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TECHNICAL COMPLETION REPORT

Project Number UCAL-WRC-W-797

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University of California Water Resources Center

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ABSTRACT

This project considers the micrometeorological processes that govern the use of water by plants and the availability of soil moisture. Evapotranspiration (ET) was obtained from the residual of the energy budget terms, including a new method, that of surface renewal, to estimate one of the energy budget terms. This method appears to offer some alternative to somewhat more cumbersome methods presently used for ET estimates and crop coefficients. Evapotranspiration estimates are considered very important to the state because evapotranspiration represents the major component of agricultural water usage.

Data from experiments carried out in 1988 through 1994 were analyzed to validate the new method. The plant canopies considered in these experiments were an English walnut orchard, a maize canopy, a grass canopy, and other short. Sensible heat was estimated using the eddy-covariance and other methods, and then compared to the new method. Project results show that regression of sensible heat flux density obtained from the surface renewal method against eddy correlation/covariance yields reasonable fits under stable conditions (standard errors of less than 20 W m^{-2}), when data were filtered or when the structure function was used. Analysis also showed the method could be used over grass and other short crop canopies, if a height greater than the canopy height was used. Some preliminary comparisons with ET data were made for some canopies.

KEY WORDS: Evapotranspiration, atmosphere, models and processes, microclimate and microclimatology.

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PROBLEM AND RESEARCH OBJECTIVES

Evapotranspiration from plant canopies is not easy to measure or estimate. Various methods are currently being used to assist in applying reference evapotranspiration (defined as evapotranspiration from a reference surface such as a grass surface which is well-irrigated and non water-stressed) to actual evapotranspiration from crop, orchard and wildland surfaces. The present method is potentially more economical to use, for the estimation of evapotranspiration.

Our objectives were:

(1) To use fast response temperature signals to estimate sensible heat, and with other energy budget measurements, estimate evapotranspiration, over plant canopies including crops and orchards.

(2) To determine the accuracy of the methods by validation with eddy-covariance and possibly other measures of sensible heat and evapotranspiration.

(3) To simplify the methods if they are shown to be accurate, so that they may be easily employed.

METHODOLOGY

Our overall objectives focused on estimating evapotranspiration, using the energy balance of a plant canopy. The energy balance of a plant canopy, such as a crop or an orchard, can be summarized as the balance between radiation received from the atmosphere, net radiation $\boldsymbol{R_n}$, convective and conductive exchange between the plants and the atmosphere, sensible heat $\boldsymbol{H}$, latent energy $\boldsymbol{LE}$ used in evapotranspiration ($\boldsymbol{ET}$), and the conductive energy exchange with the soil below a surface ($\boldsymbol{G}$):

$$R_n - G = H + LE$$

The above equation can be rearranged, to allow solution for $\boldsymbol{LE}$,

$$LE = R_n - G - H$$

and then using the identity that $ET = LE/L$, where L is the latent energy per unit mass for evaporation of water, one obtains the following equation for ET:

$$ET = \frac{R_n - G - H}{L}$$

Therefore, evapotranspiration (ET) can be calculated from the separate energy budget components. Within acceptable error margins, net radiation R_n and G can be measured using instruments (net radiometer, ground heat flux plates and soil temperature). The remaining term, the sensible heat H, is somewhat harder to measure. One general accepted method, eddy-covariance, relies on the fast-response sensing of wind velocity and temperature. The wind velocity measurement is frequently rather expensive, requiring equipment, which costs between \$2,000 and \$25,000, in the form of ultrasonic or sonic anemometers. Instead, we used a newly developed "surface renewal" method, created by the P.I. and his colleagues a few years ago.

In this method, the sensible heat flux is estimated by assuming the this heat exchange occurs during 'ramp' patterns of air temperature, which represents the heating or cooling of air by the plant canopy elements (see figures 1 and 2). The method does not require expensive and complicated velocity field measurements, but only requires fast-response temperature measurements. The first way in which the surface renewal method was applied involved using the expression,

$$H = \frac{\alpha}{2} \rho C_p \frac{\partial T}{\partial t} h_c + b$$

where α and b are semi-empirical constants, ρ is the air density, C_p is the specific heat of air, h_c is the canopy height (also the measurement height), and T is the air temperature (Snyder and Paw U, 1994; Paw U et al., 1995). The time derivative of the air temperature was determined by subtraction of the preceding points in time from current points in time, after passing the temperature signal through a Butterworth filter (Paw U et al., 1995).

