, the parcel has been enriched (depleted) with the scalar. Scalar turbulent exchange at the surface (vegetation–atmosphere interface is therefore driven by the regular replacement of air parcels that are in contact with the sources (sinks). It was previously shown that this continuous renewal process is responsible for the majority of vertical transport of a scalar (Gao et al. 1989; Lohou et al. 2000; Hongyan et al. 2004). The renewal process is associated with a coherent structure on the order of the integral scale, which is characteristic in shear flows (Warhaft 2000). The “signature” of a coherent eddy motion at a fixed measurement point can be identified when the high-frequency measurement of the scalar is plotted versus time. The signature is visualized in the trace as a regular and low-frequency ramp-like (asymmetric triangle shape) pattern. Figure 1a shows the ramp-like pattern in the temperature trace over a short time period under unstable and stable cases. Paw U et al. (1995) presented a diagram of the surface renewal process (Fig. 1b) and, in a Lagrangian sense, abstracted an ideal scheme for a ramp-like event in the trace (positions 2–4 in scheme 1) during the time that the parcel remains connected with the surface. Chen et al. (1997a) presented a slightly different ramp model (scheme 2 in Fig. 1b) that neglects the quiescent period but includes a microfront period instead of an instantaneous ejection. Regardless of the model, a ramp is characterized by amplitude \( A \) and a period \( \tau \). Considering the
FIG. 1. (a) Sonic temperature vs time for a short interval on 15 Sep. (left) The unstable case with a 40-s ramp period and 2.5°C amplitude within a sample from 1030 to 1100 PST. (right) A ramp period of 42 s and amplitude of ~0.5°C within a sample from 1500 to 1530 PST. Straight lines following the main trends were included to show the ramp-like pattern in time series. (b) Air parcel diagram of the renewal process. The time course of the scalar concentration for the positions shown in the diagram are idealized in two air temperature ramp models. Scheme 1 assumes a quiescent period and a sharp instantaneous drop in temperature. Scheme 2 neglects the quiescent period and assumes a finite microfront. Parameters $L_r$, $L_q$ and $L_f$ denote the warming, quiescent and microfront periods, respectively; $A$ is the ramp amplitude and $\tau$ is the total ramp duration.
scalar flux conservation equation for a steady and planar homogeneous turbulent flow, and assuming that 1) an air parcel comes from aloft with a volume that covers all the sources, \( V = zS \) (where \( z \geq h \), with \( h \) the canopy top and \( S \) the unit ground area), and remains in contact with the sources (Fig. 1b); 2) the flux at \( z = 0 \) is negligible, 3) during the contact the scalar transfers from the sources to the parcel changing its concentration with no losses from the parcel top; and 4) turbulent diffusion dominates the mixing within the parcel and, as a result, the parcel is uniformly mixed with no molecular diffusion. Therefore, one arrives to the following expression to estimate the sensible heat flux density at height \( z \) (Paw U et al. 1995):

\[
H = \rho C_p (a z) \frac{A}{\tau} \tag{1}
\]

where \( A \) and \( \tau \) are the temperature ramp amplitude and period determined at \( z \), respectively, and \( a \) is a parameter that corrects for all four assumptions made, though it mainly corrects for unequal mixing because a large volume of the air parcel is considered when measurements are taken at one height. Note that traces measured above the canopy are representative of the upper part of the canopy, whereas the sources at the ground were presumed negligible. Therefore, \( a \) must correct for the gradient from the bottom to the top of the parcel. Currently, there is ample evidence that half-hourly \( a \) values depend on the measurement level, stability conditions, and canopy architecture (Snyder et al. 1996; Katul et al. 1996; Castellvi 2004; Castellvi and Snyder 2009). In the appendix it is shown that when measurements are taken within the roughness sublayer, half-hourly \( a \) estimates can be obtained by the following expression:

\[
\alpha = \left[ \frac{k}{\pi} \frac{(z^* - d)}{z^2} \tau u_* \phi_h^{-1}(\xi) \right]^{1/2} \quad h \leq z \leq z^*, \tag{2}
\]

where \( u_* \) is the friction velocity, \( k = 0.4 \) is the von Kármán constant, \( \phi_h(\xi) \) is the stability function for heat transfer, and \( \xi = [(z - d)/L] \) is an stability parameter, with \( L \) the Obukhov length

\[
L = \frac{u_*^3 T_v}{g \omega T_v} \tag{3}
\]

