Analysis of a Resistance–Energy Balance Method for Estimating Daily Evaporation from Wheat Plots Using One-Time-of-Day Infrared Temperature Observations

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Accurate estimates of evaporation over field-scale or larger areas are needed in hydrologic studies, irrigation scheduling, and meteorology. Remotely sensed surface temperature might be used in a model to calculate evaporation. A resistance-energy balance model, which combines an energy balance equation, the Penman–Monteith evaporation equation, and van den Honert's equation for water extraction by plant roots, is analyzed for estimating daily evaporation from wheat using post-noon canopy temperature measurements. Additional data requirements are half-hourly averages of solar radiation, air and dew point temperatures, and wind speed, along with reasonable estimates of canopy emissivity, albedo, height, and leaf area index. Evaporation fluxes were measured in the field by precision weighing lysimeters for well-watered and water-stressed wheat. Errors in computed daily evaporation were generally less than 10%, while errors in cumulative evaporation for 10 clear sky days were less than 5% for both well-watered and water-stressed wheat. Some results from sensitivity analysis of the model are also given.

Introduction

During the past decade, several studies have been conducted to estimate evaporation using thermal infrared observations (for a recent review, see Hatfield, 1983). Interest in such studies stems from the fact that estimates of evaporation at varied spatial resolution would be logistically simpler to perform using infrared radiometer data as compared with lysimetric or Bowen ratio methods. Additionally, evaporation on a global basis might be obtained at a fairly high temporal resolution using space-borne infrared sensors.

Mathematical models are needed to convert infrared temperature observations to evaporation. Several such models have been developed (see Hatfield, 1983) with varied complexity and input data requirements. Calculations of evaporation fluxes based upon energy balance (Hatfield et al., 1984) and resistance (Verma et al., 1976; Soer, 1980) methods have been compared against lysimeter observations, and these models have also been subjected to sensitivity analysis. The errors in the calculated fluxes were generally less than 20%.

Estimating daily total evaporation from one-time-of-day infrared observations is of special interest, particularly in the application of space-borne infrared sensor data. Jackson et al. (1977) found a significant linear relationship between the difference of daily evaporation (via lysimeter) and net radiation, and the post-noon canopy–air temperature difference for wheat. Seguin and Itier (1983) (see also Choudhury and Federer, 1984) provided

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a rationale for the existence of such a linear relationship under mostly clear sky conditions, but cautioned that the coefficients of such a relationship might be crop- and climate-specific. The calculated evaporation summed over 2–4-week periods might be accurate to within 20%. Camillo et al. (1983) and Gurney and Camillo (1984) used a moisture and energy balance model to calculate daily evaporation from bare soil and wheat crop using one-time-of-day surface temperature data and hourly weather data throughout the day. For 1 day they found the calculated evaporation was within 10% of the observation.

In this paper we investigate a resistance-energy balance method, analogous to the one studied by Soer (1980), for calculating daily evaporation from wheat using post-noon infrared radiometer data. In addition to the infrared data, the present method uses half-hourly averaged weather data (air and dew point temperature, wind speed and solar radiation). The needed canopy parameters are emissivity, albedo, crop height, and leaf area index. We compared the calculated and the observed evaporations, and present some results from the sensitivity analysis of the model.

Methods

Model equations

Evaporation flux (E in $\mathrm{W\,m^{-2}}$) according to Monteith's (1981) modification of his 1965 equation is given by

$$E = \frac{\Delta R_n(1-\tau) + DC_p/r_H}{\Delta + \gamma[(r_a + r_c)/r_H]}, \quad (1)$$

where R_n is above canopy net radiation ($\mathrm{W\,m^{-2}}$) when canopy and air temperatures are equal, τ is radiation transmission coefficient, C_p is the volumetric heat capacity of air (= 1200 $\mathrm{J\,m^{-3}\,K^{-1}}$), D is air vapor pressure deficit (kPa), Δ is the slope of saturated vapor pressure curve at air temperature ($\mathrm{kPa\,K^{-1}}$), γ is the psychrometric constant (= 0.066 $\mathrm{kPa\,K^{-1}}$), r_H is effective aerodynamic resistance for heat and long-wave radiative transfer ($\mathrm{s\,m^{-1}}$), r_a is the aerodynamic resistance for heat transfer ($\mathrm{s\,m^{-1}}$), and r_c is surface resistance for evaporation ($\mathrm{s\,m^{-1}}$). The equations for net radiation above the canopy R_n and r_H are

$$R_n = (1-\alpha)S + (\varepsilon_a - \varepsilon_c)\sigma T_a^4, \quad (2)$$

$$r_H^{-1} = r_a^{-1} + \left(C_p/4\varepsilon_c\sigma T_a^3\right)^{-1}, \quad (3)$$

where α is surface albedo, S is isolation ($\mathrm{W\,m^{-2}}$), ε_a is long-wave emissivity of air (calculated according to Idso, 1981), ε_c is surface emissivity (= 0.976, Fuchs and Tanner, 1966), σ is the Stefan–Boltzmann constant (= 5.76×10^{-8} $\mathrm{W\,m^{-2}\,K^{-4}}$), and T_a is air temperature (K). The aerodynamic resistance is calculated as the sum of momentum and bluff-body terms according to Wallace et al. (1984) for neutral case

$$r_a = \frac{\ln^2[(z-d)/z_0]}{k^2U} + \frac{1.5\ln[(z-d)/z_0]}{k^2U}, \quad (4)$$

where k is von Karman's constant (= 0.4) and d and z_0 are, respectively, the zero plane displacement and roughness height (m), which are obtained from the crop height (CH) as (Legg and Long, 1975)

$$d = 0.56\text{CH}, \quad (5a)$$

$$z_0 = 0.3(\text{CH} - d). \quad (5b)$$

The wind speed U (m s^{-1}) is measured at height z (m).