In the second way to perform surface renewal analysis, the heating and cooling rate is determined from the calculation of the ramp shape and repetition interval (Paw U and Su, 1994; Paw U et al., 1995; Snyder et al., 1996), based on the following derived equation:

$$H = \alpha\rho C_p \frac{a}{l+s} z_c + b$$

where $\boldsymbol{a}$ is the amplitude of temperature ramp patterns, $(l+s)$ is the time between repetition of the ramp patterns, and $\boldsymbol{z_s}$ is the height of measurement, usually that of the canopy height.

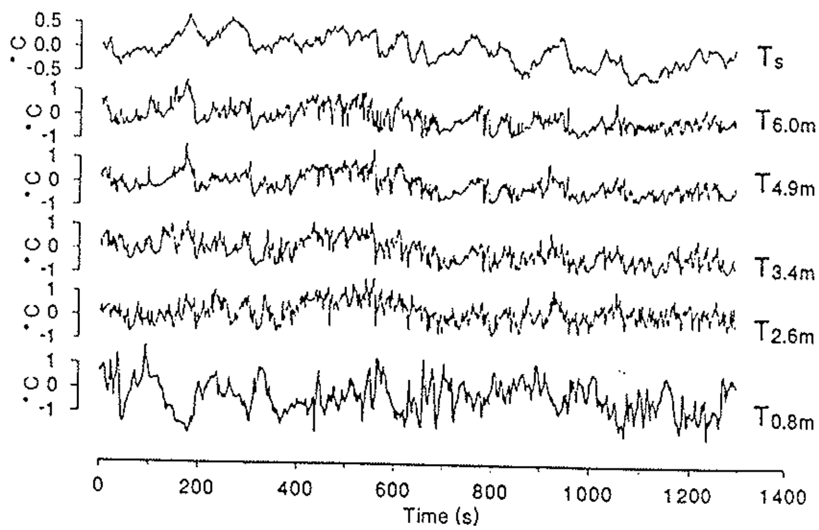

Figure 1. Temperature Trace Example. Typical ramp features evident in a temperature trace, taken from Paw U et al., 1992, over a maize (corn) canopy.

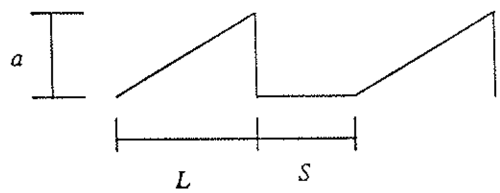

Figure 2. Idealized ramps. Pattern showing the definition of the ramp amplitude ***a***, the ramp duration ***l*** and the spacing between ramps, ***s***.

The structure function method provides the terms *a* and (*l*+*s*) from fast-response temperature time traces (Paw U and Su, 1994; Snyder et al., 1996). By definition, the nth order structure function for temperature is:

$$Sr^n(r) = \frac{1}{m}\sum_{i=1}^{m-r}[T(i+r) - T(i)]^n$$

where r is the structure function time lag, m is the number of data points, and i is the data point number. The terms ***a*** and (***l***+***s***) are estimated from calculations of the second, third, and fifth moment structure functions derived from measured data, using the cubic,

$$a^3 + [10Sr^2 - \frac{Sr^5}{Sr^3}]a + 10Sr^3 = 0$$

and

$$l + s = \frac{a^3 r}{S r^3}$$

In our project, we used measurements previously gathered in 1988 in Davis, California over a maize canopy, in 1989 over a walnut orchard in Winters, California (Paw U et al., 1992), and in 1987 in a deciduous forest in the Camp Borden military reserve, Ontario, Canada. Measurements were also carried out in 1994 over tall fescue grass in Davis, California (Snyder et al., 1996). These measurements yielded high-frequency (10 Hz) temperature and velocity data, gathered with fast-response ultrasonic ('sonic') anemometers and fine-wire thermocouples.

