Resistance-energy Balance Method for Predicting Evapotranspiration: Determination of Boundary Layer Resistance and Evaluation of Error Effects

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ABSTRACT

Accurate estimates of evapotranspiration (ET) over large areas are needed for hydrologic studies, irrigation planning and scheduling, and other practices related to efficient utilization of water resources. One approach is the use of a resistance-energy balance model of ET, the data for which can be supplied, in part, by remote sensing and in part from easily accessible records of National Weather Service observations. This model requires measurement of boundary layer resistance, crop and air temperature, net radiation, and soil heat flux. The objectives of this paper are i) to test the utility of the proposed model, ii) to determine boundary layer resistance at varying stages of crop growth, and iii) to evaluate the relative influence of errors in measurement of the meteorological and crop input parameters used.

Measurements were made in fields of sorghum [*Sorghum bicolor* (L.) Moench] and millet (*Panicum meliaceum* L.) grown at Mead and Mitchell, Neb. Boundary layer resistance was estimated from friction velocity measurements used in a stability-corrected aerodynamic method. Friction velocity was computed by means of the Deacon-Swinbank approach. Evapotranspiration rates estimated by the resistance model compared well with results of lysimetric and energy balance measurements, on both a short-period and a daily basis.

The error analysis, in conjunction with field measurement, indicates that the resistance model evapotranspiration estimates are quite sensitive to errors in crop temperature measurement, especially in nonadvective conditions, but are less strongly affected by errors in the estimation of boundary layer resistance.

Additional index words: **Sorghum, *Sorghum bicolor* (L.) Moench, Millet, *Panicum meliaceum* L., Advection, Lysimeters, Energy Balance, Error Analysis, Micrometeorology, Microclimate, Stability correction, Exchange coefficient, Turbulent transfer, Sensible heat transfer, Latent heat transfer.**

EVAPOTRANSPIRATION models which consider the effects of both meteorological and plant variables have been proposed by Raschke (1960), Monteith (1963), Wiegand and Bartholic (1970), Brown and Rosenberg (1973), and others. These models take into account the resistance to flow of water vapor through the stomates of plant leaves and the resistance to heat and/or water vapor transport across the turbulent boundary layer. Tanner (1963) and Phillip (1966) have presented theoretical objections to the application of such models to crop surfaces. They argue that the location of sinks and sources of sensible heat, latent heat, and momentum within a crop canopy may not be identical, and that the boundary layer resistance value obtained from sensible heat transfer may differ from that applicable to latent heat transfer. Nevertheless, Black et al. (1970), Brun et al. (1972), and Brown and Rosenberg (1973) have found that resistance models provide reasonably accurate evapotranspiration estimates.

The resistance model (e.g., Rosenberg, 1974 p. 84 and 168) considered in this paper is:

$$LE = -(A + Rn + S) = -\left(\rho C_p \frac{T_a - T_c}{r_a} + Rn + S\right) \quad [1]$$

where LE, A, Rn, and S are the flux densities of latent heat, sensible heat, net radiation, and soil heat, respectively. Ta_a is the air temperature; T_c, the crop temperature; ρ, the air density; C_p, the specific heat at constant pressure; and r_a, the boundary layer resistance. Rn, S, and T_a can be measured routinely. T_c can be measured with leaf thermocouples and/or thermal radiometers (Blad and Rosenberg, 1976). In order to use the resistance model however, information is needed about r_a over various crops and the functional relationship of r_a with the controlling meteorological parameter — windspeed.

Stone and Horton (1974) and others have attempted to estimate r_a based on an equation of the type:

$$r_a = (k^2U)^{-1} \ln (z-d)/z_o, \quad [2]$$

where U is the windspeed at an elevation z; d, the zero plane displacement; z_o, the roughness parameter; and k, the von Karman constant. This method requires measurements of z_o and use of the assumption of equality in the exchange coefficient for heat (K_h) and momentum (K_m) transfer. The estimation of z_o is subject to large errors. Also, the assumption $K_h = K_m$ is strictly valid for conditions of neutral atmospheric stability which prevail, generally, for only very short periods of time. Under non-neutral conditions this assumption may lead to significant errors.

In this paper we evaluate r_a by means of measurements of friction velocity applied to an aerodynamic method corrected for atmospheric stability conditions (details given in the next section). We employ the Deacon-Swinbank approach (Deacon and Swinbank, 1958; Bradley, 1972; Pierson and Jackman, 1975) to obtain values of the friction velocity. Results obtained in fields of sorghum [*Sorghum bicolor* (L.) Moench] grown at Mead and millet (*Panicum meliaceum* L.) grown at Mitchell, Neb. are presented. The r_a values so obtained are used in the resistance model (Eq. 1) to provide estimates of evapotranspiration rate. These computed results are compared with lysimetric and Bowen ratio-energy balance measurements. An error analysis is also presented in which we evaluate the relative influence of errors in measurement of each of the input parameters used in the resistance model.