We estimated net radiation from solar radiation and air temperature because remote sensing techniques might provide solar radiation, and air temperature may be available from weather stations. A knowledge of the diurnal surface temperature is not assumed.

The surface resistance depends in a complex manner on the soil wetness, fractional ground cover, and plant physiological parameters (Szeicz and Long, 1969). This resistance is essentially plant-dependent when the soil is dry or ground cover is complete, and then it varies diurnally in response to radiation, and is a function of leaf water potential. We assume this resistance to be a plant physiologic parameter (canopy resistance), and from Choudhury and Idso (1985) we obtain the following empirical equation for the canopy resistance of wheat:

$$r_c = \frac{1000\left[1 + (-\psi/230.8)^{5.51}\right]}{\text{LAI}\,0.986 + 0.025R_n(1-\tau)}, \quad (6)$$

where ψ is the leaf water potential (m) and LAI is leaf area index.

The evaporation flux can be alternately expressed by van den Honert's (1948) equation for water uptake by plant roots, with the interpretation of flux as an electrical current moving under the potential gradient between soil and leaf (Ohm's law),

$$E = \left[(\psi_s - \psi)/(R_s + R_p)\right]L, \quad (7)$$

where ψ_s is soil water potential (m), R_s and R_p, are, respectively, the resistances (s) of water flow from bulk soil to the root surface, and from root surface to leaf stomata (Choudhury and Idso, 1985), and L is volumetric heat of vaporization ($= 2.47 \times 10^9$ J m^{-3}). For completeness, a short discussion of r_c, R_s, and R_p is given in the Appendix.

The energy balance equation for evaporation flux is

$$E = R_n(1-\tau) - C_p(T_c - T_a)/r_H, \quad (8)$$

where T_c is the surface temperature. Note that in Eqs. (1) and (8) we have considered only the energy available for evaporation from plant (also called transpiration), namely $R_n(1-\tau)$, since canopy temperature is more closely linked with canopy evaporation than soil evaporation. We have ignored the soil heat flux.

Approach

Equations (1), (6), (7), and (8) form simultaneous equations, which are to be solved for four unknowns E, r_c, ψ_s, and ψ. To accomplish this task, we assumed a value for the soil water potential (a representative value of ψ_s for the well-watered plot was about -5 m). Then, Eqs. (1), (6), and (7) were solved for E, r_c, and ψ using known weather data for each day at 1300 h and crop characteristics. From the calculated value of E we obtained the canopy temperature from Eq. (8). If the observed canopy temperature at 1300 h was higher than the calculated canopy temperature, then the soil water potential was decreased, and the above procedure of calculating the canopy temperature was repeated until the two temperatures agreed to within 0.5 K. Then, with this value of soil water potential we used half-hourly weather data throughout the day to calculate E by solving Eqs. (1), (6), and (7). These half-hourly E values were integrated to obtain the daily total evaporation.

Field Observations

On 10 December 1981, Anza wheat was seeded at a rate of approximately 60 $kg ha^{-1}$ onto an Avondale loam soil at the U.S. Water Conservation Laboratory in Phoenix, AZ. The field was subsequently divided into several plots; one always remained well watered, while others were differentially stressed. The present analysis is based upon 10 clear sky days of data between anthesis and the commencement of senescence (days 104–120) collected over well-watered and water-stressed plots.

The weather data at the height of 1.5 m were logged automatically as half-hourly averages of solar radiation (by Eppley* solarimeter), air wet and dry bulb temperature (by Bendix* aspirated psychrometers), and wind speed (by Young* cup anemometer). Half-hourly average evaporation rates were measured by precision weighing lysimeters of 1-m^2 area. Canopy temperatures were measured by an Everest Interscience Model 110 infrared thermometer with a 4° field-of-view. Six temperatures were measured by viewing the crop at about a 30° angle from the horizontal. Three measurements from the east and three from the west were arithmetically averaged to obtain the mean canopy temperature. These infrared temperatures were corrected for reflection of atmospheric longwave radiation for a crop emissivity of 0.976.

Crop height and leaf area index were measured on several days during the study period. The crop height was about 0.9 m, and the leaf area index varied from 3.4 to 6.3 for the well-watered plot, and from 1.1 to 6.3 for the water-stressed plot (Table 1). The diurnal course of albedo was measured in a separate experiment on wheat at the U.S. Water Conservation Laboratory. These albedos were in good agreement with the observations of Denmead (1976).

Results and Discussion

The daily evaporation on each day is calculated by integrating evaporation fluxes at half-hourly intervals throughout the day. In the following, we compare the half-hourly estimates of evaporation flux with the lysimeter observations for a few days, and then the daily estimates of evaporation with the lysimeter data.

Diurnal trends of weather data on days of the year 106, 109, and 118 are shown in Fig. 1, and computed and observed evaporation fluxes for well-watered and water-stressed plots are shown in Fig. 2. The midday evaporation flux of the well-watered plot is greatest on day 109, primarily because of its higher wind speed and vapor pressure deficit compared to the other two days. The computed evaporation fluxes closely followed the observations, although during the pre-noon period the computed values are generally larger by 10–15%. These errors are comparable to those found by Verma et al. (1976), Heilman and Kanemasu (1976), and Hatfield et al. (1984) for en-

*Trade names and company names were included for the benefit of the reader and imply no endorsement or preferential treatment by either NASA or USDA.

