Surface renewal method for estimating sensible heat flux

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Abstract

For short canopies, latent energy flux may be estimated using a shortened surface energy balance from measurements of sensible and soil heat flux and the net irradiance at the surface. The surface renewal (SR) method for estimating sensible heat, latent energy, and other scalar fluxes has the advantage over other micrometeorological methods since the method requires only measurement of the scalar of interest at a point and the method may be applied close to the canopy surface, thereby reducing fetch requirements. The SR analysis for estimating sensible heat flux from canopies involves high-frequency air-temperature measurements (typically 2 to 10 Hz) using unshielded and naturally-ventilated 25- to 75-µm diameter fine-wire thermocouples. The SR method is based on the premise that a parcel of air connected to the surface, after it has been enriched or depleted, is renewed by an air parcel from above. There are 2 SR analysis approaches: the ideal SR analysis approach which presumes a constant α factor; and a set of SR approaches that avoid the use of the α calibration factor. The weighting factor α depends on measurement height, canopy structure and stability conditions since it depends on the capability of the highest frequency eddies to mix the scalar within the air parcels renewed by coherent structures. A combination approach using SR and either similarity theory, that requires friction velocity or wind-speed measurements, or dissipation theory, has also been used to estimate H. The combination SR and dissipation method only requires high-frequency air-temperature data and may be considered not to require calibration. The ideal SR and combination SR/dissipation approaches are the least expensive micrometeorological methods for estimating sensible heat flux and also latent energy flux if one forces closure of the surface energy balance. However, application of SR analysis using slow data-loggers require some expertise since high-frequency air temperature data are not usually stored with the slower data-loggers. Some structure functions can be stored for post-processing and determination of ramp amplitude and ramp period, but the appropriate time lags have to be chosen *a priori*. Fortunately, modern data-loggers avoid this problem and complex SR analysis approaches can now be applied. However, for routine purposes, applications using the ideal SR analysis approach with slow data-loggers may be of interest since it is a very affordable method.

Keywords: surface energy balance, sensible heat flux, latent energy flux, evaporation

Introduction

Accurate and routine measurement of latent energy flux λE is crucial in micrometeorology, agriculture and water resources management. In spite of this need, routine evaporation estimates over temporal and spatial scales are not yet readily available (Bezuidenhout et al., 2006; Jarmain et al., 2009). The latent energy flux may be estimated using a variety of techniques, including weighing lysimetry, soil-water monitoring, and micrometeorological methods. Lysimeters are too expensive and mainly used in agriculture. Soil-water monitoring is labour intensive and is often inaccurate unless averaged over a long period of time. Micrometeorological methods for estimating scalar fluxes, such as eddy covariance, Bowen ratio energy balance, surface renewal, flux variance, and optical scintillation methods, do not disturb the microenvironment and they minimise sampling problems by integrating fluxes over a large area. The eddy covariance (EC) method directly measures the turbulence, but it is stringent (Drexler et al., 2004), and requires many post-processing corrections, favourable wind directions, careful sensor positioning and alignment. The Bowen ratio energy balance (BREB) and the flux variance methods are limited by constraints imposed by extensive fetch requirements with the latter based on Monin-Obukhov similarity theory (MOST) which refers to an atmospheric layer over an extensive flat and homogeneous surface. The surface layer consists of a roughness sub-layer adjacent the surface and an inertial sub-layer above that. MOST applies to the inertial sub-layer. The scintillation method provides path-averaged estimates of sensible heat flux (see e.g. Hill, 1992; Hill et al., 1992; Thiermann and Grassl, 1992; Green et al., 1994; De Bruin et al., 1995; Anandakumar, 1999; Meijninger and De Bruin, 2000; Savage et al., 2004; Savage, 2009; Savage et al., 2010). A scintillometer is a device that optically measures the intensity fluctuations of visible or infrared radiation, caused by interference due to inhomogeneities of the refractive index of air along the path of propagation (Hill, 1992). In contrast to point measurements, displaced-beam scintillometers combined with MOST provide path-averaged measurements of sensible heat and momentum fluxes over distances of between 50 m and 250 m (Thiermann and Grassl, 1992) although distances of up to 350 m have been used (Savage, 2009). Nevertheless, the cost of the scintillometer is high. Despite the availability of different methods for estimating λE directly or indirectly (i.e. by forcing closure of the energy balance), based on the assumptions made, accuracy, simplicity, spatial representation, robustness, fetch requirements, and cost, each method has advantages and disadvantages. Thus the search for methods integrating most of the advantages and avoiding most of the disadvantages is a matter of intensive research.

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Radiation and energy balances: the shortened energy balance method

Solar radiation is a significant source of energy available at the earth's surface used for heating the air and soil, evaporating water, and driving photosynthesis within the earth-atmosphere system (Campbell and Diak, 2005). Net irradiance is the difference between the sum of all incoming and sum of all outgoing irradiances at the earth's surface (Arya, 2001). For a smooth, horizontal, homogeneous, and extensive surface, net irradiance R_n is the sum of the incoming shortwave I_s and infrared L_d irradiances, less the reflected shortwave $r \cdot I_s$ and emitted infrared L_u irradiances:

$$R_n = I_s - r \cdot I_s + L_d - L_u \quad (1)$$

Net irradiance, typically expressed in $W \cdot m^{-2}$, is the major source of energy flux for heating and cooling at the surface of the earth and is one of the major components of the surface energy balance.