where \( g \) is the acceleration resulting from gravity and \( T_v \) is the virtual temperature. To be consistent with derivations the near-neutral conditions made in the appendix, the following formulation for \( \phi_h(\xi) \) is considered (Högström 1988):

\[
\phi_h(\xi) = \begin{cases} 
1 + 7.8\xi & 0 \leq \xi \\
(1 - 12\xi)^{-1/2} & \xi < 0 
\end{cases} \tag{4}
\]

b. Determination of the roughness sublayer depth

The roughness sublayer depth extends from the ground to the bottom of the inertial sublayer. Because turbulence is characterized by the presence of distinct coherent structures mainly generated by shear near the canopy top and thermal plumes for convective conditions, it is well known that similarity does not apply in the roughness sublayer and that \( z^* \) varies with roughness elements, stability, and turbulence intensity (Thom 1971; Oliver 1971; Antonia et al. 1979; Garrat 1980; Shaw and Pereira 1982; Dolman 1986; Meyers and Paw U 1986; Raupach et al. 1991; Gao et al. 1989; Paw U et al. 1992; Cellier and Brunet 1992; Physick and Garratt 1995; Raupach et al. 1996; Möldér et al. 1999; Pingtong and Takahashi 2000; Finnigan and Shaw 2000; Graefe 2004; Harman and Finnigan 2007). Determination of \( z^* \) requires knowledge of detailed profiles of wind speeds and temperatures to discriminate the height were similarity starts to hold. According to analysis shown in the appendix, it may be estimated as

\[
(z^*_N - d) = \frac{1}{n} \bar{\alpha}_{N(z)} \frac{\pi(z^*_N - d)}{2} \sum_{j=1}^{n} (\tau u_* j)^{-1}, \tag{5}
\]

where \( \bar{\alpha}_{N(z)} \) is the mean \( \alpha \) value for near-neutral cases and \( n \) denotes the number of samples taken around neutral conditions.

3. Materials and methods

a. The field experiment

The campaign was carried out from 28 August 2007 [1400 Pacific standard time (PST)] through 18 October 2007 (1300 PST). The drip-irrigated vineyard (Thompson Seedless Grapes) was about 1.4 ha (168 \times 82 m²), and was mainly surrounded by annual and perennial crops and some bare soil. The space between vine trunks in a row was 2.15 m and across the rows it was 3.5 m. The canopy height was 2.3 m; the foliage extended from 0.4- to 2.3-m height above the ground, and there was about 2.5 m of clear space between foliage from one row to the next. The terrain was flat, the rows were aligned east–west, and the prevailing wind direction was from the north-northwest. The measurement tower was set up near the midpoint of the plantation with approximately 84 m in the prevailing wind direction. No half-hourly samples with wind direction parallel to the row alignment were observed.
The three wind speed components and the sonic temperature were recorded at 10 Hz at a height of 2.8 m above the ground using a 3D sonic [31000RE, R. M. Young, EXW (EX Works) Traverse City, Michigan]. The raw data were stored in binary format using a CR1000 logger (Campbell Scientific, Inc., Logan, Utah). Postprocessing consisted of conversion of the half-hourly data files to ASCII and processing the data using the protocol from Mauder et al. (2007) to determine means, variances, and covariances. The 3D classic coordinate rotation method was used instead of the planar rotation method.

No rainfall, calm winds, and high-amplitude daily temperatures were observed during the experiment. Table 1 shows the maximum, minimum, mean, and standard deviations observed for the wind speed, air temperature, friction velocity, sensible heat flux for unstable and stable atmospheric surface layer conditions, and the number of samples collected under stable and unstable conditions. Regional advection was common, and the atmospheric surface boundary layer typically became neutral around 1430 PST. Regional advection results from air movement from large nonirrigated areas, which surround the San Joaquin Valley, over the irrigated cropped areas on the valley floor.

### b. Sensible heat flux determination

Ramp dimensions, friction velocity, roughness sublayer depth, the zero-plane displacement, and the stability parameter are required as input to estimate the sensible heat flux iterating Eqs. (1)–(5).