TABLE 1 Leaf Area Index and Estimated and Observed Soil Water Potentials on Different Days for Well-Watered and Water-Stressed Plots[a]

Day of the Year	Leaf Area Index	Soil Water Potential (m) From Model	Soil Water Potential (m) From Neutron Data
104	6.1 (6.3)	− 5 (− 27.5)	− 5.5 (− 12.0)
105	6.3 (6.0)	− 5 (− 27.5)	
106	6.3 (5.6)	− 5 (− 25.0)	− 6.0 (− 15.0)
108	6.3 (4.7)	− 5 (− 32.5)	
109	6.3 (4.3)	− 5 (− 32.5)	− 4.0 (− 19.0)
112	6.2 (3.3)	− 5 (− 37.5)	
113	6.0 (3.0)	− 5 (− 37.5)	− 5.5 (− 29.0)
116	5.2 (2.1)	− 5 (− 47.5)	− 4.0 (− 42.0)
118	4.3 (1.6)	− 5 (− 57.5)	− 5.0 (− 49.0)

[a] The values in the parenthesis are for the water-stressed plots.

ergy balance and resistance methods applied to sorghum, millet, alfalfa, soybean, cotton, and tomato.

Heilman and Kanemasu (1976) noted that the aerodynamic resistance for momentum, when used in the energy balance method, could lead to an overestimate of the evaporation flux. They demonstrated that the inclusion of a bluff-body correction in the aerodynamic resistance improves the evaporation estimates. Equation (4) includes the bluff-body correction, and in concurrence with Heilman and Kanemasu (1976) we found that

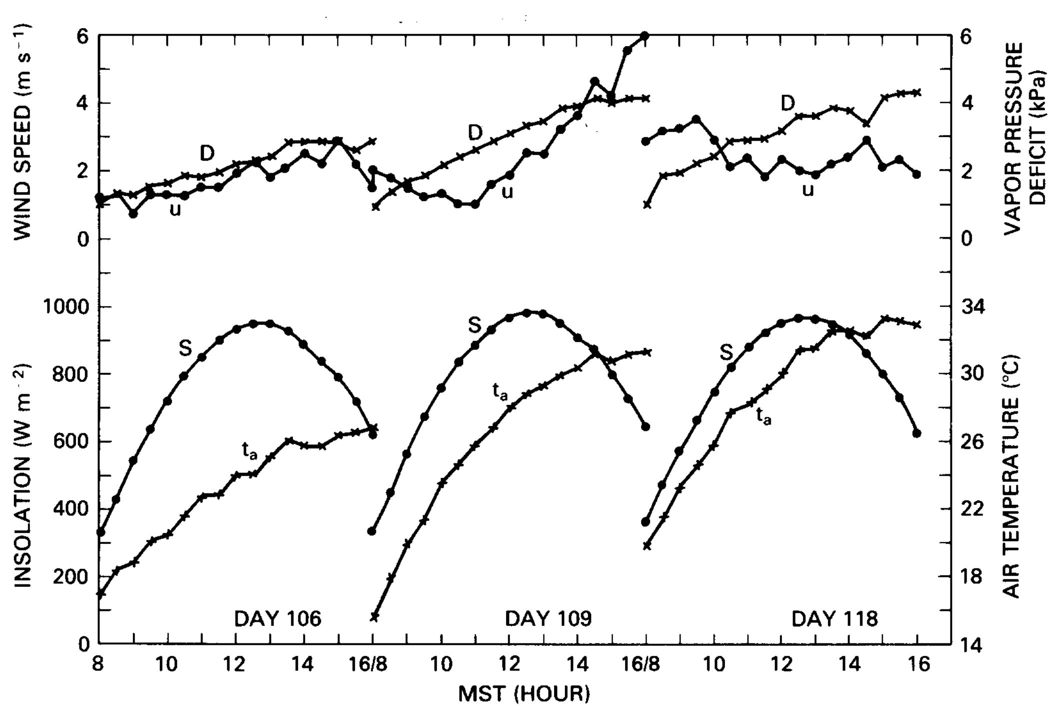

FIGURE 1. Diurnal variation of atmospheric parameters from 0600 to 2000 MST (Mountain Standard Time) for 3 days. The evaporation fluxes for these 3 days are shown in Figs. 2 and 4.