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METHODS

Theoretical Considerations

From Eq. [1], sensible heat flux A is given by:

$$A = \rho\, C_p\, (T_a - T_c)/r_a. \quad [3]$$

The exchange of sensible heat is a turbulent process. Vertical flux of sensible heat can also be written as:

$$A = \rho\, C_p\, K_h\, (\partial T)/(\partial z), \quad [4]$$

where K_h = turbulent exchange coefficient for heat transport, $\partial T/\partial z$ = temperature gradient, and z = distance in vertical direction.

Equation [4] can be rewritten as:

$$A = \rho\, C_p \left(\frac{K_h}{K_m}\right) K_m \frac{\partial T}{\partial z}$$

$$A = \rho\, C_p \left(\frac{K_h}{K_m}\right) \frac{u_*^2}{\left(\frac{\partial U}{\partial z}\right)} \frac{\partial T}{\partial z}. \quad [5]$$

where K_m = exchange coefficient for momentum transfer = $u_*^2/(\partial U/\partial z)$, u_* = friction velocity, and $\partial U/\partial z$ = wind speed gradient.

From Eq. [3] and [5]

$$r_a = \frac{(T_a - T_c)\left(\frac{\partial U}{\partial z}\right)}{\left(\frac{K_h}{K_m}\right) u_*^2 \left(\frac{\partial T}{\partial z}\right)}, \quad [6]$$

$$r_a = \frac{U}{\left(\frac{K_h}{K_m}\right) u_*^2}. \quad [7]$$

where U and T_a are the wind speed and air temperature measured at an elevation z. It is assumed that the effective crop temperature T_c is applicable at an elevation $z = d + z_0$, where d is the zero plane displacement and z_0 the roughness parameter.

Stability corrected flux-gradient formulae have been proposed as the result of recent micrometeorological investigations. The formulae used in this study are given below:

$K_h/K_m = (1\text{-}16\ Ri)^{0.25}$ for unstable stratification (Dyer and Hicks, 1970);

$= 1$ for stable stratification. [8]

where Ri = Richardson number $= g\ (\partial\Theta)/(\partial z)\Theta^{-1}\ (\partial U)/(\partial z)^{-2}$, Θ = virtual potential temperature and g = acceleration due to gravity. These relationships have been tested successfully over an oat (*Avena sativa* L.) field (Verma and Rosenberg, 1975).

Friction velocity (u_*) values were determined by Deacon and Swinbank's method (1958) where:

$$\text{shearing stress } \tau = \rho u_*^2 = \rho C_r^2 U_r^2 \quad [9]$$

$$\text{or } C_r = (u_*)/(U_r). \quad [10]$$

C_r is the drag coefficient[a] and U_r is the wind speed measured at some reference elevation z_r.

C_r may vary with thermal stability, but for $z_r - h \leqslant 0.5$ m (h = crop height), this variability is negligibly small (Deacon and Swinbank, 1958). Therefore C_r (with $z_r - h \leqslant 0.5$ m), once determined in neutral stability, can be used in conjunction with U_r in any stability (unstable to slightly stable) to provide a measure of u_* (Bradley, 1972). Recently Pierson and Jackman (1975) tested a number of flux-gradient type evapotranspiration estimation methods on an irrigated turfgrass field surface. They found that the Deacon-Swinbank approach when used with proper stability correction, agreed quite closely with direct measurements (lysimetric) of latent heat flux.

From wind speed profiles measured under nearly neutral conditions, we computed values of C_r as follows:

$$C_r = \frac{k\,(U_2 - U_1)}{U_r\left(\ln\frac{z_2 - d}{z_1 - d}\right)} \quad [11]$$

where U_1 and U_2 wind speeds at elevations z_1 and z_2. Values of C_r ranged from 0.152 to 0.183 for the sorghum (16 July - 26 Aug. 1974; h ≈ 103 to 128 cm; d/h = 0.55 to 0.65; $C_r = u_*/U_{150}$ cm) and from 0.15 to 0.16 for millet (16 to 25 Aug. 1974; h ≈ 75 to 80 cm; d/h = 0.65; $C_r = u_*/U_{110}$ cm).

[a] In classical fluid dynamics the drag coefficient has been alternatively defined as $2\,(u_*)/(U_r)^2$. Our definition of C_r is similar to that of Bradley (1972). z_r is simply a reference elevation. At times it might be convenient to choose $z_r = z_1$.

Experimental Details

Measurements were made over sorghum and millet at the Univ. of Nebraska's Agric. Meteorology field laboratories during July and August 1974. Sorghum was grown at the laboratory near Mead (41° 09′ N 96° 30′ W; 354 m above m.s.l.) and millet at the laboratory near Mitchell (40° 57′ N 103° 41′ W; 1,225 m above m.s.l.). The sorghum and millet were planted on 16 May 1974 and 19 June 1974, respectively. Data presented in this paper were obtained only during those periods when fetch from field edge to the micrometeorological instrumentation was at least 125 to 150 m. During these studies the height of the sorghum was 100 to 128 cm and the millet 75 to 80 cm.

