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Application of the surface renewal technique in two types of screenhouses: Sensible heat flux estimates and turbulence characteristics

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ABSTRACT

While the usefulness of screenhouses in crop improvement and water savings is rarely disputed in semi-arid regions, reliable evapotranspiration (ET) estimates in screenhouses remain a challenge. The surface renewal (SR) technique utilizes high frequency readings of air temperature near or above the vegetation by low-cost fine-wire thermocouples, to indirectly estimate the sensible heat flux from which the latent heat flux can be estimated assuming energy conservation. The SR technique had been successfully used in open fields, and this research investigates its applicability in screenhouses. Experiments were carried out in two field campaigns, in banana and pepper screenhouses covered with shading and insect-proof screens, respectively. The SR technique was employed by installing several miniature thermocouples at different heights. Reference measurements of sensible heat flux were conducted using the eddy covariance (EC) technique. A calibration coefficient, α, was calculated using linear regressions between SR and EC outputs. In agreement with observations in open fields, in both experiments, α was found to decrease with height, and values were smaller for stable than unstable conditions. In a separate validation period, R^2 reached 0.93 and 0.65 for measurements above the shading and insect-proof screen, respectively. For both the shading and the insect-proof screens, best coefficients of determination (R^2) of these regressions were obtained just above the screen, at 1.02 and 1.12 of the screen height, respectively. Turbulence characteristics were observed to be affected by the porosity of the screen, which is conjectured to be the main cause for reduced performance of the SR technique in the insect-proof than the shading screenhouse. In addition, it was concluded that in screenhouse conditions sampling frequency can be relaxed to as low as 2 Hz with little effect on performance. The specifications provided here allow for a low cost deployment of the SR system in shading screenhouses. Such systems can be available for day-to-day use by farmers to improve irrigation management.

1. Introduction

Covering fruit and vegetable crops with screens is a common practice in Israel, Italy, Spain, Chile and other countries. Under screens, produce quality can increase through modification of the crop microclimate and protection from harsh weather conditions like wind and hail storms and supra optimal solar radiation. However, accurate estimates of irrigation demands under screens are still a challenge. To create better irrigation schemes, both accurate and low-cost quantification of evapotranspiration (ET) is sought. While irrigation demands for crops in open fields are well documented in the literature (Allen et al., 1998), their modifications by different types of screenhouses are less understood.

A widely used and direct method for estimating the water vapor exchange between the crop and the atmosphere is the eddy covariance (EC) technique. While this method has been shown to produce satisfactory estimations of LE, it requires relatively expensive equipment and post-processing capabilities that renders it unattainable for farmers' day-to-day use.

A family of simpler methods relies on estimating the vertical sensible heat flux (H) and deducing LE, either as the residual of the energy balance (by measuring the net radiation and the soil heat flux which are both relatively simple measurements), or by other linear approximations (e.g., the Bowen ratio). A relatively low cost

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Abbreviations: C1, campaign 1 (banana, shading screen, summer 2011); C2, campaign 2 (pepper, insect-proof screenhouse, autumn 2012–spring 2013); DOY, day of year; EC, eddy covariance; ET, evapotranspiration; fTc, fine-wire thermocouple; SR, surface renewal; TCS, turbulent coherent structures.

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Nomenclature

List of symbols

a	Ramp amplitude, in °C
A, B	Regression coefficients of a validation plot
C_p	Specific heat of dry air at constant pressure, in $\mathrm{J\,g^{-1}\,K^{-1}}$
C_v	Volumetric heat capacity of the soil, in $\mathrm{J\,m^{-3}\,K^{-1}}$
C_d	Dry soil heat capacity, in $\mathrm{J\,g^{-1}\,K^{-1}}$
d	Zero-plane displacement, in m
D_i	Duration of quadrant i
f	Sampling frequency, in Hz
f_c	Filtering criterion
G	Soil heat flux, in $\mathrm{W\,m^{-2}}$
h_c and h_s	Canopy and screen height, in m
H	Sensible heat flux, in $\mathrm{W\,m^{-2}}$
H_{NC}	Sensible heat flux estimated by SR method, before calibration, in $\mathrm{W\,m^{-2}}$
H_{SR}	Sensible heat flux estimated by SR method, after calibration, in $\mathrm{W\,m^{-2}}$
H_{EC}	Sensible heat flux measured by EC system, in $\mathrm{W\,m^{-2}}$
j	Time lag in units of samples
l, s	Duration of gradual change in T, quiescent phase, respectively, in s
LE	Latent heat flux, in $\mathrm{W\,m^{-2}}$
LE_{EC}	Latent heat flux measured by EC system, in $\mathrm{W\,m^{-2}}$
N	Number of points in a graph
Q_i	i$^{\mathrm{th}}$ quadrant
r	Time lag, in s
r_{TT}	Two point space-time autocorrelation of the temperature
R^2	Coefficient of determination
$\mathrm{RE_H}$	Relative error of H, between SR and EC reference measurement
R_n	Net radiation flux, in $\mathrm{W\,m^{-2}}$
T	Temperature trace, in °C
V/A	Volume per unit area, in m
z	Sensor height above ground level, in m
z_h	Sensor height normalized to canopy height
z_s	Sensor height normalized to screen and canopy heights
α	Calibration coefficient
α_{st}, α_{uns}	corresponding to stable and unstable conditions
γ	Energy balance closure ratio
ΔT	Temporal temperature difference between two samples separated by time lag r, in °C
ΔT_c, ΔT_r	Coherent and random parts of a ramp-like pattern in ΔT, in °C
λ	Temporal shift in the two point correlation, in s
ρ	Density of air at sea level, in $\mathrm{kg\,m^{-3}}$
τ	$=l+s$; ramp duration, in s
ϕ'	The fluctuating component of ϕ