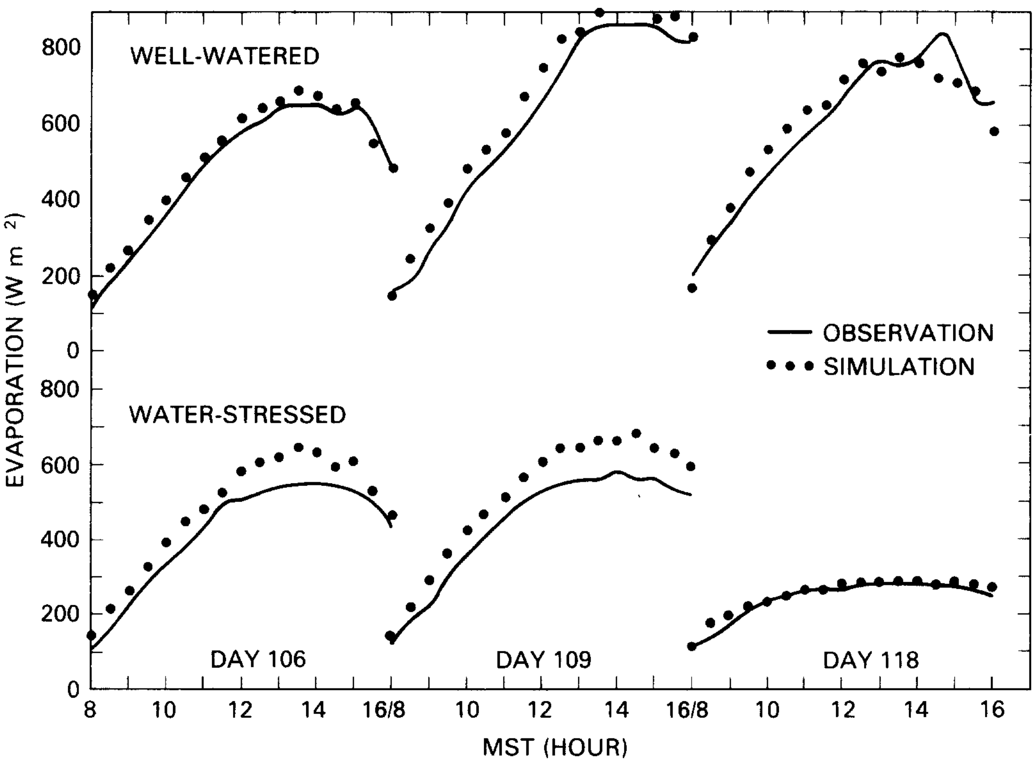

FIGURE 2. Observed (solid line) and simulated (filled circles) diurnal variation of evaporation flux for well-watered and water-stressed wheat using neutral aerodynamic resistance.

without this correction the evaporation fluxes are overestimated throughout the day.

For well-watered crops, Hatfield et al. (1984) found that aerodynamic resistance without a stability correction could lead to an overestimate of evaporation flux by the energy balance method. This correction is not included in Eq. (4), because a proper accounting of this correction would require a knowledge of the diurnal course of the surface temperature to estimate the daily total evaporation. An approach to including this correction, when only post-noon canopy temperature is known, is discussed in the next section.

The calculated and observed daily total evaporations for 10 days are shown in Fig. 3. The results for the well-watered plot are shown by the symbol *O*, while those for the water-stressed plot are shown by the symbol *X*. The 1:1 line shown in the figure illustrates that evaporation from the well-watered plot is overestimated by roughly 1 mm, while for the water-stressed plot the evaporation estimates are not uniformly biased. The computed values for the water-stressed plot with respect to the observations is such that, as the field dried progressively, the initial overestimate of evaporation gradually becomes an underestimate. The calculated cumulative evaporation for 10 days for the well-watered plot is 91 mm, which is about 3% larger than the observation. For the water-stressed plot, the cumulative evaporation is 63.3 mm, which is about 4% larger than the observation.

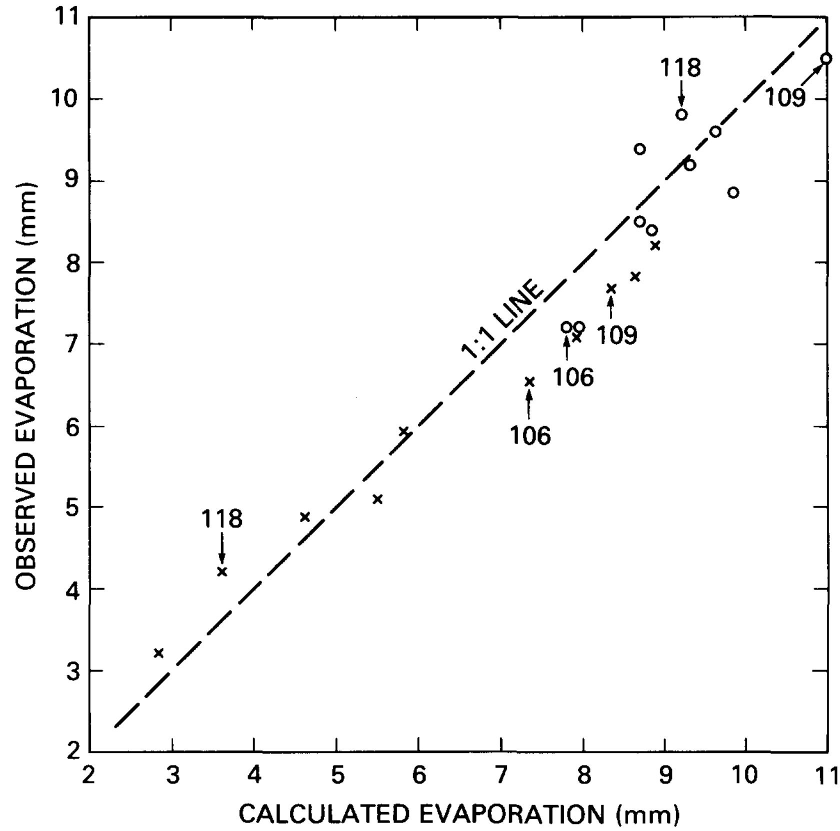

FIGURE 3. Comparison of calculated and observed daily total evaporation for 10 days. The daily totals for days 106, 109, and 118, for which the fluxes are shown in Fig. 2, are annotated on this figure.

Stability Correction

An approximate equation for stability-corrected aerodynamic resistance (Monteith, 1973), which Hatfield et al. (1983) found useful in estimating evaporation by the energy balance method, is

$$r_{ac} = r_a \left[1 - \frac{5g(z-d)(T_c - T_a)}{u^2 T_a} \right], \quad (9)$$

where g is the acceleration due to gravity ($= 9.8\ \mathrm{m\,s^{-2}}$) and other symbols are as defined in Eqs. (4) and (8). The effect of this stability correction is to increase the aerodynamic resistance when $T_a > T_c$ (the stable condition) and decrease the resistance when $T_a < T_c$ (the unstable condition), as compared to the neutral state resistance r_a.

