Evaluation of the surface renewal method to estimate crop evapotranspiration of a cotton field

Jose Payero[1,2] and Trevor Harris

[1]Queensland Alliance for Agriculture and Food Innovation (QAAFI), University of Queensland, Email j.payero@uq.edu.au
[2] Agri-Science Queensland, Department of Employment, Economic Development & Innovation, www.deedi.qld.gov.au

Abstract

Crop evapotranspiration (ET) can be directly measured using weighing lysimeters or using micrometeorological methods such as eddy covariance (EC) and Bowen ratio systems. A cheaper alternative is to estimate ET from a given surface as a residual from the one-dimensional energy balance equation using the surface renewal (SR) method. The objective of this study was to evaluate the performance of the SR method with respect to the EC method to estimate daily ET under Australian conditions. Another objective was to test if thermocouple height (TH), time lag (TL), thermocouple (TC) and measurement periods (MP) had an effect on the SR measurements. Concurrent 30-min EC and SR measurements were made on a cotton field near Dalby, Queensland, during 2008-09. Air temperature measurements for SR were made at two heights (1.6 m, 2.0m), using two thermocouples at each height and two time lags (0.25 s and 0.50 s). Results showed that TH, TL, and MP had a significant effect on measured 30-min H with SR. However, when comparing daily ET between SR and EC, good correlation was found and no significant differences were found. These results, however, are preliminary and additional testing with other crops and environments are now underway. These results, however, show potential for using the SR method as a cheaper alternative to lysimeters and EC to directly measure daily ET.

Key Words

Evapotranspiration, Surface Renewal, Eddy Covariance, Cotton

Introduction

Population growth and drought are putting tremendous pressure on already scarce water resources in many parts of the world. The beneficial and efficient use of water is, therefore, a requirement for sustaining and improving our current standard of living. Irrigated agriculture is a main user of water and accurate information on crop water use, usually known as evapotranspiration (ET), is needed for proper irrigation planning and scheduling. Because ET is difficult and expensive to measure, procedures have been developed to estimate it from weather data and empirical factors (crop coefficients) that have been developed for specific crops (Allen et al. 1998). To develop these empirical factors, for new crops or new crop varieties, direct measurements of ET are needed. ET can be directly measured using weighing lysimeters or using micrometeorological methods such as eddy covariance (EC) and Bowen ratio (BR) systems. The instruments needed to apply these methods are expensive, which severely limit the number of measurement sites that can be established in practice. A cheaper alternative is to estimate ET from a given surface as a residual from the one-dimensional energy balance equation using the surface renewal (SR) method to estimate the sensible heat flux (H) component. Since SR uses inexpensive fire-wire thermocouples to measure H, the cost of measuring ET is significantly reduced. This method is relatively new and has been tested by researchers in just a few locations, mainly in California (Paw U et al. 1995; Snyder et al. 2006; Snyder et al. 2007). The objective of this study was to evaluate the performance of the SR method with respect to the EC method to estimate daily ET under Australian conditions. Another objective was to test if thermocouple height (TH), time lag (TL), thermocouple (TC) and measurement period (MP) had an effect on the SR measurements.

Methods

Surface renewal theory

Observations of air temperature and other scalars collected at high frequency are known to show ramp-like behaviour. These ramp-like temperature structures are characterized by gradual increase or decrease in temperature, followed by a sudden drop or increase. Gradual increase and sudden drop occurs during unstable atmospheric conditions, and the opposite occurs during stable conditions. The magnitude and frequency of these ramp-like temperature changes is indicative of the exchange of sensible heat flux (H) between the surface and the atmosphere above. The surface renewal (SR) method estimates H assuming the hypothetical model of the ramps illustrated in Fig. 1, with a transient period, followed by a steady increase or decrease, and then a sudden drop or increase.

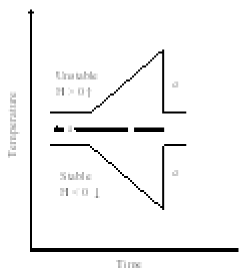

Figure 1. Hypothetical temperature ramps for unstable and stable atmospheric stability conditions. The arrows indicate the direction of heat flux with respect to the surface. H=sensible heat flux, a = ramp amplitude, and (l+s) = inverse ramp frequency.