The effective crop temperature was measured with thermocouple junctions (30 gage, copper-constantan) connected in parallel and inserted into the midribs of six leaves in the upper part of the plant canopies (Blad and Rosenberg, 1976). Thermocouple junctions were moved to a new set of leaves every 2 days.

Air temperature and vapor pressure profiles were measured (at four elevations in 1-m air layer above the canopy) with thermocouple psychrometer assemblies described by Rosenberg and Brown (1974). Profiles of windspeed were measured (at five elevations in 1.5-m air layer above the canopy) with three-cup light chopping Casella anemometers [model 442 (2)].

Net radiation was measured with Swissteco net radiometers (Type S-1). Soil heat flux was obtained with heat flux plates buried about 4 cm deep in the soil. A direct measure of evapotranspiration rate was obtained with van Bavel-Myers type precision weighing lysimeters (modified by Rosenberg and Brown, 1970).

Temperature (crop and air), vapor pressure, net radiation, and soil heat flux were measured every 7 min. Windspeed and lysimeter weight change were measured every 15 min. Data were logged on punch paper tape with an automatic analog to digital data system. The data were converted from the digitized emf or count record of individual sensors into parametric forms with a series of computer programs. All data were averaged over half-hour periods.

Error Analysis

The magnitude of errors (or a measure of the uncertainty interval) in the calculation of LE by Eq. [1] due to the errors in measurement of the constituent input parameters are estimated below by the "root sum square" error analysis technique of Kline and McClintok (1953). LE is estimated by Eq. [1]:

$$LE = -[\rho C_p\, (T_a - T_c)/(r_a) + Rn + S], \quad [1]$$

and the error in LE, σ(LE), is estimated by:

$$\sigma(LE) = \left[\left[\frac{\partial(LE)}{\partial(T_a - T_c)}\sigma(T_a - T_c)\right]^2 + \left[\frac{\partial(LE)}{\partial r_a}(\sigma r_a)\right]^2 + \left[\frac{\partial(LE)}{\partial(Rn+S)}\sigma(Rn+S)\right]^2\right]^{1/2} \quad [12]$$

or,

$$\sigma(LE) = \left[\left[\frac{\rho C_p\, \sigma(T_a - T_c)}{r_a}\right]^2 + \left[\frac{-\rho C_p\, (T_a - T_c)\,\sigma(r_a)}{r_a^2}\right]^2 + |\sigma(Rn+S)|^2\right]^{1/2} \quad [13]$$

Table 1. Relative errors in LE as functions of input parameters and associate errors.

Input Parameters			Evapotranspiration	Relative errors in LE: $\sigma(r_a)/r_a = 0.10$, $\sigma(T_a-T_c) = 0.5$ C, $\sigma(Rn+S)/(Rn+S) = 0.05$				$\sigma(r_a)/r_a = 0.20$, $\sigma(T_a-T_c) = 0.5$ C, $\sigma(Rn+S)/Rn+S = 0.05$	$\sigma(r_a)/r_a = 0.10$, $\sigma(T_a-T_c) = 1.0$ C, $\sigma(Rn+S)/Rn+S = 0.05$	$\sigma(r_a)/r_a = 0.10$, $\sigma(T_a-T_c) = 0.5$ C, $\sigma(Rn+S)/Rn+S = 0.10$
Rn + S ly min^{-1}	r_a sec cm^{-1}	T_a-T_c C	LE ly min^{-1}	$\frac{(\sigma LE)_T}{LE} \times 100$	$\frac{(\sigma LE)r_a}{LE} \times 100$	$\frac{(\sigma LE)_{Rn+S}}{LE} \times 100$	$\frac{\sigma(LE)}{LE}$ 100		$\frac{\sigma(LE)}{LE} \times 100$	
				%						
0.8	0.3	2.6	-0.94	2.9	-1.5	4.3	5.3	5.9	7.3	9.1
0.8	0.2	2.6	-1.01	4.0	-2.1	4.0	6.0	7.0	9.2	9.1
0.8	0.1	2.6	-1.22	6.7	-3.5	3.3	8.2	10.1	14.1	9.9
0.8	0.3	1.0	-0.85	3.2	-0.6	4.7	5.7	5.8	7.9	9.9
0.8	0.2	1.0	-0.88	4.6	-0.9	4.5	6.5	6.7	10.3	10.2
0.8	0.1	1.0	-0.96	8.5	-1.7	4.2	9.6	10.0	17.5	12.0
0.8	0.3	-2.6	-0.66	4.1	2.1	6.1	7.6	8.5	10.4	13.0
0.8	0.2	-2.6	-0.59	6.9	3.6	6.8	10.3	12.1	15.8	15.7
0.8	0.1	-2.6	-0.38	21.6	11.2	10.6	26.5	32.9	45.9	32.3
0.8	0.3	-1.0	-0.75	3.6	0.7	5.4	6.5	6.6	9.1	11.4
0.8	0.2	-1.0	-0.72	5.7	1.1	5.6	8.0	8.3	12.7	12.5
0.8	0.1	-1.0	-0.64	12.8	2.6	6.3	14.5	15.1	26.4	18.1
0.4	0.3	1.0	-0.45	6.0	-1.2	4.4	7.5	7.8	12.8	10.7
0.4	0.2	1.0	-0.48	8.4	-1.7	4.1	9.6	10.0	17.5	12.0
0.4	0.3	-1.0	-0.35	7.8	1.6	5.7	9.9	10.2	16.8	14.1
0.4	0.2	-1.0	-0.32	12.7	2.5	6.3	14.4	15.1	26.4	18.1
0.2	0.3	1.0	-0.25	10.7	-2.1	3.9	11.6	12.1	21.8	13.4
0.2	0.2	1.0	-0.28	14.4	-2.9	3.5	15.2	16.0	29.3	16.4
0.2	0.3	-1.0	-0.15	18.6	3.7	6.9	20.2	21.2	38.0	23.4
0.2	0.2	-1.0	-0.12	34.3	6.9	8.4	35.9	37.9	69.4	38.8