To include this correction in estimating daily evaporation, one needs to have either diurnal observations of canopy temperature or one may solve iteratively Eqs. (1), (6), (7), (8), and (9) for the unknowns E, r_c, ψ_s, ψ, and r_{ac}. We investigated a simpler approach of correcting the aerodynamic resistance using only the post-noon canopy–air temperature difference $(T_c - T_a)_{1300}$, i.e., we used the approximation

$$r_{ac} = r_a\left[1 - \frac{5g(z-d)(T_c - T_a)_{1300}}{u^2 T_a}\right]. \tag{10}$$

We reasoned that since the diurnal variation of canopy–air temperature difference under clear sky conditions attains its maximum about the 1300 h, the above correction should provide a better estimate of the aerodynamic resistance than the neutral resistance (r_a) under stable atmospheric conditions. Furthermore, the numerical procedure for solving the model equations (see Approach in the Methods section) remains unchanged under this correction.

Evaporation fluxes calculated with the stability-corrected aerodynamic resistance are shown in Fig. 4 for days 106, 109, and 118. Comparison of these fluxes with those in Fig. 2 shows that the stability correction generally improved agreement with observations for the well-watered plot during the prenoon period. During the afternoon period, the wind speed was fairly high compared to the prenoon period (Fig. 1). One could see from Eq. (10) that when the wind speed is high, the stability correction has much less effect on the aerodynamic resistance, and thus the fluxes calculated with and without stability correction do not differ significantly during the afternoon period. The effect of stability correction on the fluxes of the water-stressed plot is smaller

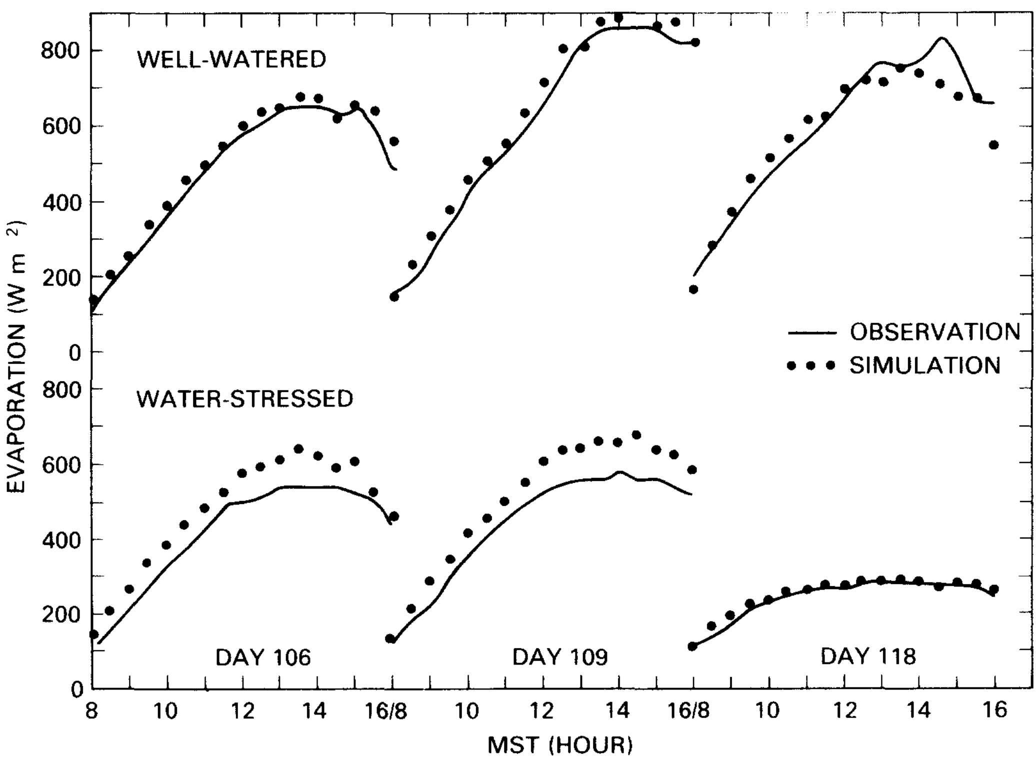

FIGURE 4. Illustration of the effect of stability correction on the evaporation flux for days 106, 109, and 118. The simulated fluxes during the pre-noon period agree better with observations. See text for further details.

compared to the well-watered plot because of the smaller canopy–air temperature difference at 1300 h (-5.8 and $+0.4$ K, respectively, for the well-watered and water-stressed plots for day 109).

The computed daily evaporation totals are compared with observations in Fig. 5. For all days, the stability correction decreased the calculated evaporation for the well-watered plot. The calculated cumulative evaporation is 88.2 mm, which is only 0.5% lower than what was observed. For the water-stressed plot, the present stability correction did not improve agreement with observation. The calculated cumulative evaporation is 63.3 mm, which is equal to the evaporation calculated using the neutral aerodynamic resistance, and is about 4% larger than the observations. However, since a 5% error in estimating cumulative evaporation for several days is probably acceptable in some applications, the present stability correction appears to be useful.