and simple method by which H can be estimated up to a calibration factor is the surface renewal (SR) method. This technique utilizes high frequency (~10 Hz) temperature traces collected by a fine-wire thermocouple (fTc). A statistical analysis filters out noise and reveals a ramp-like pattern of the temperature time-series. The sensible heat flux H is assumed to be linearly dependent on the ratio between the ramp amplitude and duration.

The SR technique has been successfully applied to a wide range of agricultural crops in open fields, where it has been shown that the SR calibration factors depend on the measurement height, and stability conditions (Paw U et al., 2009). However, the utility of the SR method in plantations covered by screens remains underexplored (Mekhmandarov et al., 2012).

1.1. Turbulent coherent structures and the SR mechanism

Current paradigms of turbulent flow near plant canopies are based on the dominance of turbulent coherent structures (TCS) (Finnigan, 2000). TCS can be classified into several distinct types, amongst which are ejections and sweeps (Antonia, 1981). These are commonly observed in shear flows over vegetated canopies, and are considered to be responsible for the observed ramp-like structures in scalar traces near canopies (Paw U et al., 1992; Gao et al., 1989; Shaw and Periera, 1982).

In a thermally stratified boundary layer ejections and sweeps would replace the volume of air which was previously in contact with the surface. During its residence time near (or within) the canopy, the "parcel" of air exchanges heat with the canopy via convection. This gradually increases (or decreases) the mean temperature of the air parcel, which is manifested as a ramp-like pattern in the temperature trace. The SR method is based on this exchange of air parcels and allows estimation of the sensible heat flux via a weighting factor that partially depends on the eddy penetration into the canopy. The method requires calibration for specific crop type, sensor height, and stability conditions (in the thermal sense). A summary of the development and refinement of the SR method, including its development by Higbie (1935) and its first application in vegetated canopies (Paw U et al., 1995) can be found elsewhere (Katul et al., 1996 pp. 251, 253; Paw U et al., 2009). Typically the ramp is characterized by its ramp amplitude, a, and duration (or period), τ, which is comprised of a gradual temperature change, l, and a quiescent phase, s. These parameters can be obtained by the simple structure function approach, suggested by Van Atta (1977) and described below.

1.2. The ramp-like pattern and sensible heat estimates

The temperature difference in time between two samples separated by r, also denoted as the time-lag, is given as (Van Atta, 1977; Chen et al., 1997):

$$\Delta T(t) = T(t) - T(t-r) \tag{1}$$

Van Atta (1977) suggested a Reynolds decomposition to separate the temperature difference into a coherent and a random part, T_c and T_r, respectively:

$$\Delta T = \Delta T_c + \Delta T_r \tag{2}$$

Geometrically, the coherent part consists of a linear ramp with amplitude a that is terminated abruptly after a duration l followed by a quiescent phase of duration s, where the overall period is denoted by τ. The random part consists of small-scale fluctuations superimposed on the coherent part, which are assumed to be locally isotropic, and are the results of fine-scale turbulent flow of air around the sensor.

The expression for H was first suggested by Paw U et al. (1995) as follows:

$$H = \rho C_p \frac{V}{A}\frac{\mathrm{d}T}{\mathrm{d}t} \tag{3}$$

where ρ ($\mathrm{kg\,m^{-3}}$) is the air density and C_p ($\mathrm{J\,kg^{-1}\,K^{-1}}$) is the specific heat of air at constant pressure. The term $\mathrm{d}T/dt$ accounts for the total time derivative (i.e., following the motion) of the air parcel temperature (T). V/A (m) is the volume of air per unit area exchanged between the atmosphere and the canopy. The height of the air parcel's upper edge is assumed to be the sensor height, z, thus $V/A = z$. This assumption is correct up to the first order using the calibration coefficient α, defined below (Eq. (5)).