Let $[\rho C_p \sigma(T_a - T_c)]/r_a = (\sigma LE)_T$ = error in LE due to an error in $(T_a - T_c)$; [14]

let $[\rho C_p (T_a - T_c)\sigma(r_a)]/r_a^2 = (\sigma LE)_{r_a}$ = error in LE due to an error in r_a; [15]

and let $\sigma(Rn+S) = (\sigma LE)_{Rn+S}$ = error in LE due to an error in (Rn+S). [16]

Eq. [13] then becomes:
error in LE,

$$\sigma(LE) = [(\sigma LE)_T^2 + (\sigma LE)_{r_a}^2 + (\sigma LE)^2_{Rn+S}]^{1/2}. \qquad [17]$$

Relative error in LE,

$$\frac{\sigma(LE)}{LE} = \left[\left[\frac{(\sigma LE)_T}{LE}\right]^2 + \left[\frac{(\sigma LE)_{r_a}}{LE}\right]^2 + \left[\frac{(\sigma LE)_{Rn+S}}{LE}\right]^2\right]^{1/2} \qquad [18]$$

RESULTS AND DISCUSSION

Error Analysis

Table 1 shows the relative errors[4] in computation of LE rate where the errors in the input parameters are as follows:

$$|\sigma(r_a)|/r_a = 0.10; \ \sigma(T_a - T_c) = 0.5 \text{ C; and}$$
$$[\sigma(Rn+S)]/(Rn+S) = 0.05 \qquad [19]$$

A wide range of ambient conditions are considered: r_a varying from 0.1 to 0.3 sec cm^{-1} and $(T_a - T_c)$ from —2.6 to 2.6 C. Initially a value of 0.80 ly min^{-1} is chosen for (Rn+S).

$T_a > T_c$ corresponds to advective conditions (sensible heat flux to the surface) and $T_a < T_c$ corresponds to nonadvective conditions (sensible heat flux away from the surface). A detailed discussion of the magnitude and significance of the advective and nonadvective conditions encountered under field conditions is given in Rosenberg (1974).

For advective conditions, $(\sigma LE)_{Rn+S}/LE = 3.3$ to 4.7%, $(\sigma LE)_T/LE = 2.9$ to 8.5%, $(\sigma LE)r_a/LE = -0.6$ to —3.5%. The net error in LE ranges from 5.3 to 9.6%. For nonadvective conditions, when $r_a = 0.2$ and 0.3 sec cm^{-1}, the net error is only slightly greater $[\sigma(LE)/LE = 6.5$ to 10.3%]. However, when $r_a = 0.1$ sec cm^{-1} under nonadvective conditions, the net error in LE = 14.5 to 26.5% [with $(\sigma LE)_{Rn+S}/LE = 6.3$ to 10.6%, $(\sigma LE)_T/LE = 12.8$ to 21.6% and $(\sigma LE)r_a/LE = 2.6$ to 11.2%]. It should be noted that low r_a values correspond to high windspeeds (U ≈ 3.5