#### 1) RAMP DIMENSIONS

Determination of coherent structures assuming a sequence of ideal ramps combined with the use of structure functions of different order (Van Atta 1977; Chen et al. 1997a) is an objective technique to estimate ramp dimensions (Paw U et al. 2005) which is desirable to provide an independent method to estimate scalar surface fluxes. Scheme 1 (Fig. 1b) was used. It requires a lower frequency than scheme 2 (the microfront time is on the order of few seconds). Once the ramp amplitude was determined, several time lags \( r \) were used to linearize the relationship, which holds for \( r \ll L_r \),

\[
A^3 = -\{[S^3(r)]/\langle r \rangle \},
\]

where \( S^3(r) \) is the third-order structure function for solving the ramp period. According to Chen et al. (1997a), 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. Based on a ramp model shown in scheme 2, the second global maximum for scheme 1 occurs at a time lag \( r_{2G} \), giving \( r_{2G} \approx \frac{3}{4} \tau \). According to Qiu et al. (1995), \( L_q \approx 0.25 \tau \) and, therefore, \( r_{2G} \approx L_r \). The last time lag used for linearization was determined as 1% of \( r_{2G} \) or \( r_{end} \approx 0.01 L_r \) to ensure that \( r_{end} \ll L_r \). Therefore, the structure functions were evaluated within a range of time lags that provides a close ramp amplitude (Chen et al. 1997a) and total period (Chen et al. 1997b) to ramp model in scheme 2.

#### 2) FRICTION VELOCITY

For \( h < z < z^* \), the following expression holds (Kaimal and Finnigan 1994):

\[
\nu^*_w = 0.4 \sigma_u,
\]

where \( \sigma_u \) is the horizontal wind speed standard deviation.

#### 3) ROUGHNESS SUBLAYER DEPTH, ZERO-PLANE DISPLACEMENT, AND SENSIBLE HEAT FLUX ESTIMATION

If one selects samples at near-neutral conditions, \( (z^*_N - d) \) can be determined by rearranging terms in Eq. (5) by setting the appropriate \( \overline{\sigma}_{N(0)} \) value recommended in the appendix. If available, net radiation minus soil heat flux may help to identify near-neutral cases. If unavailable, the transition from stable to unstable cases is detected when the ramp amplitude changes its sign from negative to positive (Fig. 1b). For simplicity, it was assumed that \( (z^*_N - d) \) remains fairly constant, giving \( (z^*_N - d) = (z^* - d) \) regardless of the stability conditions.

Some scientists found that \( d \) depends on the wind speed and stability conditions (Rosenberg 1974; Brutsaert 1988; Raupach 1994; Verhoef et al. 1997; Gao et al. 2003;...
Harman and Finnigan 2007), but others have not found this dependency, which suggests that $d$ likely depends on the canopy architecture (Munro and Oke 1973; Adrie and Van Boxel 1988). Expressions for estimating $d$ that depends exclusively on $h$, such as $d = ch$, where $c$ is a constant in the 0.5–0.95 range, were reported for uniform canopies and plants in rows when the wind direction was not aligned with the rows (Stanhill 1969; Kondo 1971; Brutsaert 1988; Wieringa 1993; Verhoef et al. 1997; Oue 2001; Takagi et al. 2003). We note that most studies to determine $d$ are based on fitting the wind log law by measuring the wind speed at different heights using cup anemometers. To ensure high-quality measurements, samples were typically not used when $u < 2$ m s$^{-1}$. Consequently, under light wind conditions over a heterogeneous surface, it is difficult to assign a priori a value for coefficient $c$ for the scale $d = ch$.

A procedure based on two steps is proposed to solve $H$. The procedure avoids $d$ determination or subjective estimation and assumes that it remains constant. The appropriate expression for $\phi_h(\zeta)$ [Eq. (4)] is known after determining the ramp dimensions for temperature. The two steps are described below.

(i) Step 1

Equation (1), with a constant $a$ parameter, is used to estimate $H$ for near-neutral cases. The $\bar{z}_{N(z)}$ value to solve for $(z_{N}^* - d)$ in Eq. (5) applies for the actual $a$ at near-neutral conditions.