The present method for calculating evaporation also leads to an estimate of the root-zone soil water potential (ψ_s). These estimated potentials are given in Table 1, together with the potentials obtained from neutron probe observations (weighting the observations for each layer by the corresponding layer thickness, up

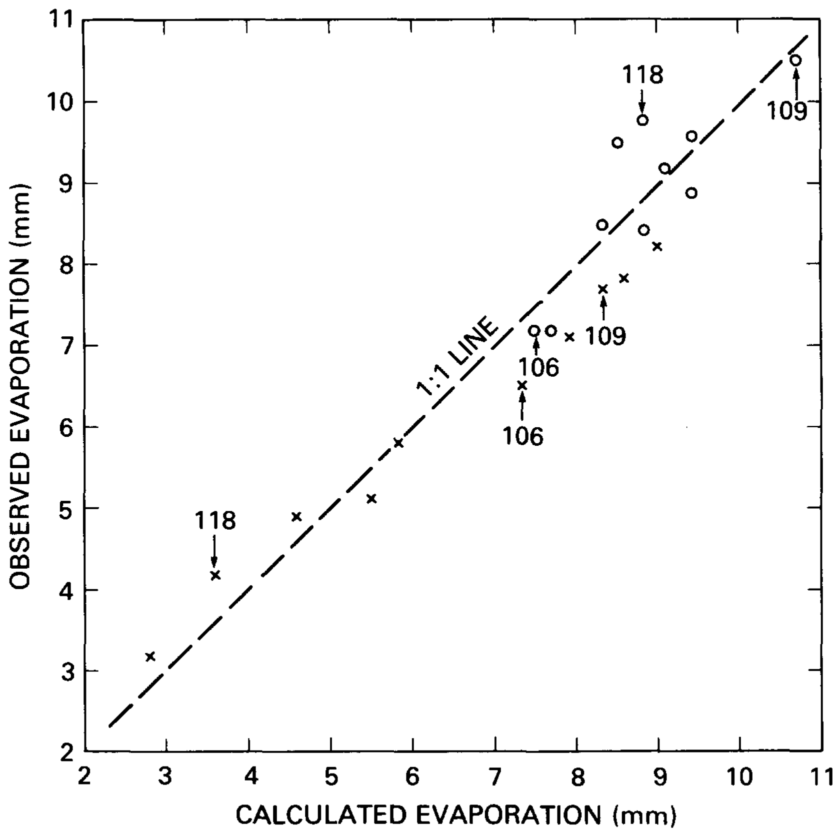

FIGURE 5. Comparison of calculated and observed daily total evaporation with stability corrected aerodynamic resistance. It is seen, by comparing with Fig. 3, that stability correction decreased the calculated evaporations for the well-watered plot.

to a depth of 1.5 m). The model estimated potentials for the water-stressed plot are generally about 10 m lower than those calculated from the neutron probe data. By analyzing a multilayer water extraction model for plant roots, Federer (1979) suggested that root-zone soil water potential should be calculated by weighting the soil water potential of each layer by the corresponding root length per unit area. When the rooting density is uniform, the observed soil water potentials for different layers could be weighted by the corresponding layer thickness to obtain the root-zone soil water potential. Since the rooting density is generally not uniform, the present method of calculating the root-zone soil water potential from the neutron probe data might not be totally realistic. However, because the rooting density was not measured, we cannot calculate the root-zone soil water potential according to Federer's (1979) suggestion.

Results of Sensitivity Analysis

The model was subjected to sensitivity analysis for uncertainties in the observations of leaf area index and canopy temperature, and also uncertainties in defining the stomatal response to radiation (Fig. 6) and the plant resistance (Fig. 7). The sensitivity results are given in terms

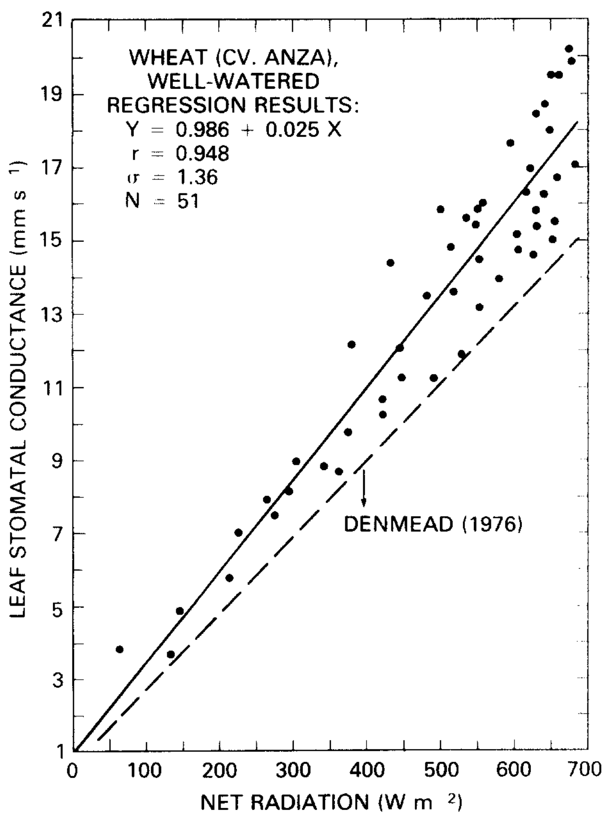

FIGURE 6. Empirical representations of leaf stomatal conductance of well-watered wheat.