During a given time period, H is calculated as:

$$H = \alpha \rho C_p \frac{a}{l+s} z \qquad (1)$$

where ρ = air density (kg m^{-3}), C_p = specific heat of air at constant pressure (J kg^{-1} $^{o}C^{-1}$), z = measurement height (m), α = weighting factor (unitless), and a = ramp amplitude (^{o}C), and (l+s) = inverse ramp frequency (in seconds). The α factor accounts for differential heating below the measurement height, since it depends on factors like the characteristics of the surface, measurement height, thermocouple size, etc. It usually needs to be determined empirically as the slope of the line of uncorrected H values determined by surface renewal (H_{SR}) [using Eq (1) for α =1.0] against values determined with eddy covariance (H_{EC}), assuming intercept = 0. To estimate H, a and *(l+s)* are estimated from high frequency temperature data, collected with fine-wire thermocouples, using a structure function (Paw U and Brunet, 1991; Snyder et al., 1996; Spano et al., 1997, Van Atta, 1977) as:

$$S^n(r) = \frac{1}{m-j} \sum_{i=1+j}^{m} (T_i - T_{i-j})^n \qquad (2)$$

where m = number of data points in the time interval measured at frequency f (Hz), n =order of the structure function, j = sample lag between data points corresponding to a time lag (r=j/f, e.g., r=1/4=0.25 s). T_i = $_i$th temperature sample. The values of n =2, 3 and 5 are used to determine the 2^{nd}, 3^{rd} and 5^{th} moments of the structure function. An important restriction of the SR method is that r << (l+s), otherwise, the correct "*a"* and "*l+s*" cannot be determined, which is common when H values are small. When r << (l+s), the values of "*a"* and "*l+s*" can be determined following procedures described by Snyder et al.

(1996). The measured H, combined with measured net radiation (R_n) and soil heat flux density (*G*), can be used to determine the latent heat flux density (*LE*) as:

$$LE = R_n - G - H \qquad (3)$$

where *E* = water vapor flux density (kg?m^{-2}?s^{-1}), *L* = latent heat of vaporization (*L*?≈?2.45?10^{6}?J?kg^{-1}) and all other variables are in W?m^{-2}. Daily ET is obtained by converting LE to water depth (mm).

Field data collection

Data for this study were collected from a cotton (*Gossypium hirsutum L.*) field near Dalby, Australia, during 2008-09. The field had a heavy clay soil and was surface-irrigated using a furrow system with siphon tubes. The field was fully-irrigated to prevent water stress during the entire season to maximise yield. A Bollgard II cotton variety was planted at 1 m spacing in mid October 2008 and was harvested in early May 2009. An eddy covariance (EC) and a surface renewal (SR) system were installed side by side in the middle of the field, with the distance from the edge of the field exceeding 200 m in all directions. The data collection period was from 9 March to 20 May 2009. However, the eddy covariance system failed twice due to power loss and no EC data were available from 19 to 26 March and from 6 to 26 April. There were no problems with the SR system. Therefore, EC data were available for three periods, 9 to 18 March (Initial), 27 March to 5 April (Mid), and 27 April to 20 May (End).

For the SR system, two pairs of 76.2 ?m diameter thermocouples were used, one pair was installed at 1.6 m above the soil surface and the other at 2.0 m. Air temperature data was sampled at a frequency of 4 Hz (every 0.25 s) using a CR1000 datalogger. The datalogger then calculated and recorded 30-min averages of the 2nd, 3rd, and 5th moments of the structure function [Eq(2) with n = 2,3 and 5] for time lags of 0.25 and 0.50 seconds. Data was downloaded to a computer and H was then calculated for each thermocouple, measurement height, and time lag (8 H values) using the SR_Excel spreadsheet (Snyder et al. 2006). The EC system (Campbell Scientific, Inc., Logan, Utah) measured all the components of the energy balance equation [Eq. (3)], in addition to CO_2 flux. Both systems were powered by marine deep-cycle batteries charged by solar panels. Data from the EC system was recorded by a CR3000 datalogger.

Results

Comparison of LE from SR and EC

Table 1 shows that the measured 30-min H values were significantly affected by thermocouple height (TH), time lag (TL) and measurement period (MP), but not by thermocouple (TC). However, although significant differences were detected, the absolute differences were relatively small. Considering that the magnitude of R_n in Eq. 3 is much higher than H, these small differences in H would have little impact on daily LE (same as ET). Comparison of daily LE values from SR and EC are shown Fig. 2. Results of regression analysis and t-test are shown in Table 2. Although with some outliers, values roughly followed the 1:1 line and the slope of the line was close to 1.0 in most cases. The t-test showed no significant differences between the daily ET values from SR and EC.

Table 1. Treatment means and results of analysis of variance (ANOVA) for 30-min uncorrected sensible heat flux (H, W / m^2) measured with surface renewal at two thermocouple heights (TH =1.6m and 2.0m), two thermocouples (TC) at each height (TC1 and TC2), two time lags (TL = 0.25s and 0.50s) and three measurement periods (MP = Early, Mid and End) in a cotton field near Dalby.

