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On the performance of surface renewal analysis to estimate sensible heat flux over two growing rice fields under the influence of regional advection

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SUMMARY

High-frequency temperature data were recorded at one height and they were used in Surface Renewal (SR) analysis to estimate sensible heat flux during the full growing season of two rice fields located north–northeast of Colusa, CA (in the Sacramento Valley). One of the fields was seeded into a flooded paddy and the other was drill seeded before flooding. To minimize fetch requirements, the measurement height was selected to be close to the maximum expected canopy height. The roughness sub-layer depth was estimated to discriminate if the temperature data came from the inertial or roughness sub-layer. The equation to estimate the roughness sub-layer depth was derived by combining simple mixing-length theory, mixing-layer analogy, equations to account for stable atmospheric surface layer conditions, and semi-empirical canopy–architecture relationships. The potential for SR analysis as a method that operates in the full surface boundary layer was tested using data collected over growing vegetation at a site influenced by regional advection of sensible heat flux. The inputs used to estimate the sensible heat fluxes included air temperature sampled at 10 Hz, the mean and variance of the horizontal wind speed, the canopy height, and the plant area index for a given intermediate height of the canopy. Regardless of the stability conditions and measurement height above the canopy, sensible heat flux estimates using SR analysis gave results that were similar to those measured with the eddy covariance method. Under unstable cases, it was shown that the performance was sensitive to estimation of the roughness sub-layer depth. However, an expression was provided to select the crucial scale required for its estimation.

Introduction

The simplified expression for the surface energy-balance equation is Rn – G = H + LE, where Rn is the net radiation, G is the soil heat flux, LE is the latent heat flux, and H is the sensible heat flux, which holds for most agricultural applications because the other remaining energy terms are small (Brutsaert, 1988; Oncley et al., 2007). Measurements of Rn and G are affordable, and therefore, closure of the surface energy-balance equation has been employed to estimate LE using the Bowen ratio, BR (=H/LE), where LE = (Rn − G)/(1 + BR), or by rearranging terms to solve for LE as the residual, LE = Rn – G − H which is the best procedure to estimate LE is a difficult question to address (Twine et al., 2000). The flux-gradient Bowen ratio energy-balance, BREB, method (Brutsaert, 1988) is not recommended in locations influenced by regional advection because similarity for temperature and humidity cannot be assumed (Motha et al., 1979; Lee et al., 2004). The eddy covariance, EC, method is widely used, but the expense, complexity, and the lack of energy-balance closure have prevented its widespread adoption by most agronomists and engineers for applied purposes in agriculture. Since LE over irrigated crops is often similar in magnitude to the available energy, Rn – G, adding the small contribution from sensible heat flux, is a simple method to refine LE estimates for a wide range of vegetated surfaces. Consequently, methods to estimate H requiring low-budget instrumentation are valuable, especially in agriculture. For more than four decades, the later has constituted an intensive field of research (Wyngaard et al., 1971; Tillman, 1972; Paw et al., 1995, 2005; Hsieh et al., 1996; Hsieh and Katul, 1997; Wang and Brass, 1998; Fitzmaurice et al., 2004). Methods that work when measurements are taken close to the canopy top (i.e., in the roughness sub-layer) are of special interest because they reduce the fetch requirements and avoid the need to modify the measurement level as the vegetation grows. The depth of the roughness sub-layer varies depending on canopy–architecture and on atmospheric surface layer stability conditions (Garrat, 1980; Raupach and Thom, 1981; Raupach et al., 1991; Cellier and Brunet, 1992; Physick and Garratt, 1995; Graefe, 2004; Harman

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and Finnigan, 2007). Therefore, when instruments are located at a fixed level, the measurements could come from either the roughness or the inertial sub-layer even on a given day. Because similarity relationships do not hold for data collected in the roughness sub-layer and the sub-layer depth changes with atmospheric conditions, some method to determine the sub-layer depth is needed to better estimate H from data collected at a fixed height. Surface renewal, SR, analysis for estimating surface fluxes (Paw et al., 1995) operates both in the roughness and inertial sub-layers. The problem is that, until recently, the SR method required calibration against a sonic anemometer to obtain accurate H values (Zapata and Martínez-Cob, 2001; Drexler et al., 2004). The SR methodology proposed in Castellvi (2004), however, does not require calibration. The revised approach does depend on the stability function for heat transfer. When operating in the inertial sub-layer under the influence of regional advection of sensible heat flux, the SR-similarity combination has provided reliable estimates of sensible heat, latent heat, and carbon dioxide fluxes (Castellvi et al., 2008). In this paper, sensible heat flux was estimated over the entire season for two rice fields. The fetch distance was large, but the difference between the measurement height and the canopy top was changing with time because the measurement height was fixed. For a crop such as rice, to keep the measurements at a fixed height is convenient because it is difficult to access the instruments in the field without causing damage to the crop. The campaigns were carried out north–northeast of Colusa, California (in the Sacramento Valley). Half-hourly H estimates were compared against H measured with the eddy covariance method to test the SR method.