To reduce the cost in estimating λE, micrometeorological methods for estimating sensible heat flux are combined with the energy balance equation. The shortened energy balance equation for a short and flat surface is expressed as:

$$R_n = G + H + \lambda E \quad (2)$$

where:

R_n is the net irradiance

G the soil heat flux

H the sensible heat flux where advection is assumed to be negligible

The energy flux associated with photosynthesis and respiration, and energy flux stored in plant canopies are usually small compared with the other terms (Thom, 1975).

Historical development of the surface renewal method

Surface renewal (*SR*) theory was originally developed in the field of chemical engineering by Higbie (1935) to investigate interfacial heat transfer between a liquid and a gas and the SR analysis to estimate scalar exchange in the vegetation-atmosphere interface was originally conceived as a simple 'transilient' theory (Stull, 1984) that is Lagrangian in nature and based on the scalar conservation equation (Paw U et al., 1995; Castellví, 2009). This theory arises from the concept that turbulent exchange can be described as the exchange of air parcels from a known height to another, with weighting factors assigned to the fraction of exchange to a height from each of many other heights (Paw U et al., 2005). Scalars such as air temperature, water vapour pressure, carbon dioxide concentration, for which SR theory could be applied, would have relevance in biometeorology.

Several studies have reported on the use of the SR analysis for estimating H above different surfaces in the past decade. The original SR method as used by Snyder et al. (1996) must be calibrated against another standard method, such as the EC method. Currently, the most used SR analysis approaches are: an ideal SR analysis equation that only requires the temporal trace of the scalar as input (Snyder et al., 1996; Chen et al., 1997a) and the other SR analysis equations that require the temporal trace of the scalar and friction velocity as inputs (Chen et al., 1997b; Castellví et al., 2002; Castellví, 2004). Combination approaches, for example, using SR/similarity and SR/dissipation methods have also been used, by Castellví (2004) and Castellví and Snyder (2009a) respectively. The SR/similarity combination method requires calibration and also wind speed measurements whereas Castelví and Snyder (2009a) showed that the SR/dissipation method requires only air-temperature trace measurements.

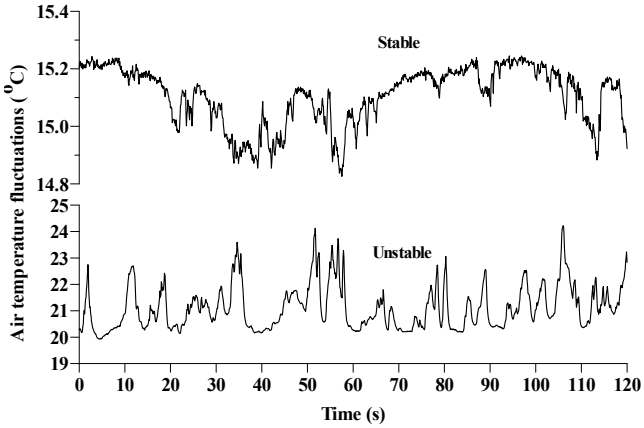

Figure 1

Air-temperature ramps observed in a sample of 120 s of 10 Hz air-temperature traces. The measurements were taken at 0.5 m above grass (0.3 m tall) for unstable (10:00) and stable conditions (01:00), in the Bellevue area neighbouring Ashburton and close to Pietermaritzburg, South Africa for day of year 321 (2003)

Surface renewal analysis is a relatively new, low-cost, attractive and simple method for estimating scalar fluxes (Paw U et al., 1995; Snyder et al., 1996; Spano et al., 1997a, b, 2000; Savage et al., 2004; Paw U et al., 2005; Castellví et al., 2006a, 2008; Castellví, 2007). For estimating sensible heat flux, high frequency air temperature measured at a point in the flow using unshielded and naturally-ventilated fine-wire thermocouples is required as an input for the ideal SR approach and the SR combination approaches. The low cost of the method allows for replication of the method in field trials (Snyder et al., 2008).

The SR analysis is based on the premise that an air parcel from above sweeps to the surface and replaces a parcel that has been enriched (depleted) of scalar during its contact with the sources (sinks). Therefore the air parcel is ejected from the canopy scalar into the atmosphere. Coherent structures (Fig. 1) are responsible for transport of momentum, heat and other scalar quantities (Raupach et al., 1989; 1996; Qui et al., 1995). Temperature traces, typically between 2 Hz and 10 Hz often exhibit organised coherent structures which resemble ramp events (Bergström and Högström, 1989; Gao et al., 1989; Shaw et al., 1989; Paw U et al., 1992). The analysis of the observed ramp events in temperature traces is required to estimate H (Paw U et al., 1992). The use of air-temperature structure functions was suggested by Van Atta (1977) and Chen et al. (1997b). Low-pass filtering techniques (Paw U et al., 1995; Katul et al., 1996) and other techniques such as wavelet transforms have also been used to extract the air-temperature ramp amplitude and ramp period. The ideal SR analysis equation (Snyder et al., 1996) only requires the trace as an input. Therefore, for estimation of H, only air-temperature measurements are required but the method requires calibration against a standard method such as eddy covariance.