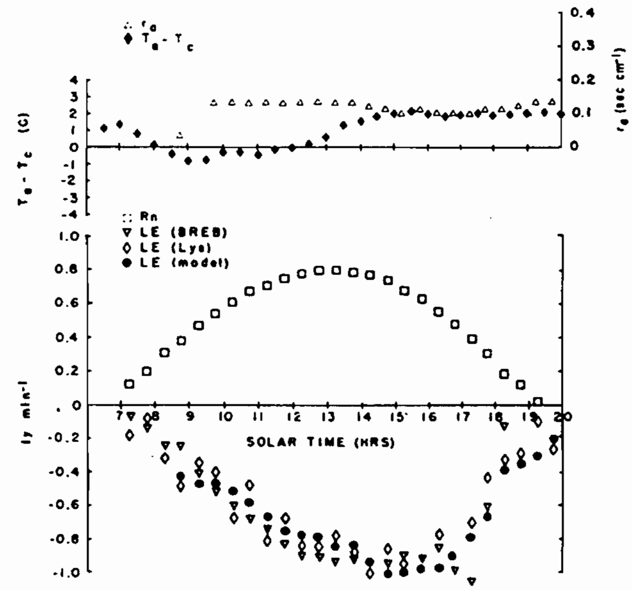

Fig. 1. LE flux over sorghum at Mead, Neb. estimated by the resistance (model), lysimetric, and energy balance methods (16 July 1974). Daily patterns of Rn, r_a, and $(T_a - T_c)$ are also shown.

[4] Relative errors in computation of LE rates $[(\sigma LE)r_a]/LE$, $[(\sigma LE)_{Rn+S}]/LE$, $[(\sigma LE)_T]/LE$, and $[\sigma(LE)]/LE]$ are expressed in terms of percentage. Relative errors in input parameters [e.g. $[\sigma(r_a)]/r_a$, $[\sigma(Rn+S)]/(Rn+S)$ are expressed in fractions.

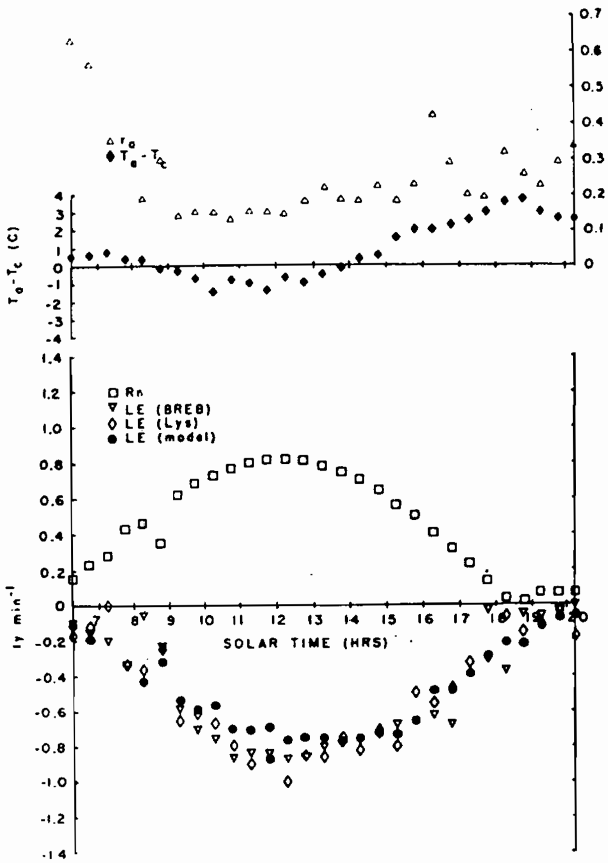

Fig. 2. As in Fig. 1 except on 23 July 1974.

— 4.0 m sec^{-1}), when r_a can be estimated with much better accuracy.

Also shown in Table 1 is the effect of larger errors in the input parameters. The effect of doubling $\sigma(r_a)/r_a$ on the net error, σ(LE)/LE, is relatively small (0.1 to 1.9%), except when $r_a = 0.1$ and $(T_a - T_c) = -2.6$ C. Doubling σ(Rn+S)/(Rn+S) has a slightly greater effect (1.7 to 5.4%) on σ(LE)/LE. The effect of doubling $\sigma(T_a - T_c)$, however, is relatively large, leading to an increase[5] in σ(LE)/LE by 2 to 8% under advective conditions and by 3 to 19.4% under nonadvective conditions.

The errors corresponding to smaller (Rn+S) values (with pertinent r_a and $T_a - T_c$: Table 1) are relatively larger, especially for Rn+S = 0.2 ly min^{-1} under nonadvective conditions. This combination of environmental conditions, however, corresponds to low LE values (about —0.10 ly min^{-1}) and prevails for short periods only. The effects of larger input errors are similar to those described above.

The error analysis indicates that LE estimates obtained through Eq. [1] are relatively more sensitive