(ii) Step 2

Assuming $d = ch$ and coefficient $c$ is known regardless of the wind direction (i.e., flow direction variability did not sense drastic roughness changes), Eqs. (1)–(4) can be iterated to solve for $H$. Starting with $\zeta = 0$ and $(z_{N}^* - d)$, the first approximations for $a$, $H$, and $L$ are found for the actual atmospheric surface layer. Using $L$, the first approximation for $\zeta$ is determined. Then, the process is iterated until convergence is achieved for $\zeta$. Coefficient $c$ is solved by trial and error to match $H$ from steps 1 and 2; $H$ estimates from step 1 are taken as a reference. Thus, coefficient $c$ is estimated for near-neutral conditions by forcing agreement between Eqs. (2) and (5) through Eq. (4) via $\zeta$. A method based on simulating annealing (SA) was used to solve for $c$. SA is a global optimization method that distinguishes between different local optima. By giving the different boundaries for the unknown coefficients involved in the function to be optimized, starting from an initial point, the algorithm takes a random step and the function is evaluated. After minimizing (or maximizing) the function, any downhill step is accepted; however, some uphill steps may also be accepted. Acceptability implies that the initial process starts. The uphill decision is made by the Metropolis criteria (Metropolis et al. 1953). As the optimization process proceeds, the length of the steps decline until it closes in a global optimum. SA is recommended as a local optimizer for difficult functions because it has proven superior to multiple restarts and conventional optimization routines for difficult problems. SA is even capable of providing solutions out of initial boundaries for very complicated functions, but it requires a powerful computer. Because boundaries for coefficient $c$ can clearly be restricted between 0 and 1, a standard computer can accomplish the SA calculations (Goffe et al. 1994). The root-mean-square error (rmse) was the target function to be minimized.

4. Results

a. Estimating $(z_{N}^* - d)$

According to vineyard architecture, the degree of heterogeneity was considered moderate, and thus according to the appendix $\bar{z}_{N(z)} = 0.55$ was set in Eq. (5). Post noon, half-hourly samples of near-neutral stability cases were not included because convection may be important during that period and Eq. (4) may differ from unity. Selection was constrained to two half-hourly samples before sunrise and two after sunrise when the estimated friction velocity was $u_f \geq 0.2$ m s$^{-1}$. It was assumed that the $u_f$ threshold resulted in good ventilation of the canopy and rows (i.e., the transfer of momentum was capable of renewing the entire air layer from the ground to above the measurement height providing a near-zero temperature vertical gradient). The latter is required to ensure that Eq. (4) is close to unity and that the ramp frequency remains fairly constant with height (Paw U et al. 2005). They are both leading hypotheses in evaluating the recommended mean $\alpha_{N(h<z<1.2h)}$ given in the appendix. A total of 96 samples were observed that gave a minimum, mean, and standard deviation for...
Figure 3 shows that the sign of the ramp did not match the sign of EC, or when \( H_{EC} \) is the actual sensible heat flux. Table 2 shows slope, intercept, and for all data. No bias was observed, and the rmse for all the data, the results (Table 2) would be obtained for \( (z_h^* - d) \).

**b. Estimating the zero-plane displacement and sensible heat flux**

The optimum SA downhill gave the scale \( d = 0.62h \). The \( H \) estimates comparing step 2 \( H_{SR2} \) and step 1 \( H_{SR1} \) are shown in Fig. 2. The linear fit had the following: slope = 1.00, intercept = 1.0 W m\(^{-2}\), and \( R^2 = 0.98 \). Figure 3 shows \( H_{SR2} \) versus \( H_{EC} \) for all of the data. The performance was generally excellent, with some spurious samples observed for a few stable cases when the sign of the ramp did not match the sign of \( H_{EC} \), or when \( H_{SR2} \) was close to zero. The worst estimates corresponded to samples gathered around 1500 (early September) to 1700 (October) PST during the transition from unstable to stable atmospheric conditions and during the night under calm conditions. However, the total number of spurious data was small, regardless of the stability case. Table 2 shows slope, intercept \( R^2 \), rmse, and \( D \) obtained for \( H_{SR2} \) versus \( H_{EC} \) for the unstable and stable cases and for all data. No bias was observed, and the rmse was small.