Theory

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 ejects upward and is replaced by another parcel sweeping in from aloft. During the connect time with the surface, scalars transfer 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 in contact with the sources (sinks). This continuous renewal process is responsible for the majority of vertical transport (Gao et al., 1989; Lohou et al., 2000; Hongyan et al., 2004). The renewal process is associated to an organized low-frequency flow (coherent structure). 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. Fig. 1a shows the ramp-like pattern in the temperature trace over a short time period under unstable and stable cases. Paw et al. (1995) presented a diagram of the surface renewal process (Fig. 1b) and abstracted an ideal scheme for a ramp-like event in the trace (Fig. 1b Scheme 1). Chen et al. (1997a) presented a slightly different version (Fig. 1b Scheme 2), which neglects the quiescent period but includes a micro-front period instead of an instantaneous ejection. Whatever the model, a ramp is characterised by an amplitude, A, and period, τ. According to Katul et al. (1996), the different visual time course of the scalar between Fig. 1a and Schemes in Fig. 1b is mainly attributed to high frequency eddies attached to the organized motion. By denoting time and scalar concentration as t and c, respectively, SR analysis evaluates the source of the scalar, S_c, averaged in time and depth (denoted by $\langle\rangle$) in the air parcel through the scalar conservation equation assuming an incompressible flow, $d\langle c\rangle/dt = \langle S_c\rangle$, by identifying and removing the high-frequency fluctuations to leave the time averaged coherent (ramp-like) part in the trace. When an air parcel of volume V, which is large enough to include the vertical extent of the source, sweeps to the surface where it, (1) remains connected with the source until ejection, (2) is enriched with the scalar while in contact with the source, with no loss or gain of mass (or scalar) from the parcel top, and (3) is well mixed with negligible gradients and molecular diffusion, the source enrichment rate, S_c, averaged in time and depth for the parcel with height, z, per unit area, A is:

$$\frac{V}{A}\frac{d\langle c\rangle}{dt} = z\langle S_c\rangle = z\frac{A_c}{L_r} \tag{1}$$

where A_c is the amplitude of the mean scalar ramp and L_r is the mean length of the ramp period. For sensible heat, $c = \rho C_p T$, where ρ and C_p are the density and specific heat of dry air at constant pressure and T is the air temperature. Multiplying Eq. (1) by the ratio of the ramp period duration, L_r, to the ramp plus quiescent period duration, τ, (i.e., L_r/τ), the mean sensible heat flux density, H, at height, z, is estimated as in Paw et al. (1995) as:

$$\rho C_p z\frac{A_T}{L_r}\frac{L_r}{\tau} \approx H = \rho C_p(\alpha z)\frac{A_T}{\tau} \tag{2}$$

where A_T for temperature replaced A_c for a scalar. The parameter α is included to correct for all the assumptions in Eq. (2). Several studies on the SR scalar traces have shown that half-hourly α value is not constant and it mainly depends on the measurement level, Obukhov length, and canopy–architecture (Snyder et al., 1996; Katul et al., 1996; Castellvi, 2004). From derivations based on the one-dimensional (vertical) turbulent diffusion equation, similarity concepts and the ramp model shown in Scheme 2 (Fig. 1b), the following relationship for estimating α over the averaging period (typically half-hour) was proposed when data are collected above but close to the canopy top (Castellvi, 2004)

$$\alpha = \begin{cases} \left[\frac{k}{\pi}\frac{(z-d)}{z^2}\tau\, u_*\phi_h^{-1}(\varsigma)\right]^{1/2} & z > z^* \\ \left[\frac{k}{\pi}\frac{(z^*-d)}{z^2}\tau\, u_*\phi_h^{-1}(\varsigma)\right]^{1/2} & z \leqslant z^* \end{cases} \tag{3}$$

In Eq. (3), d is the zero-plane displacement, z^* is the roughness sub-layer depth, u^* is the friction velocity, $k \approx 0.4$ is the Von Kármán constant, $\varphi h(\zeta)$ is the stability function for heat transfer (valid for any scalar) described below in Eq. (5), and ζ is an stability parameter defined as, $(z-d)/L$, with L being the Obukov length defined by (Brutsaert, 1988) as

$$L = -\frac{u_*^3}{kg(\overline{w'T'_v})}T_v \tag{4}$$

where g is the acceleration due to gravity and T_v is the virtual temperature, which can be replaced with T in dry environments. The accepted formulation for $\varphi h(\zeta)$ from Högström (1988) and Foken (2006) is:

$$\phi_h(\varsigma) = \begin{cases} (0.95 + 7.8\varsigma) & 0 \leqslant \varsigma \leqslant 1 \\ 0.95(1-116\varsigma)^{-1/2} & -2 \leqslant \varsigma \leqslant 0 \end{cases} \tag{5}$$

Determination of the roughness sub-layer depth

For convenience, the z-axis origin is set at the canopy top (height h_c). Thus, $(z^* - h_c)$ defines the sub-layer that extends from the canopy top to the bottom of the inertial sub-layer. It is well-known that similarity does not apply in the roughness sub-layer