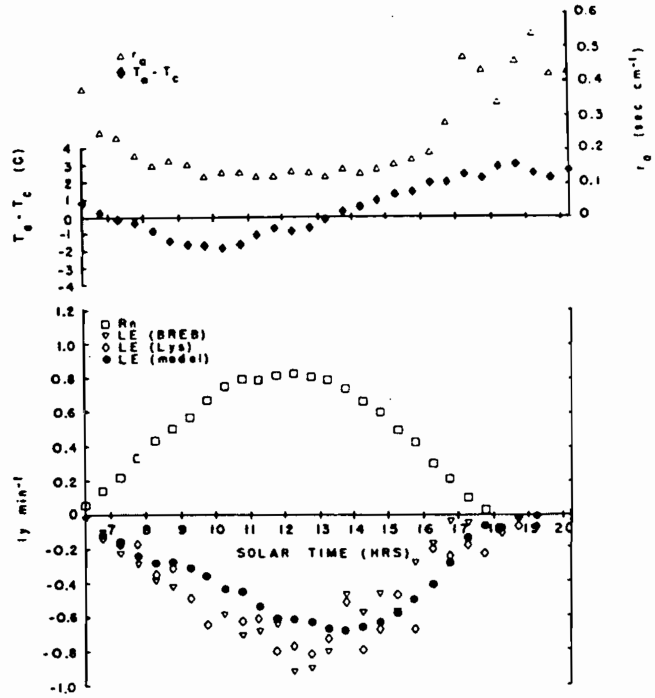

Fig. 3. As in Fig. 1 except on 26 Aug. 1974.

to errors in temperature (especially crop temperature) measurement than to errors in r_a estimation. Only moderate accuracy in r_a is required, whereas crop temperature must be measured with considerable precision.

Comparison of Resistance Model Estimates with Lysimetric and Energy Balance Measurements of Evapotranspiration

Boundary layer resistance (r_a) for sorghum and millet was computed by means of Eq. [8] through [12]. Using these r_a values in conjunction with the measurements of Rn, S, T_a, and T_c in Eq. [1], evapotranspiration rates [LE (model)] were calculated. LE (model) rates were compared with precision lysimeter [LE (Lys)] and with Bowen ratio-energy balance measurements [LE (BREB)] (see e.g. Blad and Rosenberg, 1974). Typical results are shown in Fig. 1-4[6]. Fig. 1 and 2 present results for sorghum grown at Mead on 16 and 23 July 1974. Height of the sorghum was 103 to 112 cm, and leaf area index (LAI) was about 7. For most of the day on 16 July r_a was about 0.10 to 0.13. On 23 July between 0800 and 1500 hours, r_a ranged from 0.15 to 0.20 and was 0.20 to 0.40 for the remainder of that day. LE (model) estimates compare well with LE (Lys) and LE (BREB) on both days — with some underestimation during the late morning and early afternoon hours of 23 July. On 16 July mild lapse conditions ($T_a - T_c \approx 0.5$ C in general) existed until 1100 hours and inversion conditions ($T_a - T_c \approx 1$ to 2 C) thereafter. On 23 July, however, temperature gradients (between air and crop) were moderately lapse ($T_a - T_c \approx -1$ to -1.5 C) especially during the late morning and early afternoon hours, and inverted ($T_a - T_c \approx 1$ to 3.0 C) after 1300 hours.

[5] Alteration in the value of σ(LE)/LE due to changes in the independent variables are expressed in the absolute percentage. For example, when $(T_a - T_c)$ is increased from 0.5 to 1.0 C [with $\sigma(r_a)/r_a = 0.1$, σ(Rn+S)/(Rn+S) = 0.05, Rn+S = 0.8 ly min^{-1}, $r_a = 0.3$ sec cm^{-1}, $(T_a - T_c) = 2.6$ C], σLE/LE increases from 5.3 to 7.3% (see Table 1).

[6] A summary of weather conditions on these days is given in Table 2.

Table 2. Comparison of daily model LE estimates with lysimetric and energy balance measurements.

Date	Crop (location)	Rs	Rn	Mean temp.† (0600–2000 hrs)	Mean wind speed† (0600–2000 hrs)	Mean vapor press.† (0600–2000 hrs)	LE Model	LE Lysimetric	LE Energy	Percentage Error $\frac{LE(model)-LE(Lys)}{LE(Lys)} \times 100$	Percentage Error $\frac{LE(model)-LE(BREB)}{LE(BREB)} \times 100$
1974		ly day^{-1}		C	m sec^{-1}	mbar		ly day^{-1}		%	
16 July	Sorghum (Mead)	704.7	383.1	28.29	3.29	17.08	-444.8	-409.6	-409.8	8.6	-9.4
18 July	Sorghum (Mead)	684.1	386.6	32.48	2.48	21.30	-578.8	-507.9	-559.8	13.9	3.4
23 July	Sorghum (Mead)	686.8	388.5	28.28	1.58	18.23	-407.6	-425.1	-437.7	-4.1	-6.9
24 July	Sorghum (Mead)	667.6	381.9	28.56	2.40	18.03	-450.0	-456.3	-423.6	-1.4	6.2
25 Aug.	Sorghum (Mead)	528.7	326.8	27.41	2.78	28.10	-297.7	-316.8	-243.7	-11.7	14.8
26 Aug.	Sorghum (Mead)	563.1	361.2	28.35	2.28	30.85	-290.1	-339.6	-305.1	-14.6	-4.9
17 Aug.	Millet (Mitchell)	618.9	387.6	21.95	0.61	15.47	-288.9	-286.6	-319.3	0.8	-9.5
22 Aug.	Millet (Mitchell)	421.0	248.8	21.02	1.97	15.90	-156.7	-173.8	-148.0	-9.8	5.9
23 Aug.	Millet (Mitchell)	622.9	355.2	22.92	2.45	14.20	-211.8	-236.7	-220.6	-10.5	-4.0
25 Aug.	Millet (Mitchell)	608.7	312.3	25.35	1.21	15.36	-228.4	-256.5	-226.3	-10.9	0.9

† Elevation of measurements: Mead - 150 cm; Mitchell - 105 cm (after 20 Aug. 1974) and 110 cm (before 20 Aug. 1974).