For all data, Eq. (6) provided reliable friction velocity estimates with linear fitting \( u_0 = 0.38r_0 \) and \( R^2 = 0.91 \). In Eq. (5), the mean value found for \( (z_h^* - d) \) seemed small in comparison with other studies. Cellier and Brunet (1992) reported that the scale \( (z_h^* - d) / \delta \), where \( \delta \) is the mean clear distance between rows aligned across the flow, fell between 3.0 and 4.0 over a 2.35-m-tall maize canopy, with \( \delta = 0.8 \) m. For trees (savannah), Garrat (1980) found \( (z_h^* - d) \approx 3 \delta \), where \( \delta \) is the mean horizontal spacing between trees. Fazu and Schwerdtfeger (1989) reported a factor of 4.6 and Wenzel et al. (1997) found a factor of 8.0 for a coniferous forest. Figure 4 shows the actual \( a \) [i.e., by rearranging terms in Eq. (1) and using \( H_{EC} \) as the actual \( H \)] versus \( L \) for all of the data. When turbulence was mainly mechanically driven, the actual \( a \) values tended to fall within the interval (0.4, 0.6), so an \( \bar{\alpha}(N) = 0.5 \) for \( z/h = 1.22 \) was realistic. The relationship \( d = 0.62h \) was slightly smaller than the typical \( d = 0.8h \) value recommended over crops (Brutsaert 1988), and one might expect a higher value for \( d \) because of the calm winds at a site (Rosenberg 1974; Gao et al. 2003). It is difficult to quantify the regional advection influence on the \( H \) estimates because the uncertainty with Eq. (4) only can be assessed by a parallel experiment as described in Högsström (1988), where measurements over a nearby homogeneous surface provide \( \phi_h(\zeta) \) for the area and \( d \) is determined in the vineyard.

**ANALYSIS OF SENSITIVITY**

If trial and error was directly applied to adjust \( (z_h^* - d) \) and \( d \) by minimizing the rmse between \( H_{SR2} \) and \( H_{EC} \) for all the data, the results (Table 2) would be obtained for \( (z_h^* - d), (d/h) \) pairs vs \( H_{EC} \) for unstable (Unst) and stable (Stab) cases, and for all data (All). Linear regression analysis: slope \( a \) and intercept \( b \) (W m\(^{-2}\)), \( R^2 \), rmse (W m\(^{-2}\)), and \( D \) are defined in the text.

<table>
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<th>Unst</th>
<th>Stab</th>
<th>All</th>
<th>Unst</th>
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</table>
different pairs of \((z_N^* - d)\) and \(d/h\). For example, the local downhill providing the pair \((3.5, 0.95)\) gave the following: slope = 1.0, intercept = -5.0 W m\(^{-2}\), \(R^2 = 0.96\), rmse = 15.0 W m\(^{-2}\), and \(D = 1.01\). If \(L_R\) denotes the rmse corresponding to a local downhill and \(G_R\) corresponds to the global downhill (i.e., the optimum) rmse, then the total of 46 local downhills gave \(L_R - G_R \leq 5\) W m\(^{-2}\). This implies that the two-step process is useful for reliable \(H\) estimates, but the best estimates for \((z_N^* - d)\) and \(d\) will remain unknown.

Table 2 shows the \(H_{SR^2}\) performance for the other two pairs. The pair \((2.58, 0.4)\) corresponding to \(z_N = 0.51\), which was recommended in the appendix for regular canopies, and the pair \((3.26, 0.85)\), which corresponds to \((z_N^* - d) = 1.42 h\) (the expected scale found in the appendix for moderate heterogeneous canopies). Table 2 shows that all three pairs gave \(H_{SR^2}\) values close to \(H_{EC}\). The pair provided using Eq. (5) performed closer to \(H_{EC}\). However, all pairs provided good estimates. Therefore, the typically reported scale of 3-4 for \((z_N^* - d)/d\) in field crops is unrealistic for the grape vineyard. As a rule of thumb, if one takes the intermediate scale \((z_N^* - d)/d \approx 3.5\), for our case of study results \((z_N^* - d) \approx 8.5\) m. Even assuming \(d = h\), \(H_{SR^2}\) overestimated \(H_{EC}\) by 62% though the intercept was negligible and \(R^2 = 0.96\). Because multiple \([z_N^* - d, d/h]\) pairs obtained by the two-step process lead to \(H_{SR^2}\) close to \(H_{EC}\), Eq. (1) implies that distinct pairs must provide similar half-hourly \(\alpha\) values after convergence is achieved. Figure 5a shows the iterated half-hourly \(\alpha\) values obtained from the pair \((2.58, 0.40)\) versus the pair \((3.00, 0.62)\). The iterated \(\alpha\) values nearly matched and the linear regression statistics were the following: slope = 1.03, intercept = 0.02, and \(R^2 = 0.99\). Thus, \((z_N^* - d)\) and Eq. (4) through \(\zeta\) adjusted Eq. (2) to converge to the same value. Figure 5b shows the iterated \(\alpha\) values corresponding to the pair \((3.00, 0.62)\) versus the actual \(\alpha\) value. The agreement was good.