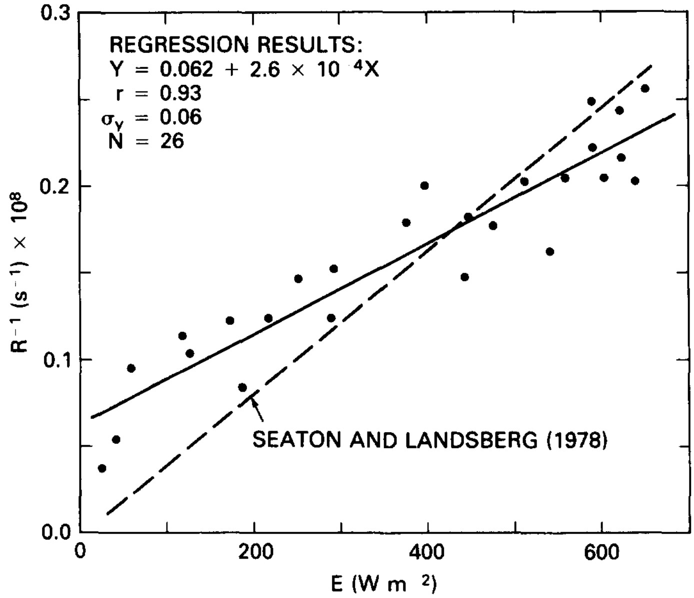

FIGURE 7. Derivation of empirical relationship for plant resistance.

of fractional percent difference (p) in the calculated daily total evaporation, defined as

$$p = \{[E(0) - E(\delta)]/E(0)\}100, \quad (11)$$

where $E(0)$ is the daily total evaporation calculated using the actual observations and empirical relations (as discussed in the previous section) and $E(\delta)$ is the daily total evaporation as obtained by modifying the observations and empirical relations.

The sensitivity results for leaf area index and canopy temperature are given in Table 2. Asrar et al. (1984) found that the leaf area index of wheat could be estimated to an accuracy of 0.5 from red and

TABLE 2 Sensitivity of the Model to Uncertainties in Leaf Area Index and Canopy Temperature (at 1300 h)[a]

Day of the Year	Leaf Area Index		Canopy Temperature	
	LAI + 0.5	LAI − 0.5	T_c + 0.5	T_c − 0.5
104	− 2.2	3.3	2.2	− 4.4
105	− 2.3	2.3	5.8	− 5.8
106	− 5.5	1.4	2.7	− 4.1
108	− 2.5	3.2	7.1	− 2.5
109	− 3.6	4.8	3.6	− 6.0
112	− 5.2	10.3	12.1	− 9.5
113	− 9.1	9.6	7.3	− 5.5
116	− 12.2	17.4	5.7	− 3.6
118	− 22.2	27.8	4.4	− 11.1
120	− 35.7	58.2	15.4	− 9.3

[a]As indicated by the fractional percent difference in daily total evaporation from the water-stressed plot (p, see text).

near-infrared reflectances. Even for this accuracy in estimating LAI, the present model could lead to errors in excess of 20% when the actual LAI is less than 2 (Table 2). If the LAI is over- (under-) estimated, the calculated evaporation will also be over- (under-) estimated. Uncertainties in the measurement of canopy temperature by 0.5 K would lead to errors generally less than 10%.

The stomatal response to radiation, which we observed (Fig. 6), differs somewhat from the response observed by Denmead (1976). For Denmead's (1976) response function, the canopy resistance would be given by

$$r_c = \frac{1000\left[1 + (-\psi/230.8)^{5.51}\right]}{\left[0.5\mathrm{LAI} + 0.021 R_n(1-\tau)\right]}. \quad (12)$$

Additionally, the empirical equation for plant resistance [Eq. (A8)], which we derived, differs from the one obtained by Seaton and Landsberg (1978) [Eq. (A9)]. The sensitivity results for differences in these two empirical equations are given in Table 3. Under identical radiation, Denmead's (1976) equation gives a higher canopy resistance, and, consequently, the calculated daily evaporations are lower. The fractional differences are in excess of 10% for wet and moderately dry soils. The model appears to be sensitive to plant resistance only for fairly dry soils. The fractional differences are, however, generally less than 10%.

TABLE 3 Sensitivity of the Model to Canopy and Plant Resistances

Day of the Year	r_c[Eq. (12)]	R_p[Eq. (A9)]
104	15.0	1.3
105	17.9	1.9
106	13.0	0.5
108	11.0	2.2
109	10.6	2.3
112	12.6	1.9
113	8.7	2.0
116	5.7	6.5
118	4.7	9.2
120	5.4	16.1

Summary

A model based upon an energy balance equation, the Penman–Monteith equation, and an equation for water extraction by plant roots was analyzed for estimating daily total evaporation from wheat using post-noon canopy temperature data. Daily evaporations were computed by integrating evaporation fluxes at half-hourly intervals. The simulated fluxes and daily total evaporation agreed well with lysimeter observations. The accuracy of the model improved when the aerodynamic resistance was corrected for the atmospheric stability using the post-noon canopy temperature. The calculated cumulative evaporation for 10 clear sky days was within 5% of what was observed for both well-watered and water-stressed crops. Sensitivity analysis of the model showed that substantial error could occur in calculating daily evaporations when 1) the LAI is less than 2 and is uncertain by 0.5, and 2) the stomatal response to radiation is not represented accurately.

Appendix

Canopy resistance

The empirical equation for wheat canopy resistance was derived using 111 sets of observations on sunlit leaves of well-watered and water-stressed plants for stomatal resistance and leaf water potential on days 89, 112 and 120. The stomatal resistances were measured by an LI-COR 1600 Steady State Porometer, and leaf water potentials were measured by Scholander-type pressure bomb.