Thermocouple height (TH) = 1.6m	Thermocouple height (TH) = 2.0m

	TC1	TC1	TC2	TC2	**TC 1**	**TC2**	**1.6m**	TC1	TC1	TC2	TC2	**TC 1**	**TC 2**	**2.0 m**
MP	0.25 s	0.50 s	0.25 s	0.50 s	**Av g**	**Avg**	**Avg**	0.25s	0.50s	0.25s	0.50 s	**Av g**	**Av g**	**Avg**
Initial	61	28	57	27	**43**	**40**	**42**	67	26	76	32	**43**	**51**	**47**
Mid	96	53	100	52	**72**	**72**	**72**	110	62	117	74	**83**	**93**	**88**
End	157	96	159	103	**121**	**126**	**123**	164	102	170	102	**128**	**129**	**128**
Avg	**123**	**74**	**124**	**77**	**95**	**97**	**96**	**134**	**80**	**140**	**83**	**103**	**107**	**105**

ANOVA

	Treatment				**Treatment Interaction**				
	TH	**TC**	**TL**	**MP**	**THxTL**	**TCxTL**	**THxMP**	**TCxMP**	**TLxMP**
Pr(>F)	**	ns	***	***	ns	ns	ns	ns	**
df	**1**	**2**	**1**	**1**	**1**	**2**	**1**	**2**	**1**

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1, TH=thermocouple height, TC = thermocouple, TL = time lag, MP= measurement period, ns=not significant, df=degrees of freedom.

Table 2. Results of regression analysis and two-sample t-test comparisons between daily crop evapotranspiration (ET) measured with the surface renewal and eddy covariance methods in a cotton field near Dalby. The labels 1.6m and 2m are the measurement heights above the soil surface, TC1 and TC2 are each of two thermocouples used at each height, and 0.25s and 0.50s are the time lags used to estimate the sensible heat flux (H).

Analysis/	1.6m	1.6m	1.6m	1.6m	2.0m	2.0m	2.0m	2.0m
Parameter	TC1	TC1	TC2	TC2	TC1	TC1	TC2	TC2
	0.25s	0.50s	0.25s	0.50s	0.25s	0.50s	0.25s	0.50s
Regression:								

Intercept	0.280	0.174	0.258	0.170	0.460	0.243	0.386	0.198
Slope	0.921	0.983	0.961	0.982	0.880	0.956	0.910	0.977
R^2	0.45	0.55	0.45	0.54	0.36	0.50	0.37	0.49
df	38	38	38	38	38	38	38	38
t-test:								
Mean LE-SR (mm/d)	1.87	1.86	1.82	1.86	1.76	1.85	1.79	1.85
Mean LE-EC (mm/d)	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Pr>|t|	0.62(ns)	0.59(ns)	0.51(ns)	0.60(ns)	0.40(ns)	0.56(ns)	0.44(ns)	0.57(ns)

ns=no significant, df=degrees of freedom, SR=Surface renewal, EC=Eddy covariance

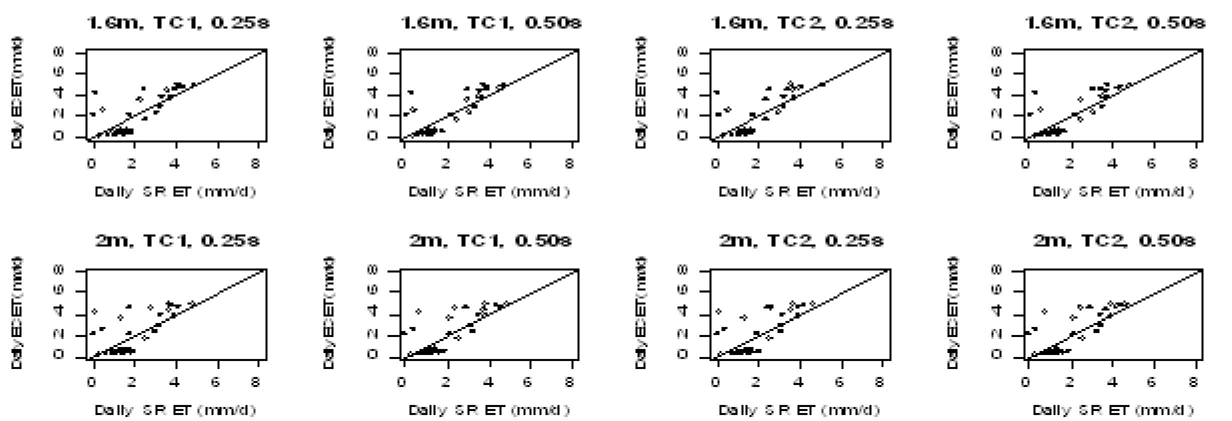

Figure 2. Comparison of daily evapotranspiration (ET) measured with surface renewal (SR) and Eddy covariance (EC) over a cotton field near Dalby during 2008-09. The labels 1.6m and 2m are the measurement heights above the soil surface, TC1 and TC2 are each of two thermocouples used at each height, and 0.25s and 0.50s are the time lags used to calculate H (H corrected using intercept=0).

Conclusions

Results showed no significant differences in daily ET measured with SR and EC under the conditions of this study. Because of failure of the EC systems during some periods, the number valid values of H and LE from EC were much less than those available from SR, which limited the comparison. These results, therefore, are preliminary and additional testing with other crops and environments are now underway. These results, however, show potential for using the SR method as a cheaper alternative to lysimeters and EC to directly measure daily ET. There is, however, a need to develop procedures to fill missing data for times when the assumptions of the SR method are not met.

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