RESULTS AND DISCUSSION

Our first section of research, to examine the feasibility of using surface renewal analysis to estimate the sensible heat flux, yielded some exciting results. When we used Butterworth filtering and raw data to obtain the temperature ramp amplitudes, the sensible heat as estimated with surface renewal analysis matched eddy-covariance within reasonable accuracy limits under stable conditions (standard errors of less than 20 W m^{-2}, Paw U et al., 1995). Unstable conditions exhibited slightly greater errors when using this methodology (figure 3). The factor α was close to 0.5 when the Butterworth filtering was used, but much less than 0.5 when raw data were used (Paw U et al., 1995). These errors were attributed to inaccurate assessment of the temperature ramp amplitudes using raw data, and violation of the assumptions made for surface renewal analysis under certain conditions.

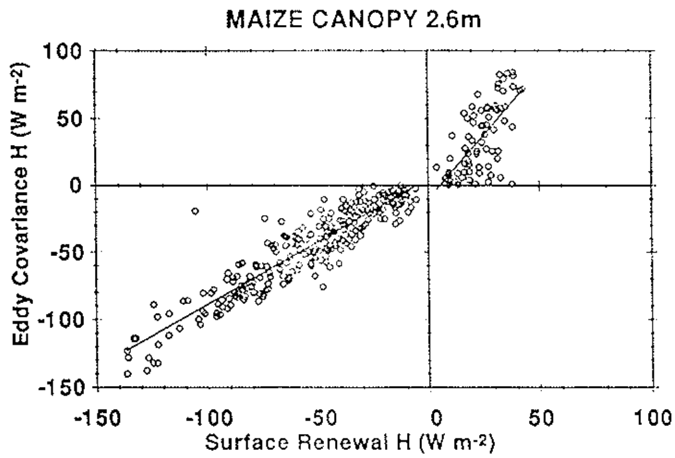

Figure 3. Surface renewal analysis compared with eddy-covariance data. Analysis is based on low-pass Butterworth filtering, taken from Paw U et al., (1995), for measurements taken at the canopy height over a maize crop.

In our second section of research, we simplified the method by using structure functions (Paw U and Su, 1994; Snyder et al., 1996) yielding better results with α set to fixed values (0.25 for unstable and 0.7 for stable atmospheric conditions) based on preliminary trials (Paw U and Su, 1994), for temperature measurements taken at the canopy height (figure 4). When tested over a short fescue grass canopy, the measurements were taken at some height above the canopy. In this case α was very close to unity (ranging from 0.93-1.16), which raised the issue that α may not be a universal constant, but may vary with canopy height, canopy density, and measurement height.

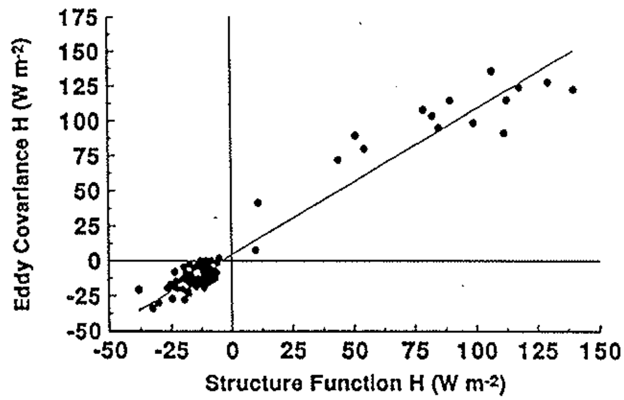

Figure 4. Surface renewal analysis and eddy-covariance. Taken from Paw U and Su (1994), for measurements taken at the canopy height over a maize crop, and data analyzed with structure functions.

Regression of sensible heat flux density obtained from the surface renewal method against eddy correlation/covariance yielded reasonable fits under stable conditions (standard errors of less than 20 W m^{-2}), when data were filtered with a Butterworth filter or when the structure function was used. Analysis also showed the method could be used over grass and other short crop canopies (See table 1), if a height greater than the canopy height was used (Snyder et al., 1996). Some preliminary comparisons with ET data were made for some canopies, shown if figure 5 (Snyder et al., 1996), showing excellent agreement between eddy-covariance derived ET and that calculated using the known energy budget terms.

Table 1. Regression equations and coefficients over a grass surface, for Sensible Heat.

