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Research Paper

Surface renewal and eddy covariance measurements of sensible and latent heat fluxes of cotton during two growing seasons

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Measuring evapotranspiration (ET) of agricultural crops is crucial for accurate irrigation and efficient water management. The surface renewal (SR) technique, which relies on high-frequency measurements of air temperature by a miniature sensor, is a simple technique for estimating ET. Sensible heat flux is estimated from the temperature-time series and evapotranspiration is deduced from the energy-balance closure. We examined the use of the SR technique for cotton, for the first time. Field experiments were carried out at the same site during two consecutive summers, with an eddy covariance (EC) system used for calibration of the surface-renewal weighting factor. Regressions between sensible heat flux values as measured by EC and SR, yielded coefficients of determination of up to 0.86. The SR weighting factor decreased with increasing height but above the canopy top this decrease was small. The ratio between weighting factors obtained during the two years depended strongly on the temperature sensor quality; for the ultrasonic anemometer with a high-frequency response a mean ratio of 0.90 ± 0.06 was obtained. A maximum deviation of 7% was found between daily ET obtained by EC and SR methods during validation. Reducing the frequency of data analysis from the commonly used 10 Hz down to 1 Hz, increased the weighting factor but did not much affect the ET results, which indicates that the SR technique could be realised by using low-cost data acquisition systems.

1. Introduction

In modern irrigation, evapotranspiration (ET) measurements are crucial for sustainable and efficient irrigation management. The most common technique for field-scale ET measurements has been the eddy covariance (EC) method (Anandakumar, 1999; Baldocchi, 2003; Simmons, Wang, Sammis, & Miller, 2007; Wilson, Hanson, Mulholland, Baldocchi, & Wullschleger, 2001). The EC method involves simultaneous high-frequency measurements of vertical air velocity and scalar concentration, followed by computation of their covariance which represents the vertical flux of the measured scalar. Although the EC technique is reliable for research purposes, its applicability at the farm level is limited, mainly because of the high cost of the sensors, complexity of

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Nomenclature

a	Ramp amplitude (C)
b	Slope of the energy-balance equation regression (–)
C_p	Specific heat of air at constant pressure (J kg^{-1} K^{-1})
d	Zero-plane displacement (m)
dT/dt	Total derivative of T with respect to time (C s^{-1})
ET	Evapotranspiration (mmH$_2$O day^{-1})
f	Measurement sampling frequency (Hz)
f_H	Sampling frequency f = 10 (Hz)
f_M	Sampling frequency corresponding to each α_M (Hz)
G	Soil heat flux (W m^{-2})
h	Canopy height (m)
H	Sensible heat flux (W m^{-2})
H_{NC}	Non-calibrated estimate of H with the SR method (W m^{-2})
H_{EC}	H estimated with the EC method (W m^{-2})
H_{SR}	H estimated with the SR method (W m^{-2})
l	Gradually increasing or decreasing temperature ramp period (s)
LAI	Leaf area index (–)
LE	Latent heat flux (W m^{-2})
LE_{EC}	Latent heat flux obtained with EC method (W m^{-2})
LE_{ECf}	Latent heat flux as residual from energy-balance closure (W m^{-2})
LE_{SR}	LE obtained with the SR method (W m^{-2})
r	Time lag used in Structure Functions analysis (s)
R^2	Coefficient of determination of a linear regression (–)
Rn	Net radiation (W m^{-2})
s	Quiescent ramp period (s)
t	Time (s)
T	Temperature (C or K)
u_h	Horizontal wind speed (m s^{-1})
z	Measurement height (m)
z_n	Normalised measurement height (–)

Greek letters

α	Calibration coefficient (weighting factor) of the SR technique (–)
α_H	α obtained by sampling at f = 10 Hz (–)
α_M	α obtained by sampling at frequencies other than 10 Hz (–)
ρ	Air density (kg m^{-3})

Abbreviations

DOY	Day of the year
EC	Eddy covariance method
IRGA	Infrared gas analyser
RMSE	Root mean square error (units depend on the parameter)
S1	Experimental season number 1 (summer 2011)
S2	Experimental season number 2 (summer 2012)
SR	Surface Renewal method
TC	Thermocouples

their operation, and the intensive data analysis. Therefore, in recent years, simpler techniques for ET measurements have been examined.

One of these methods is the surface renewal (SR) technique (Katul, Hsieh, Ellsworth, Oren, & Phillips, 1996; Paw U et al. 1992; Rosa, Dicken, & Tanny, 2013; Spano, Snyder, Duce, & Paw U, 1997), which is based on high-frequency measurement of air temperature near or above the canopy. The SR mechanism is based on the observation that air parcels near the canopy are continuously exchanged with new ones that descend from the atmosphere above. The temperature rise (or drop) for each air parcel during its residence time near (or within) the canopy enables an estimate of the surface sensible heat flux (up to a calibration factor). Hence, temperature time series exhibit ramps associated with turbulent coherent structures that undergo ejections and sweeps. Using structure function theory (Van Atta, 1977) the characteristics of these ramps can be determined from the high frequency temperature time series, thereby enabling an estimate of the sensible heat flux, H_{SR} (W m^{-2}), calculated as (Spano, Snyder, Duce, & Paw U, 2000):

$$H_{SR} = \alpha H_{NC} = \alpha \rho c_p \frac{dT}{dt} z \approx \alpha \rho c_p \frac{a}{l+s} z \qquad (1)$$

in which α is the calibration (weighting) factor, H_{NC} (W m^{-2}) is the non-calibrated sensible heat flux, ρ (kg m^{-3}) is the air density, c_p (J kg^{-1} K^{-1}) is the specific heat of air at constant pressure, T (K) is air temperature, t (s) is time, dT/dt accounts for the total derivative (i.e., following the motion) of the air temperature, a (K) and $(l + s)$ (s) are the ramp temperature amplitude and ramp duration, respectively, and z (m) is the measurement height.

Due to its simplicity and low cost, the SR technique may be more accessible to the individual farmer as an aid for day-to-day irrigation management. However, application of this technique requires adaptation for each crop and agro-environment. Previous studies examined the application of the SR technique for various crops (Anandakumar, 1999; Castellví & Snyder, 2009a, 2009b; Chen, Novak, Black, & Lee, 1997a, 1997b; Mekhmandarov, Pirkner, Achiman, & Tanny, 2015; Mengitsu & Savage, 2009; Moratiel & Martinez-Cob, 2012, 2013; Nile, 2010; Paw U, Qui, Su, Watanabe, & Brunet, 1995; Paw U, Snyder, Spano, & Su, 2009; Poblete-Echeverría, Sepúlveda-Reyes, & Ortega-Farías, 2014; Rosa et al. 2013; Simmons et al. 2007; Snyder & O'Connell, 2007; Snyder, Spano, Duce, Paw U, & Rivera, 2008; Spano et al., 1997, 2000). However, to the best of our knowledge, there has been no report of the application of the SR technique to cotton. Thus, the general goal of the present study was to examine the applicability of the SR technique to cotton, and to provide guidelines for its optimal operation.

The SR technique requires high sampling rate of air temperature signals in order to correctly capture the turbulent motion of ejections and sweeps. In most literature reports sampling rates are usually between 8 and 10 Hz (Rosa, 2012), though sampling frequencies as low as 2 Hz have also been reported (Mengitsu & Savage, 2009). Rosa et al. (2013), in their study of processing tomatoes, were the first to compare