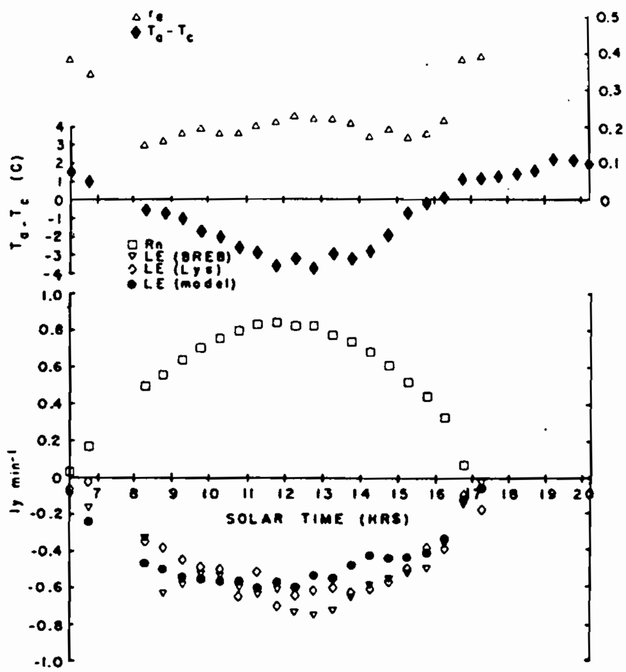

Fig. 4. LE flux over millet at Mitchell, Neb. estimated by the resistance (model), lysimetric, and energy balance methods (17 Aug. 1974). Daily patterns of Rn, r_a, and (T_a—T_c) are also shown.

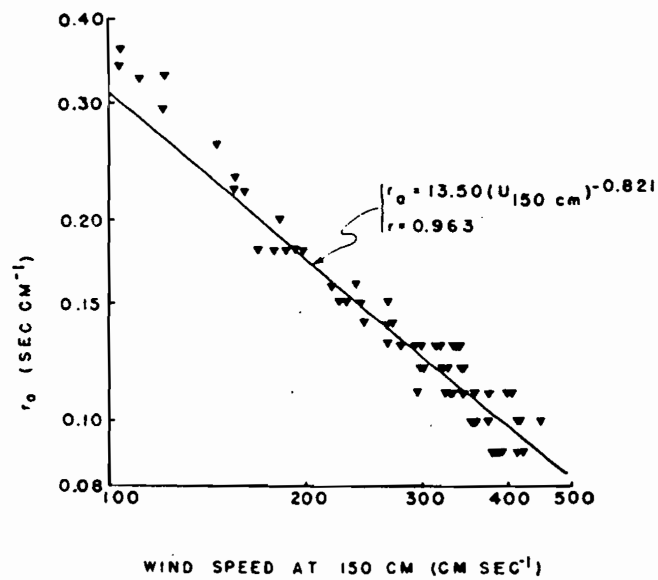

Fig. 5. r_a over sorghum at Mead, plotted as a function of windspeed. Windspeed was measured at 150 cm above the ground surface. Crop height ≈ 103 to 112 cm.

Figure 3 shows the results on 26 Aug. 1974 over 128 cm tall sorghum (LAI ≈ 5) grown at Mead. There was a range in r_a from 0.13 to 0.25 from 0900 to 1500 hours and from 0.15 to 0.50 for the remainder of the day. Even though there is some underestimation during the morning hours, the overall agreement of LE (model) with LE (Lys) and LE (BREB) seems reasonably good. An 26 August, temperature gradients were moderately lapse (T_a—T_c ≈ —1 to —2 C) until 1230 hours and inverted (T_a—T_c ≈ 1 to 3 C) for the remainder of the day.

The results for millet on 17 Aug. 1974 at Mitchell are shown in Fig. 4. For most of the day on 17 August (h = 75 cm) r_a ranged from 0.15 to 0.23). Except for some underestimation in the afternoon hours, LE (model) estimates compare well with LE (Lys) and LE (BREB). Temperature gradients were strongly lapse (T_a—T_c ≈ —1 to —3 C) for most of the day except during the late afternoon hours when T_a—T_c ranged from 0 to 2 C.

As seen in Figure 1-4, reasonably good argeement between LE (model) and LE (Lys) was generally obtained on a short term basis except for some periods which appear to have been associated with moderate to strongly lapse temperature gradients (T_a—T_c ≈ —1 to —3 C). The error analysis suggests to us that these differences may have been due to the errors involved in crop temperature measurements, primarily.