Chen et al. (1997b) presented a new 3rd order structure function for estimating H that uses the zero plane displacement

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and friction velocity as inputs. Castellví et al. (2002) proposed a new method that combined SR analysis and similarity theory. Castellví (2004) explained the companion method presented by Castellví et al. (2002) and derived a new method that is exempt from calibration. However, unlike the ideal SR analysis, the methods proposed by Chen et al. (1997a) and Castellví (2004) also require wind-speed measurements. Using a result from Hsieh and Katul (1997) concerning the dissipation method which is based on turbulent kinetic energy, scalar variance and MOST, Castellví and Snyder (2009a) used a combination SR/dissipation method which appears to be exempt from calibration requiring only measurements at frequencies of between 4 and 10 Hz.

If λE is obtained as the residual of the shortened energy balance equation (Eq. (2)), H estimated using SR analysis is convenient since it operates either in the roughness or the inertial sub-layers and it is relatively inexpensive. In the next section, the most commonly-used SR approach will be described in detail.

Ideal surface renewal analysis model based on an air-temperature structure function analysis

Paw U et al. (1995) expressed H as the change in heat energy content of air with time across a unit horizontal area:

$$H = \alpha \rho c_p \frac{dT}{dt}\frac{V}{A} \quad (3)$$

where:

α is a weighting factor (regression coefficient fit to the above equation when H is measured independently using a standard method such as EC)
ρ the density of air (kg·m^{-3})
c_p the specific heat capacity of air (J·kg^{-1}·K^{-1})
dT/dt the rate of change in air temperature (^{o}C·s^{-1})
V/A the volume of air per unit horizontal area

If the air-temperature measurement is taken at canopy height, then V/A (which is equal to the vertical distance) will be the canopy height (h). High frequency air-temperature data are measured at a fixed point and hence the use of Eq. (3) assumes that dT/dt is approximately equal to dT/dt and internal advection is negligible (Paw U and Brunet, 1991; Paw U et al., 1995). This assumed proportional relationship between the advective term dT/dt and the total derivative dT/dt has been discussed in detail by Paw U et al. (1995). However, this assumption may not be correct under all conditions. For example, the assumption may be invalid when there is strong local advection and under high wind shear close to the canopy top of low vegetation and soil surface (Snyder et al., 1996). Low-pass filtering techniques were used by Paw U et al. (1995) to smooth the high frequency air-temperature data to remove the internal advection and to determine H. However, the filtering technique is cumbersome, due to the necessity of choosing filtering functions and use of numerical methods to identify scalar increases or decreases (Paw U et al., 2005).

When high frequency air-temperature measurements are taken at a point at or above the canopy top, ramps are observed (Fig. 1) in the air-temperature traces. These air- temperature ramps are characterised by an amplitude a (^{o}C), a ramp period L_r (s) where the change in air temperature with time occurs, and a quiescent period L_q (s) for which there is no change in air temperature with time (Snyder et al., 1996, 1997).

The total ramp duration τ (s) is the sum of ramp period L_r and quiescent period L_q (Fig. 2). The amplitude a is positive when the atmosphere is unstable and (the sign of H is positive) and a is negative for stable atmospheres (H is negative).

For estimating H, Paw U et al. (1995) simplified and modified the SR analysis by substituting dT/dt in Eq. (3) by a/τ (^{o}C·s^{-1}) for the average rate of change in air temperature for the total ramp period:

$$H = \alpha \rho c_p \frac{a}{L_r + L_q} z \quad (4)$$

where:

α is a weighting factor accounting for the spatially-averaged (vertical) air-temperature derivative from the bottom to the top of the air parcel (a correction factor for unequal heating or cooling below the sensor)

The weighting factor α depends on z (which is the measurement height), canopy structure and atmospheric stability conditions. According to Castellví and Snyder (2009a), the factor α is a measure of the capability of the turbulence to mix the scalar within the air parcel to be renewed. Also in the factor α, one may include other aspects such as thermocouple size and the frequency available to determine the ramp parameters (Snyder et al., 1996; Spano et al., 1997a, b, 2000; Paw U et al., 2005). Generally, for near-neutral conditions, α = 0.5 as shown over mixed deciduous forest, Walnut orchard, and maize canopies (Table 1, next page) for measurements taken at canopy height (Paw U et al., 1995). For a short turf grass (0.1 m tall), excellent estimates of H were obtained using α = 1, when the measurements are taken in the inertial sub-layer for mainly unstable conditions (Snyder et al., 1996).