Based on Physick and Garratt (1995), it is questionable to consider \((z_N^* - d)\) a constant. The authors suggested that \((z^* - d)\) linearly decays to about 37% of \((z_N^* - d)\) when \((z_N^* - d)/L \geq 0.2\), whereas \((z^* - d)\) remains fairly close to \((z_N^* - d)\) for unstable cases. The same stability correction was implemented in the iteration procedure. For stable cases, \(H_{SR^2}\) underestimated \(H_{EC}\) by about 6% (\(D = 0.94\)). The intercept and rmse were the same as that shown in Table 2, but the regression statistics were slightly worse, with slope = 0.78 and \(R^2 = 0.77\). In essence, it was found that the \(H\) estimates captured a higher portion of the \(H_{EC}\) variability when \((z_N^* - d)\) was assumed constant. A variable \((z^* - d)\) stability correction could provide better estimates in other experiments. The actual \(z^*\) and \(d\) was unavailable.
Because Eq. (4) is based on similarity theory, the procedure is only recommended for flat terrain. Castellví et al. (2008), however, showed that SR analysis, operating in the inertial sublayer, performed well for sensible heat, latent heat, and carbon dioxide fluxes over moderately sloping grassland located in the foothills of the Sierra Nevada Mountains near Ione, California, where similarity did not hold.

In the SR analysis, fetch requirements require further research (i.e., according to the authors’ knowledge; there is no publication on this topic). Therefore, it is difficult to address how the different footprints sensed by SR analysis and the EC method might alter the results shown in Table 2.

It is of interest to remark that the site showed little change in surface roughness with wind direction. Thus, the observed performance shown in Table 2 corresponds only to flows across rows. For wind direction that is parallel to the rows, a new pair [(zN, d), d] might be needed.

5. Summary and concluding remarks

A new procedure to iterate H in SR analysis was presented. The results were close to H from the EC method. Only a few spurious H estimates were obtained, and they mainly corresponded to periods where ramps were not well formed. Because Eq. (6) is a key part of the estimation procedure, reliable measures of σu are crucial. Therefore, use of an affordable, two-dimensional sonic anemometer is recommended to ensure accurate inputs at low wind speeds of the wind direction and standard deviation. The work of expansion of air parcels under constant pressure needs to be included for closure of the surface energy balance. Using the sonic “near virtual” temperature addresses this problem (Paw U et al. 2000).

To conclude, a two-dimensional sonic anemometer operating close to the canopy can provide all of the inputs required to estimate half-hourly H and the work of expansion of air parcels under constant pressure in the new SR method. The combination of the SR procedure and the simplified surface energy balance equation appears to be an affordable alternative to be considered for estimating water use at sites influenced by regional advection of sensible heat flux.

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APPENDIX

The Parameter α: A Qualitative Analysis for Neutral Cases

In the following, though valid for any scalar, derivations are made for temperature. If one may consider that at a point in flow above the canopy the heat transfer is predominantly vertical, it can be described by the one-dimensional diffusion equation

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( K_h \frac{\partial T}{\partial z} \right),$$  \hspace{1cm} (A1)

where t denotes time and T is the mean air temperature over a period t – t0. To evaluate how T and its vertical gradient at a measurement height z change with time, a neutral initial condition is assumed. The Laplace transform of temperature with respect to time is denoted as TL(s). Assuming that the turbulent eddy diffusivity for heat Kh is constant over a period (t – t0), the Laplace transform with respect to time in Eq. (A1) leads to

$$sTL(s) = K_h \frac{\partial^2 TL(s)}{\partial z^2}. \hspace{1cm} (A2)$$

The general solution for (A2) is

$$TL(s) = A(s)e^{-\sqrt{s}/\sqrt{K_h}} + B(s)e^{\sqrt{s}/\sqrt{K_h}}. \hspace{1cm} (A3)$$

A realistic physical solution for (A3) requires $B(s) = 0$ (a finite temperature value is needed when $z$ is large). The derivative of (A3) versus $z$ is

$$\frac{\partial TL(s)}{\partial z} = -\sqrt{\frac{1}{K_h}} sTL(sz) \sqrt{s^{-1}}. \hspace{1cm} (A4)$$

The inverse of the Laplace transform and the definition of convolution in (A4) leads to
\[
\frac{\partial T_{(z,t)}}{\partial z} = -\frac{1}{\sqrt{\pi K_h}} \int_t^t \frac{\partial T_{(z,s)}}{\partial s} \frac{\partial s}{\sqrt{(t-s)}} . \tag{A5}
\]