Height (m)	Equation	R^2	Standard Error ($W\ m^{-2}$)
0.3	y=1.03x	0.98	12.1
0.6	y=0.98x	0.98	12.4
0.9	y=0.96x	0.94	19.4
1.2	y=0.93x	0.89	25.4

PRINCIPAL FINDINGS AND SIGNIFICANCE

We have found that a new method for determining one energy budget term, the sensible heat flux density, is very promising. The possibility of using this method is exciting, because it is simpler and more economical to use the conventional micrometeorological methods such as eddy-covariance. This surface renewal method was able to estimate sensible heat exchange very accurately, and latent energy with even more accuracy. However, the method also appears to require calibration, because of a coefficient that does not seem constant and may depend on measurement and plant canopy height. This coefficient may also depend on the type of instrument used to measure temperature fluctuations. We recommend further study to determine how the method may be improved, and to quantify the factors that influence the coefficient α.

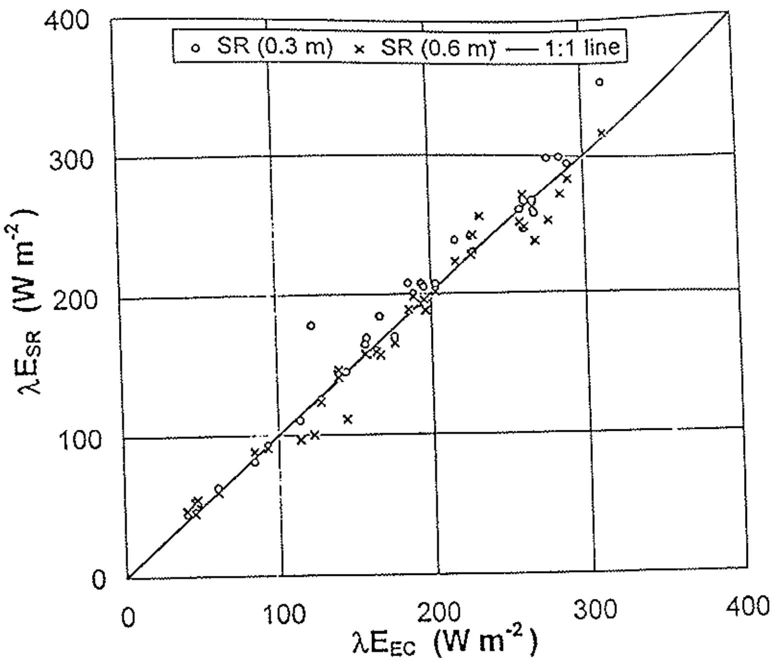

Figure 5. Evapotranspiration expressed as latent energy flux density. From surface renewal analysis at several heights above a 0.1 m high fescue grass, for 37 half-hour periods during 1994 (Snyder et al., 1996)

SUMMARY

A new method for determining evapotranspiration and sensible heat exchange has been developed. It is based on the surface renewal concept that temperature fluctuations in the atmosphere, close to a surface or plant community, reflect heating or cooling caused by the surface. Quantification of the 'ramp' patterns of temperature yields estimates of heat exchange, which when combined with net radiation and ground heat storage, can produce latent energy or evapotranspiration estimates.

We tested this method for several types of plant canopies, using several variants of the method. The method was found to be potentially very accurate, almost to the accuracy of two identical types of sensors inter-compared. However, because an adjustable coefficient must be introduced in some cases, further study is warranted over different plant covers and at different measurement heights, to make the method more universal.

ACKNOWLEDGMENTS

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PUBLICATIONS AND PROFESSIONAL PRESENTATIONS

Publications in Refereed Journals

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Presentations & unrefereed publications

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GRADUATE STUDENT TRAINING

Note: Although several bachelor's level and graduate students worked under this grant, the topics of the graduate theses were not directly covered in this report, because their work and training for this grant was not directly within their theses areas. Instead, the supported students worked on analyzing the experimental data reported in the papers listed as products of this grant and summarized in this report.

Stuart Malkin, 1992-1994 support, B.S. in Atmospheric Science

Jie Qiu, 1992-1993 support, Ph.D. in Atmospheric Science

Alistair Moles, 1993-1994, M.S. in Atmospheric Science in progress