Snyder et al. (1996) used structure functions of air temperature and the analysis technique of Van Atta (1977) to estimate the amplitude a and the ramp period $\tau = L_r + L_q$ as shown in Fig. 2. The structure function value $S^n(r)$ is calculated for each averaging period, typically sub-hourly, from high-frequency

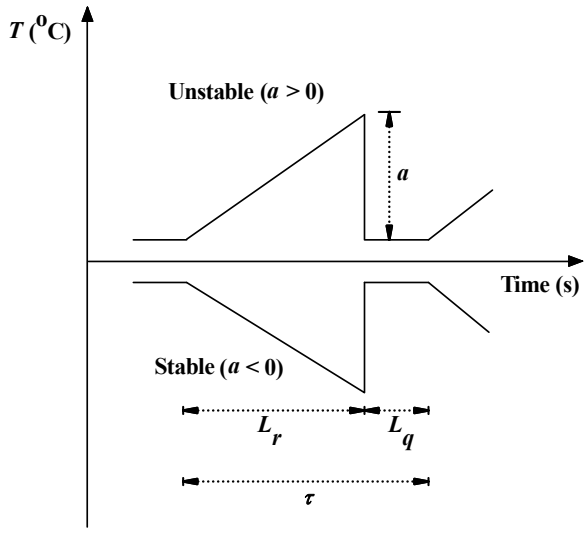

Figure 2
An ideal surface renewal analysis ramp model, assuming a sharp instantaneous drop in air temperature with amplitude a>0 *for unstable and* a<0 *for stable atmospheric conditions. The ramp period is* L_r *and* L_q *the quiescent time period with* $\tau = L_r + L_q$ *the total ramp period (inverse ramp frequency)*

TABLE 1
The weighting factor α for a range of surfaces using different time lags and sensor sizes during unstable conditions. The slope of the regression of H estimated using the SR method vs. H obtained using a standard method (eddy covariance) yields α for linear fits forced throuh the origin.

Surface	Canopy height (m)	Height above canopy (m)	Sensor size (μm)	Sampling frequency (Hz)	Time lag r (s)	α	Authors
Bare-soil	0.00	-	12.7	8	0.25	0.90	Duce et al. (1998)
Bare-soil	0.00	-	25.4	8	0.25	1.04	Duce et al. (1998)
Bare-soil	0.00	-	76.2	8	0.25	1.88	Duce et al. (1998)
Bare-soil	0.00	0.03	25.0	10	0.10	0.69	Chen et al. (1997b)
Endorreic salty lagoon	0.00	0.90	76.2	8	0.75	1.00	Zapata and Martínez-Cob (2001)
Open water	0.00	1.0, 1.3, 1.9, 2.6	75	10	0.4, 0.8	0.2, 0.25	Mengistu and Savage (2010)
Mulch	0.05	0.09	25.0	10	0.10	0.51	Chen et al. (1997b)
Grass (alta fescue)	0.10	0.35	76.2	8	0.75	1.00	Snyder et al. (1996)
Grass (alta fescue)	0.10	0.30	76.2	8	0.25	0.97	Duce et al. (1997)
Irrigated pasture (tall fescue)	0.08 to 0.12	0.75 (0.6)	75	4	0.25, 0.5	0.35 (0.4)	Snyder et al. (2008)
Wheat	0.70	0.30	76.2	8	0.50	1.00	Duce et al. (1997)
Sorghum	0.70	0.30	76.2	8	0.75	1.02	Duce et al. (1997)
Wheat	0.90	0.50	25.4	16	0.30	1.00	Anandakumar (1999)
Sugarcane	> 1 m	0.2, 0.5, 0.75, 1.5	75	10	0.4, 0.8	0.55 to 0.66	Nile (2010)
Sparse grape vine	2.20	0.00	76.2	8	0.50	0.87	Spano et al. (1997b)
Maize	2.60	0.00	12.5	10	0.10	0.50	Paw U et al. (1995)
Peach orchard	3.95	1.55	Sonic temperature	10	Several	0.95	Castellví and Snyder (2009)
Citrus	4 to 4.5	0 to 0.5	76.2	4	0.5, 1.0	0.227	Snyder and O'Connell (2007)
Avocado	5.20	0.00	76.2	8	0.50	0.59	Spano et al. (1997b)
Walnut orchard	6.00	0.00	12.5	10	0.10	0.50	Paw U et al. (1995)
Flood-irrigation pecan	12.8	-3.7, 0	-	4	1.0	1.1 ($z = d$), 0.5 ($z = h$)	Simmons et al. (2007)
Douglas-fir forest	16.70	6.30	25.0	2	0.50	0.52	Chen et al. (1997b)
Mixed deciduous forest	18.00	0.00	12.5	10	0.10	0.50	Paw U et al. (1995)

air-temperature measurements at frequency f (Hz) using the relation:

$$S^n(r) = \frac{1}{m-j}\sum_{i=1+j}^{m}(T_i - T_{i-j})^n \quad (5)$$

where:

m is the number of data points in the averaging period
n is the power of the function
j is the number of time lags between data points corresponding to a time lag (s)
$r = j/f$
T_i is the i^{th} temperature sample

Van Atta (1977) suggested that τ must be much less than r, typically $\tau > 10\,\tau$, or otherwise the structure-function theory is invalid. Snyder et al. (2007) used the condition that $\tau > 5\,\tau$ and imposed an upper limit for τ of 600 s.