For convenience, however, expression (A5) is rewritten as
\[
\frac{\partial T_{(z,t)}}{\partial z} = \frac{2}{\sqrt{\pi K_h}} \int_t^t \frac{\partial T_{(z,s)}}{\partial s} d \left[ \sqrt{(t-s)} \right] . \tag{A6}
\]

According to Fig. 1b, ramps in temperature traces represent injections of heat into the bulk flow that fits the local temperature gradient. Based on the ramp model in scheme 2, which is more realistic than scheme 1, for unstable cases \( \delta T/\delta s \) equals \( A/L_f \) when the air parcel is in contact with the surface and \( -A/L_f \) during the renewal phase. Thus, when the integration is over a ramp event, the solution for the integral in Eq. (A6) can be expressed as
\[
\int_0^\tau \frac{\partial T_{(z,s)}}{\partial s} d \left[ \sqrt{(t-s)} \right] = -\frac{A}{L_r} \sqrt{L} + \frac{A}{L_f} \left( \sqrt{\tau} - \sqrt{L_r} \right) . \tag{A7}
\]

For a stable case, (A7) has the opposite sign. According to (A2), the integration must begin at an instant \( t_0 \) when the temperature gradient is negligible. Canopy-scale coherent structures are of interest in SR analysis; thus, the rapid incursion of a “fresh” air parcel located at level \( z_r \) (position 1 in Fig. 1b) with temperature \( T(z_r) \) allows for the assumption that \( T(z_{(s)}) \) is close to that observed at the baseline of the ramp. If the fraction of the ramp duration corresponding to the heating period (or cooling period under stable conditions) is denoted as \( p \), then \( L_r = \rho \sigma \) and \( L_f = (1-p)\sigma \). Consequently, from (A6) and (A7) the temperature gradient can be expressed as
\[
\frac{\partial T_{(z,t)}}{\partial z} = \frac{2A}{\sqrt{\rho \sigma K_h}} \left[ \frac{1}{\sqrt{\rho}} - \frac{1-\sqrt{\rho}}{(1-p)} \right] . \tag{A8}
\]

The fraction \( p \), expressed as a percentage, ranges between 94% and 99.9% (Chen et al. 1997a). For convenience, Eq. (A8) can be simplified to
\[
\frac{\partial T_{(z,t)}}{\partial z} = \frac{A}{\sqrt{\rho \sigma K_h}} . \tag{A9}
\]

We note that (A9) links the vertical gradient with the ramp amplitude and total ramp period observed in the time series. Thus, because the microfront time period is not required, reasonable frequencies can be used. Above the canopy the flux gradient relationships hold, so sensible heat flux can be expressed as \( H = \rho C_p K_h (\partial T/\partial z) \). When combined with Eqs. (6) and (A9), the \( \alpha \) parameter can be expressed as \( \alpha = [(K_h/\pi)(\tau/\rho)]^{1/2} \). If \( z > z^* \), Monin–Obukhov similarity theory holds, and \( K_h = \rho(z-d)u_\tau \phi_h^{-1}(\zeta) \). When \( h \leq z \leq z^* \), gradients above the canopy are weaker than in the inertial sublayer, and thus \( K_h \) is enhanced. Observations support an enhancement factor of \( (z^* - d) \) over \( (z - d) \) (Cellier and Brunet 1992; Grafe 2004), so \( K_h = k(z^* - d)u_\tau \phi_h^{-1}(\zeta) \) is valid for \( h \leq z \leq z^* \). This leads to the following expression to estimate \( \alpha \) at height \( z \) in the roughness sublayer:
\[
\alpha(z) = \frac{k(z^* - d)}{2} \left( \frac{z^*}{z} \right)^b u_\tau \phi_h^{-1}(\zeta)^{1/2} . \tag{A10}
\]

The ramp period remains fairly constant with height (Gao et al. 1989; Paw U et al. 2005), and because \( u_\tau \) is \( z \)-less dependent above the canopy, (A10) gives the relationship \( \zeta \alpha_{N(z)} = \alpha_{N(z=h)} \) for \( \zeta = 0 \), where \( N \) denotes near-neutral cases. Therefore, relationships valid at the canopy–atmosphere interface are applicable to relating \( (z^* - d) \) and \( \alpha_{N(z)} \). If one sets in (A10) the relationship resulting from the mixing layer analogy \( (1/\tau) = b(u_\tau/h) \) [where \( u_\tau \) is the wind speed at the canopy top and \( b \) a constant (Raupach et al. 1996)], and the scale \( u_\tau = c(u_0) \) [where \( c \) is a constant (Kaimal and Finnigan 1994)], the relationship \( (z^* - d) = a\alpha_{N(z-h)}^{2} \) is obtained, where \( a = (\pi/\rho)(b/c) \).