Table 2 presents a comparison of daily LE (model) values with LE (Lys) and LE (BREB). On most days, the model estimates agreed with the lysimetric and energy balance results to within about 10%.

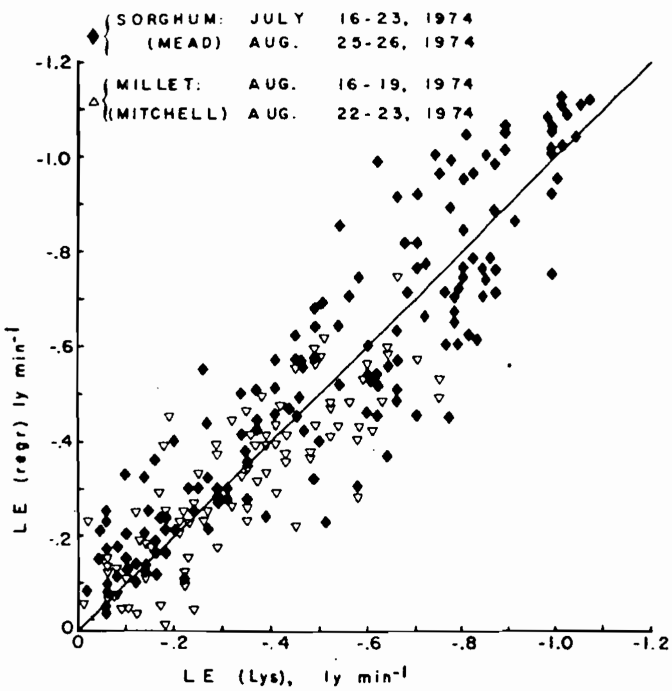

Fig. 6. Comparison of LE fluxes computed by using best fit $r_a = f(U)$ expressions with lysimetric measurements.

Boundary Layer Resistance as a Function of Wind Speed

Boundary layer resistance values for both crops (sorghum and millet) were correlated with wind speed data. Figure 5 shows a typical plot of r_a vs. U measured over sorghum during 16 to 23 July 1974 (h = 103 to 112 cm). The "best fit" expression is $r_a = 13.50$ $(U_{150\ cm})$ —0.821 with a correlation coefficient (r) of 0.963. Other r_a vs. U. correlations for sorghum and millet crops at other growth stages are presented below.

Time period	Crop	Crop ht.	Location	$r_a = f(U)$ (regr. eq.)	Corr. coeff.
		cm			r
16-23 July 1974	Sorghum	103-112	Mead	$r_a = 13.50\ (U_{150\ cm})^{-0.821}$	0.963
19-26 Aug. 1974	Sorghum	128	Mead	$r_a = 35.45\ (U_{150\ cm})^{-0.985}$	0.993
16-19 Aug. 1974	Millet	75	Mitchell	$r_a = 18.79\ (U_{110\ cm})^{-0.867}$	0.937
21-25 Aug. 1974	Millet	80	Mitchell	$r_a = 17.86\ (U_{105\ cm})^{-0.854}$	0.962

These "best fit" expressions $[r_a = f(U) = aU^{-b}]$ are similar to those reported previously in the literature (e.g. Brown and Rosenberg, 1973). Actual values of a and b, however, depend upon crop height, roughness, and elevation at which the wind speed is measured. When $r_a = f(U)$ expressions from different studies are compared one should not lose sight of the differences in these factors.

Evapotranspiration rates [LE (regr)][7] were computed by using the appropriate $r_a = f(U)$ expressions from the above table with measurements of U, Rn, S, T_a, and T_c in Eq. [1]. LE (regr) was compared against LE (Lys) and generally good agreement was obtained as is shown in Fig. 6.

SUMMARY AND CONCLUSIONS

Friction velocity measurements obtained by the Deacon-Swinbank approach were used in a stability-corrected aerodynamic method to compute boundary layer resistance, r_a. Results of these estimations made in fields of sorghum and millet are presented. The r_a values so obtained were used in a resistance model (Eq. 1) to provide estimates of evapotranspiration rates. These estimates compared with results obtained by precision lysimetry and with the Bowen ratio-energy balance method. Agreement was good both on a short-period and daily basis.

Field measurements, in conjunction with an error analysis, indicated that the LE model estimates are quite sensitive to errors in crop temperature measurement, especially under nonadvective conditions. The effect of errors in r_a estimation is relatively small.

Best fit expressions $r_a = f(U)$ were developed for the sorghum and millet crops at various stages of growth. These expressions, in conjunction with data on wind speed, net radiation, soil heat flux, and air and crop temperature entered into the resistance model (Eq. 1) can provide reliable estimates of evapotranspiration rate.

[7] Le (regr) is based on "best fit" $r_a = f(U)$ expressions, whereas LE (model) is computed from individual r_a values.

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