The Van Atta (1977) method involves estimating the mean value for amplitude a during the time interval by solving the following equation for real roots:

$$a^3 + pa + q = 0 \quad (6)$$

where:

$$p = 10S^2(r) - \frac{S^5(r)}{S^3(r)} \quad (7)$$

and

$$q = 10S^3(r) \quad (8)$$

The ramp period τ is calculated using:

$$\tau = -\frac{a^3 r}{S^3(r)} \quad (9)$$

The disadvantage of using a fixed α (Eq. (4)) is that the ideal SR method measurements of H must be calibrated using EC estimates. Slow data-loggers are limited and the weighting factor α depends on the time lag used (Snyder et al., 1996; Zapata and Martínez-Cob, 2001). The size of the air-temperature sensor affects the amplitude a and the ramp period τ, and hence α. The sensor time constant represents the time it takes for the sensor to respond to 63.2% of a step change in temperature. For a 75-μm diameter sensor for example, the time constant is 50 ms for low air flow (Medtherm, 2007). Therefore, the use of 75-μm diameter sensors, in general, is adequate for air-temperature measurements for the SR method. The α values for various surfaces using different time lags r and sensor sizes are shown in Table 1, for unstable atmospheric conditions.

Once the weighting factor α is determined for a particular canopy, it is stable and does not change from site to site regardless of the weather conditions (Drexler et al., 2004) unless there are considerable changes in vegetation canopy structure (Paw U et al., 1995; Snyder et al., 1996; Spano et al., 2000). The parameter α increases to some extent with increase in temperature-sensor size and this can cause a problem related to sensitivity of the SR model to slower response scalar sensors (Paw U et al., 2005).

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Surface renewal analysis using a ramp model with finite micro-front period

Chen et al. (1997a) proposed a more realistic ramp model, which takes into consideration a finite micro-front period L_f instead of a sharp decrease in air temperature (Fig. 3), and assumes an insignificant quiescent period L_q to avoid numerical complexity. The quiescent period exists, but when the model takes into account the quiescent period between the micro-front and formation of the next ramp, there were no significant changes in the sensible heat flux estimates.

Because very high frequencies are required to determine L_f, the approach estimates the amplitude a and total ramp duration $\tau = L_r + L_f$, from fluctuations of high-frequency air-temperature measurements using a cubic temperature structure function as:

$$\frac{a}{\tau^{1/3}} = -\gamma \left(\frac{S^3_{(r_m)}}{r_m} \right)^{1/3}, \qquad (10)$$

where:

$S^3_{(r_m)}$ is the 3rd order of the structure function for temperature

r_m is the sampling time lag at which $-(S^3_{(r)}/r)^{1/3}$ is a maximum

γ is a coefficient which corrects for the difference between $a/\tau^{1/3}$ and the maximum value of $-(S^3_{(r)}/r)^{1/3}$

Raupach et al. (1989) predicted that for canopies $1/\tau$ should scale with maximum wind shear (du/dz at $z = h$, where u is the mean wind speed and h the canopy height). In the canopy and roughness sub-layer, transport of momentum and scalar fluxes are dominated by eddies of length scale comparable to h, while in the inertial sub-layer, dominant eddies scale with $z - d$, where d is zero-plane displacement height (Raupach et al., 1996; Chen et al., 1997b).

Chen et al. (1997b) scaled $1/\tau$ as follows:

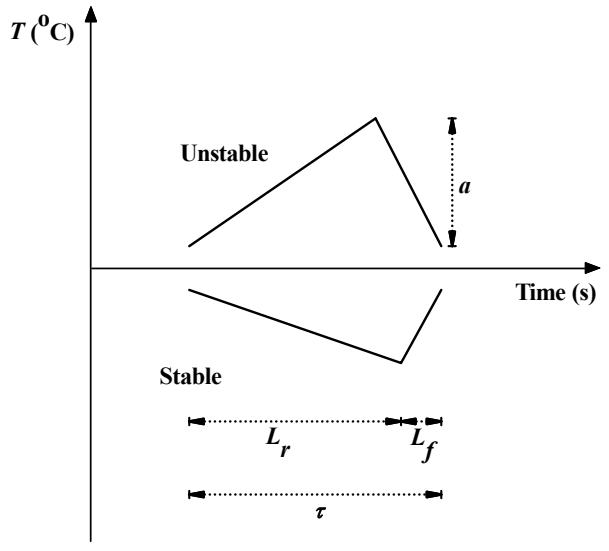

Figure 3
Surface renewal analysis ramp model which assumes a finite micro-front time, where a is the air-temperature amplitude, L_r is the ramp period, L_f is the micro-front period, and τ is the total ramp period

$$\frac{1}{\tau} = \begin{cases} \beta \dfrac{u_*}{h}, & 0.2h < z \le h + 2(h-d), \\ \beta \dfrac{u_*}{z-d}, & z > h + 2(h-d) \text{ or } z \le 0.2h, \end{cases} \qquad (11)$$

where:

β is an empirical coefficient

u_* the friction velocity ($m \cdot s^{-1}$)

Following Sellers et al. (1986), the roughness sub-layer is assumed to be between $z = h$ and $z = h + 2(h - d)$. The layer adjacent to the soil within canopies ($z \le 0.2h$) is treated the same way as the inertial sub-layer, with appropriate u_* and h for the soil or canopy understory (Lee and Black, 1993).