The relationship
\[
(z^* - d) = 4.71a_{N(z=h)}^{2} = 4.71(z_{N(z)}^{2}) \quad h \leq z \leq z^* \tag{A11}
\]

was found by setting \( \phi_h(\zeta = 0) = 1 \), which is the most realistic value from a physical point of view (Högström 1988); letting \( b = 0.2 \), which is an intermediate value from the range \( b = 0.1 \) to \( b = 0.3 \) reported by Raupach et al. (1996), Paw U et al. (1992), and Shaw et al. (1995); and setting \( c \approx 1/3 \) (Raupach et al. 1996; Grafe 2004).

The actual half-hourly \( \alpha \) values are determined after rearranging terms in Eq. (1). Assuming that \( H \) is available, one may evaluate \( \alpha_{N(z)} \) as a mean value for samples taken from near-neutral cases; however, it is not straightforward to check (A11). Determination of \( (z^* - d) \) requires detailed profile measurements of temperature and wind speed. However, a qualitative analysis is possible from observations as listed in Table A1. One may classify the surfaces in Table A1 from 1 to 4 as regular surfaces. For this set, surfaces 1 and 2 are real and the artificial surfaces 3 and 4 concur within scales observed in crops such as \( D/h \) about 0.7, \( z/h \) about 0.13, and \( z^*/h \) about 2 (Brutsaert 1988). The ratio \( D/h \) for surface 4 is realistic in crops planted in rows (\( D/h = 0.73 \)) and may be considered moderately heterogeneous. The 5–10 “wind tunnel” (“WT”) cylinder surfaces are sorted by
It is of interest to mention that the mean ratio, the standard deviation was small, as std dev $D/a$ averaged to the reference grass (Brutsaert 1988); however, $z/N$ values for all regular surfaces were $0.54$, $0.51$, and $0.49$, respectively, with std dev $= 0.03$. For savannah, the $z/N$ values were shifted about $0.35$ from regular surfaces. Strictly, according to assumptions made to arrive to (A11), the $z/N$ only applies for homogeneous surfaces, and under weather conditions and canopy characteristics that are suitable for intermediate scales. SR analysis, however, has given results close to the EC method over homogeneous and heterogeneous canopies (crops and tree orchards) when realistic $z^*$ and $d$ values were chosen (Castellví 2004; Castellví et al. 2006; Castellví and Snyder 2009). Thus, based on $z/N$ for homogeneous and moderately heterogeneous surfaces, an initial estimate is $(z^*_N - d) = 1.37h$, while for moderately heterogeneous canopies $(z^*_N - d) = 1.42h$ [i.e., in (A11) $z/N$ was set to $0.54$ and $0.55$, respectively]. The latter $(z^*_N - d)$ scales concur with the Graefe (2004) recommendation of $z^*_N = 2.4h$ as an upper limit expected for moderately tall canopies, including homogeneous and heterogeneous vegetation not exceeding $1.7$ m. The vegetation height was, however, recognized as being rather uncertain. This issue indicates that the $z$ obtained from Table A1 are realistic. However, a more objective $(z^*_N - d)$ expression than (A11) that is not relying on observed intermediate scales is obtained by rearranging terms in (A10) as
\[
(z_N^* - d) = \frac{1}{n} \frac{\pi^2}{\kappa} \frac{\pi^2}{k^2} \sum_{j=1}^{n} (\tau_{u*}^{-1}), \quad (A12)
\]

where index \(j\) indicates measurement at a height \(z\) of \(n\) samples gathered around neutral conditions and \(\pi_{N(z)}\) is an averaged value that suits (A12). Because \(\pi_{N(z)}\) is unknown, (A12) is not straightforward to apply. However, according to Table A1, when instrumentation is deployed within \(h < z < 1.2h\), the averaged \(\alpha_N\) for regular canopies \((D/h < 0.75)\) is \(\alpha_{N(z)} = 0.51\). For vegetation planted in rows with a moderate degree of heterogeneity \((0.75 \leq D/h < 3.5)\), \(\alpha_N = 0.55\). As rule of thumb, one may use these intermediate \(\alpha_N\) values for \(\pi_{N(z)}\).

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