For well-watered wheat, Denmead (1976) found that the stomatal resistance is determined almost solely by the net radiation. In substantial agreement with Denmead (1976), our observations of stomatal conductance (C_l^0 in mm s^{-1}, which is the inverse of stomatal resistance) for well-watered wheat leaves also showed high linear correlation ($r = 0.95$) with the net radiation (Fig. 6). The regression equation we find is

$$C_l^0 = 0.986 + 0.025 R_n. \qquad \text{(A1)}$$

The stomatal resistance of water-stressed plants is higher compared to that for well-watered plants under identical environmental conditions, because under water stress the guard cells progressively losses the needed turgor to keep the stomata open (Monteith, 1973). The leaf water potential may be used to describe the guard cell turgor. Fisher et al. (1981) suggest that the dependence of the ratio (f) of stomatal conductances of water-stressed and well-watered plants (so as to normalize for the dependence of stomatal resistance on radiation) on leaf water potential (ψ) could be described as

$$f = 1 \Big/ \left[1 + (\psi / a)^b\right], \qquad \text{(A2)}$$

where a and b are adjustable parameters.

We normalized all observed conductances by those predicted by Eq. (A1), and used a nonlinear least square procedure to determine the parameters a and b of Eq. (A2). The procedure is iterative, which minimizes the standard error defined as

$$\sigma_p = \frac{1}{N-2} \sum_{j=1}^{N} \left(O_j - e_j\right)^2, \qquad \text{(A3)}$$

where N ($= 111$) is the number of observations, and O_j and e_j are, respectively, the observed ratios and those computed from Eq. (A2). The best fit ($\sigma_p = 0.12$) parameters are $a = -230.8$ and $b = 5.51$ (Fig. 8).

Combining Eqs. (A1) and (A2), we get the stomatal conductance of sunlit leaves as

$$C_l = (0.986 + 0.925 R_n) \Big/ \left[1 + (\psi / -230.8)^{5.51}\right]. \qquad \text{(A4)}$$

To obtain the canopy resistance, we note that radiation flux on all leaves within the canopy will not generally be identical; the upper canopy leaves are likely to be more sunlit than those within the canopy. According to Denmead (1976), the attenuation of net radiation within a wheat canopy could be described by an exponential function. Thus, by integrating Eq. (A4) for an exponentially damped net radiation within a canopy of leaf area index (LAI), we get the canopy resistance Eq. (6).

Soil resistance

The soil resistance is calculated according to Soer (1980) as

$$R_s = 0.0013 / \left[Z_r K(\psi_s)\right], \qquad \text{(A5)}$$

where Z_r is the effective rooting depth (m) and $K(\psi_s)$ is the soil hydraulic con-

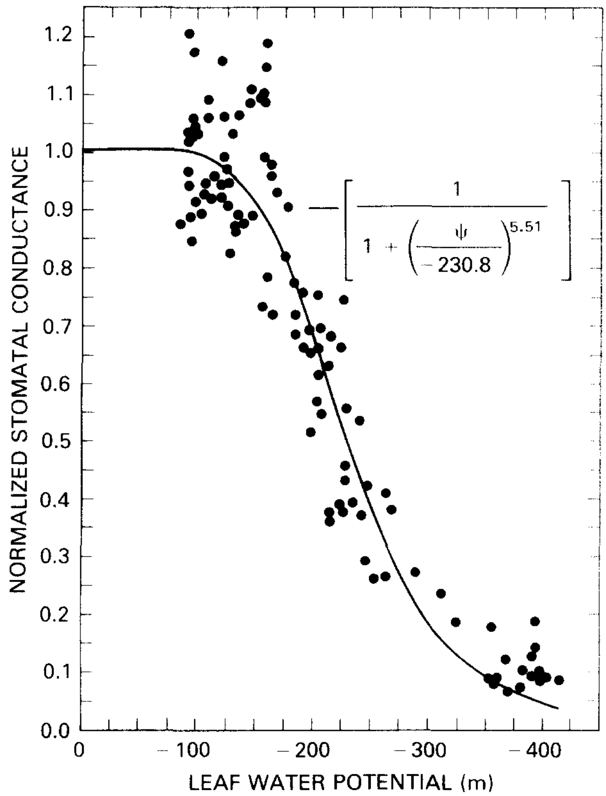

FIGURE 8. Empirical relationship for normalized stomatal conductance in terms of leaf water potential.

ductivity ($\mathrm{m\,s^{-1}}$), represented as (see Jackson, 1973)

$$K(\psi_s) = 2.0\times10^{-7}(-0.47/\psi_s)^{2.58}. \tag{A6}$$

Since the root distribution was not measured, we assumed [based upon the observations of Greacen et al. (1976) and Hamblin and Hamblin (1985)] that

$$Z_r = 1.5\ \mathrm{m}.$$

Plant resistance

Under well-watered conditions the plant resistance (R_p) would generally be an order of magnitude larger than the soil resistance, and, since there are no direct methods for measuring this resistance, it is calculated for well-watered plants using Eq. (7) [see Lascano and van Bavel (1984) and other references cited there]:

$$R_p = (\psi_s - \psi)L/E. \tag{A7}$$

The R_p values calculated using the lysimeter data for E and leaf water potentials of well-watered plants ($\psi_s = -5$ m) for day 112 are shown in Fig. 7, which can be expressed as (in units of seconds):

$$R_p = \frac{1.6\times10^9}{1+(E/240)}. \tag{A8}$$

A previous study on the plant resistance of wheat by Seaton and Landsberg

(1978) also showed that this resistance decreases as the evaporation rate increases. The equation they found for R_p is

$$R_p = \frac{2.47 \times 10^{11}}{E}. \qquad \text{(A9)}$$

The resistances we calculate are lower (higher) than those calculated from Eq. (A9) for E values lower (higher) than 450 $\mathrm{W\,m^{-2}}$. Seaton and Landsberg (1976) suggest that the magnitude of this resistance and its dependence on E could vary with the root morphology. The qualitative agreement between Eqs. (A8) and (A9) is gratifying.

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