Chen et al. (1997b) recommended that for routine application of the finite micro-front SR model, only the maximum of $-(S^3_{(r)}/r)^{1/3}$ is required from high-frequency air- temperature data. According to the model, H is proportional to $z/h^{2/3}$ in the roughness sub-layer and proportional to $z/(z-d)^{2/3}$ in the inertial sub-layer. Substituting expressions for a and τ from Eqs. (10) and (11) into Eq. (4) to obtain H yields:

$$H = \begin{cases} -\alpha\beta^{2/3}\gamma\rho c_p \left(\dfrac{S^3_{(r_m)}}{r_m} \right)^{1/3} u_*^{2/3} \dfrac{z}{h^{2/3}}, & 0.2h < z \le h + 2(h-d), \\ -\alpha\beta^{2/3}\gamma\rho c_p \left(\dfrac{S^3_{(r_m)}}{r_m} \right)^{1/3} u_*^{2/3} \dfrac{z}{(z-d)^{2/3}}, & z > h + 2(h-d) \text{ or } z \le 0.2h. \end{cases} \qquad (12)$$

The empirical combined coefficient $\alpha\beta^{2/3}\gamma$ is a common factor in both roughness and inertial sub-layers. Chen et al. (1997b) found a roughly constant value of 0.4 for the combined coefficient $\alpha\beta^{2/3}\gamma$ (Table 2), in their experiments on Douglas-fir forest, bare soil, and straw mulch.

Sensible heat flux may be estimated from the average cubic temperature structure function (using high-frequency air-temperature data) and measured or estimated friction velocity within the canopy and roughness sub-layers and inertial sub-layer, using this model for stable and unstable conditions. The approach does not require calibration but additional measurement of horizontal wind speed is needed and slow data-loggers may be limited in determining the 3rd order air-temperature structure function.

Combined surface renewal analysis model and similarity theory

Castellví et al. (2002) proposed an SR analysis model based on a turbulent diffusion approach (similarity theory), to estimate H using high-frequency air-temperature data, friction velocity, and similarity formulae. Similarity theory describes H as:

$$H = \rho c_p K_h \frac{dT}{dz} \qquad (13)$$

TABLE 2
Average coefficients α, β, γ and the combined coefficient $\alpha\beta^{2/3}\gamma$, for Douglas-fir forest, straw mulch, and bare soil (Chen et al., 1997b)

Canopy	α	β	γ	$\alpha\beta^{2/3}\gamma$
Douglas-fir forest	0.527	0.795	1.001	0.418
Straw mulch	0.511	0.538	1.175	0.397
Bare soil	0.691	0.398	1.104	0.413

where:

K_h is the turbulent transfer coefficient ($m^2 \cdot s^{-1}$) or eddy diffusivity for H

T the average air temperature (K) during the measurement time

z the height above the surface (m)

Invoking Eq. (4) for the ideal SR model (Paw U et al., 1995), the variable αz represents the 'effective eddy size' responsible for the air-parcel renewal (Castellví et al., 2002; Castellví, 2004). Since ramp-like structures (characterised by amplitude a and total ramp duration τ) contribute to vertical transport, Castellví et al. (2002) proposed the following relationship:

$$\begin{aligned} &\frac{a}{\alpha z} \propto \frac{\partial T}{\partial z} = \beta \frac{a}{z}, \text{ for the roughness sub-layer} \\ &\frac{a}{\alpha z} \propto \frac{\partial T}{\partial z} = \beta \frac{a}{z-d}, \text{ for the inertial sub-layer} \end{aligned} \tag{14}$$

where:

β is a scale or link parameter (not to be confused with β in Eq. (11))

d the zero-plane displacement height – normally taken as $2h/3$ where h is the canopy height

When measurements are taken well above the canopy top in the inertial sub-layer, MOST can be used to express K_h as follows:

$$K_h = k\, u_* (z-d) / \phi_h(\zeta) \tag{15}$$

where:

k is the von Kármán constant (0.41)

$\phi_h(\zeta)$ is the stability function for sensible heat flux where $\zeta = (z-d)/L$ is a dimensionless buoyancy (stability) parameter

L is the Obukhov length (m):

$$L = \frac{T}{k\, g} \frac{\rho c_p u_*^3}{(H + 0.61 c_p T E)}$$

Following Businger et al. (1971), the stability function $\phi_h(\zeta)$ is:

$$\begin{aligned} &\text{unstable } \phi_h(\zeta) = 0.74 \Big/ \sqrt{1 - 9\zeta} \\ &\text{neutral } \phi_h(\zeta) = 0.74 \\ &\text{stable } \phi_h(\zeta) = 0.74 + 4.7\zeta \end{aligned} \tag{16}$$

Castellví et al. (2002) proposed the following relationship to estimate H in the inertial and roughness sub-layers by combining Eqs. (14) to (16) to yield:

$$H = \begin{cases} \rho c_p \beta_2 a\, u_*, & \text{roughness sublayer} \\ \rho c_p \beta_1 a\, u_* / \phi_h(\zeta), & \text{inertial sublayer} \end{cases} \tag{17}$$

where:

amplitude β_1 is a scale parameter for the inertial sub-layer

β_2 is a scale parameter for the roughness sub-layer

a is determined using the Van Atta (1977) approach with u_* and ζ determined by iteration

Castellví et al. (2002) found β_1 values ranging from 0.10 to 0.15 and β_2 values ranging from 0.23 to 0.33 above grass, wheat, and grapevine canopies for measurements taken in inertial and roughness sub-layers.

Castellví (2004) derived the following relationship for estimating the weighting factor α in Eq. (4) for measurements above the canopy:

$$\alpha = \begin{cases} \left(\frac{k}{\pi} \frac{(z-d)}{z^2} \frac{\tau u_*}{\phi_h(\zeta)} \right)^{1/2}, & z - d > z^* \\ \left(\frac{k}{\pi} \frac{z^*}{z^2} \frac{\tau u_*}{\phi_h(\zeta)} \right)^{1/2}, & h \le z - d \le z^* \end{cases} \tag{18}$$

where:

z^* is the roughness sub-layer depth.

Combining Eqs. (4) and (18), Castellví (2004) proposed the following expression for estimating sensible heat flux:

$$H = \begin{cases} \rho c_p \left(\frac{a}{\tau^{1/2}} \right) \left(\frac{k(z-d)}{\pi} \right)^{1/2} \left(\frac{u_*}{\phi_h(\zeta)} \right)^{1/2}, & z - d > z^* \\ \rho c_p \left(\frac{a}{\tau^{1/2}} \right) \left(\frac{kz^*}{\pi} \right)^{1/2} \left(\frac{u_*}{\phi_h(\zeta)} \right)^{1/2}, & h \le z - d \le z^*. \end{cases} \tag{19}$$

Equation (19) is valid when measurements are made over homogeneous canopies but good performance has been observed over heterogeneous canopies (Castellví et al., 2006b). In particular, however, the relationship is exempt from calibration regardless of the stability conditions (Castellví, 2004). Also by combining Eqs. (18) and (19), and invoking the relationship between the ramp period and amplitude (Eq. (10)) from the micro-front model, Castellví (2004) derived the following relationship to estimate sensible heat flux (Similar relationships are presented by Castellví and Martínez-Cob (2005) but there is a misprint in their Eqs. (5) and (6) which contains $k(z-d)^{4/5}$ instead of the correct term $(k\,(z-d))^{4/5}$):

$$H = \begin{cases} \rho c_p \left(\frac{g}{T} \right)^{1/5} \frac{(k(z-d))^{4/5}}{\pi^{3/5}} \left(-\gamma^3 \frac{S^3_{(r_m)}}{r_m} \right)^{3/5} \frac{1}{a^{3/5}} \left(\frac{1}{-\zeta\, \phi_h^3(\zeta)} \right)^{1/5}, & z - d > z^* \\ \rho c_p \left(\frac{g}{T} \right)^{1/5} k^{4/5} \left(\frac{z^*}{\pi} \right)^{3/5} z^{1/5} \left(-\gamma^3 \frac{S^3_{(r_m)}}{r_m} \right)^{3/5} \frac{1}{a^{3/5}} \left(\frac{1}{-\zeta\, \phi_h^3(\zeta)} \right)^{1/5}, & h \le z - d \le z^* \end{cases} \tag{20}$$

Equation (20) depends on the stability parameter ζ, and hence wind speed measurements are also required as an input. If one uses slow data-loggers, the method is not totally exempt from calibration because of parameter γ (Castellví, 2004; Castellví and Martínez-Cob, 2005). However, γ varies by less than 25% with respect to unity for different canopies (Chen et al., 1997b). Equation (20) performed well using $\gamma = 1.1$ (Table 2) for measurements taken at different heights above the canopy (Castellví and Martínez-Cob, 2005). The function $(-\zeta\, \phi^3_h(\zeta))^{-1/5}$ in Eq. (20) can be set to approximately 2.4 for the stability range $-3 \le \zeta \le -0.03$, with a relative error of less than 8.5% and can be expressed as (Castellví, 2004):

$$H = \begin{cases} 2.4 \rho c_p \left(\frac{g}{T} \right)^{1/5} \frac{(k(z-d))^{4/5}}{\pi^{3/5}} \left(-\gamma^3 \frac{S^3_{(r_m)}}{r_m} \right)^{3/5} \frac{1}{a^{3/5}}, & z - d > z^* \\ 2.4 \rho c_p \left(\frac{g}{T} \right)^{1/5} k^{4/5} \left(\frac{z^*}{\pi} \right)^{3/5} z^{1/5} \left(-\gamma^3 \frac{S^3_{(r_m)}}{r_m} \right)^{3/5} \frac{1}{a^{3/5}}, & h \le z - d \le z^* \end{cases} \tag{21}$$

Equation (21) holds under slightly unstable conditions, is valid in both the roughness and inertial sub-layers, only requires air-temperature data as an input, and may be considered exempt from calibration (Castellví, 2004) since β_1 in Eq. (17), approximately 0.1, is appropriate under unstable conditions over a variety of canopies. For both roughness and inertial layers, Castellví (2004) found that the value of 0.1 was robust with height.

The main advantage of this SR analysis combination approach therefore is that it is not sensitive to measurement

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height, and furthermore that it is based on the fact that vertical velocity of the mean eddies responsible for the renewal process has been properly scaled for the corresponding amplitude of the air temperature of the mean ramp events (Castellví et al., 2002).

Combined surface renewal analysis model and dissipation theory

An analysis of combining the SR method with dissipation theory was presented by Castellví and Snyder (2009a). For the dissipation method, the normalised dissipation rate for scalar *s* can be expressed as

$$\Phi_s(\zeta) = \frac{k(z-d)}{u_* s_*^2}\varepsilon_s \tag{22}$$

where:

s_* is the scalar surface scale

ε_s is the mean dissipation rate for scalar *s*

where:

$$u_* s_* = \left(\frac{k(z-d)u_*}{\Phi_s(\zeta)\varepsilon_s}\right)^{\frac{1}{2}} \tag{23}$$

Using a result of Hsieh and Katul (1997), which involved combining dimensional analysis and the traditional dissipation method, Castellví and Snyder (2009a) showed that:

$$u_* s_* = \frac{1.66}{\pi}(z-d)\frac{a_s^2}{\tau_s \sigma_s} \tag{24}$$

where:

σ_s is the scalar standard deviation

For sensible heat flux, then:

$$\alpha = \frac{1.66}{\pi}\frac{(z-d)}{z}\frac{a}{\sigma_T} \tag{25}$$

They note that the new dissipation-SR analysis, based on Eq. (24), does not require ε_s as an input and does not depend on stability or on any similarity relationships. Furthermore, for sensible heat flux, only air temperature at frequencies of between 4 Hz and 10 Hz are required. They contend that the constant 1.66 does not depend on height. Further research on this aspect is required.

Application of the SR method

Most often, crop coefficients are obtained using lysimeters to measure the evaporation and simultaneously, short-grass (or tall-crop) reference is calculated from weather data. Using SR to estimate sensible heat flux, from which evaporation was calculated using measurements of net irradiance and soil heat flux, Snyder and O'Connell (2007) obtained crop coefficients of micro-sprinkled irrigated citrus for 4 years. A similar method for estimating irrigated pasture evaporation was applied by Snyder et al. (2008) for 8 months. For a 2-year period, Hanson et al. (2007) used the SR method and other measurements in a water-short area (Eq. (2)) to investigate the effect of deficit irrigation of alfalfa on the yield and evaporation. The performance of an ecosystem evaporation model was investigated using SR measurements of sensible heat flux at a wetlands site (Spano et al., 2009). Bare-soil evaporation was modelled using a coupled heat, water vapour and liquid water flux model and the modelled estimates compared with that using the SR method and energy balance measurements (Eq. (2)) (Bittelli et al., 2008).

Noting that that the BREB method is not recommended for locations influenced by regional advection, and using the SR-similarity combination approach, Castellví and Snyder (2009b) used SR analysis to estimate sensible heat flux over 2 growing rice fields under regional advection.

Of particular relevance to studies for which there are fetch limitations, Paw U et al. (1995) demonstrated that for short canopies, there was an indication that the SR method was not sensitive to inadequate fetch. They also concluded that the SR method decreased in accuracy as height above the (maize) canopy increased.

The SR method has also been applied to flux estimates of latent energy and carbon dioxide (Castellví et al., 2008). In this investigation, surface energy balance closure over rangeland grass, using SR measurements of H and λE, by application of Eq. (18), was investigated and compared with EC closure. The EC method consistently underestimated the available energy flux ($R_n - G$ of Eq. (2)) by about 10% whereas the SR closure was always good.

For measurements in a peach orchard and using the SR/similarity theory combination method (Eq. (19)), Castellví and Snyder (2009c) found that for unstable cases, H_{SR} underestimated by about 7% and as a result, the sign of the ramp amplitude a was not in agreement with the sign of H_{EC}. They concluded that their experiment demonstrated the potential of SR as a method applicable at any height above the canopy surface for estimating H.

Recommendations for future research

The SR method is relatively new and quite simple (Paw et al., 1995; Snyder et al., 1996; Spano et al., 2000). The advantages of the SR method over other micrometeorological methods are the relatively low cost, easy installation and maintenance; apparently the method is less dependent on fetch since it is based on the theory of short-term heat transfer between a surface and that it operates in the roughness and inertial sub-layers. The ideal SR method is the most inexpensive micrometeorological method for estimating sensible heat flux, but the SR weighting factor α needs to be determined using a standard method such as the eddy covariance method. At least two calibrations are recommended: one for night-time and one for day-time conditions to better account for stability conditions. In South Africa, the SR method has been evaluated by Savage et al. (2004), Mengistu (2008) and Nile (2010) for a wide range of canopies and above water (Mengistu and Savage, 2010). Savage (2007) suggested that high frequency air-temperature-based methods may pave the way for evaporation stations from which real-time and sub-hourly estimates may be obtained relatively inexpensively.

The SR method has mostly been used for estimating sensible heat flux over different surfaces, and the latent energy flux obtained as a residual of the energy balance (Eq. (2)). The latter provides the most inexpensive procedure to estimate latent energy flux (Drexler et al., 2004).

The SR analysis can be applied to other scalars such as water vapour pressure, carbon dioxide concentration, and other gas concentrations. However, there has been little research on the application of the SR analysis to estimate the flux of other scalars. Currently there are very few published works detailing the application of SR analysis to determine latent energy flux (Katul et al., 1996; Castellví et al., 2008) and only 2 for carbon dioxide (Spano et al. 2002; Castellví et al., 2008). Therefore, further studies should focus on the use of the SR method to

estimate fluxes of water vapour, carbon dioxide, and other scalars. Also, the SR method applied here does not allow real-time estimation of sensible heat flux and further research on this aspect would be valuable for long-term monitoring. The SR methods that are exempt from calibration need to be applied to other surfaces to confirm their applicability over a wide range of atmospheric and surface conditions.

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