COMPARISON OF FIVE MODELS TO SCALE DAILY EVAPOTRANSPIRATION FROM ONE-TIME-OF-DAY MEASUREMENTS

P. D. Colaizzi, S. R. Evett, T. A. Howell, J. A. Tolk

ABSTRACT. *Calculation of regional, spatially distributed evapotranspiration (ET) is possible using remotely sensed surface temperatures from sensors aboard air or space platforms. These platforms provide instantaneous data at frequencies of days to weeks, so that instantaneous latent heat flux can be computed from energy balance algorithms. However, instantaneous latent heat flux must be converted to ET and then scaled to daily (24 h) totals for most practical applications. We compared five scaling models where a single measurement of 0.5 h ET was used to estimate the daily total during clear days. Each model takes advantage of the clear day, quasi-sinusoidal nature of daytime ET and other daytime parameters including solar radiation, available energy, or reference ET. The surfaces were fully irrigated alfalfa, partially irrigated cotton, dryland grain sorghum, and bare soil (tilled fallow sorghum). Actual ET was measured by precision weighing lysimeters. Model agreement was evaluated on the basis the modified index of agreement (D) and the modified coefficient of efficiency (ε), in addition to standard statistical parameters. For cropped surfaces, the models based on grass reference ET resulted in the best agreement between observed and predicted daily ET totals. For bare soil, the model based on available energy (i.e., evaporative fraction) resulted in the best agreement. Relative error between observed and predicted daily ET increased as daily ET decreased. Observed and predicted daily ET agreed well for the transpiring crops (RMSE of 0.33 to 0.46 mm d^{-1} for mean daily ET of 3.9 to 5.8 mm d^{-1}) but poorly for bare soil (RMSE of 0.47 mm d^{-1} for mean daily ET of 1.4 mm d^{-1}).*

Keywords. *Energy balance, Evapotranspiration, Lysimeters, Remote sensing, Water management.*

A fundamental problem in using remote sensing to estimate local and regional evapotranspiration (ET) involves the scaling of instantaneous latent heat flux (derived from remotely sensed surface temperature at a single time of day) to daily ET (the 24 h total). Remotely sensed data for this purpose are typically provided by satellite (e.g., Landsat, MODIS) or airborne platforms. Several scaling methods have been proposed that essentially rely on a ratio of latent heat flux and some other component that is available on an hourly basis, such as incoming energy or reference ET. During clear skies and in the absence of significant advected energy, daytime plots of these components will assume a quasi-sinusoidal shape, and their ratios have been observed to remain fairly constant (Crago, 1996a). This would allow estimation of daily ET provided the contribution of nighttime ET was relatively small (Jackson et al., 1983).

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One of the more common scaling methods uses the evaporative fraction (EF) (Crago, 1996a, 1996b; Crago and Brutsaert, 1996; Suleiman and Crago, 2004; Bastiaanssen et al., 1998), and daily ET is:

$$\mathrm{ET}_{24} = \left(\frac{-LE}{R_n - G}\right)\left(\frac{1000}{\rho_w \lambda}\right) R_{n24} \tag{1}$$

where ET_{24} is the daily (24 h) total ET (mm d^{-1}), LE is latent heat flux (W m^{-2}), R_n is net radiation (W m^{-2}), G is soil heat flux (W m^{-2}), ρ_w is the density of water (kg m^{-3}), λ is the latent heat of vaporization for water (MJ kg^{-1}), R_{n24} is the 24 h total net radiation (MJ m^{-2} d^{-1}), and $EF = -LE / (R_n - G)$. The numerical value of 1000 is used to convert meters to millimeters. The sign convention is positive towards the canopy.

Jackson et al. (1983) proposed a method based on incoming solar radiation:

$$\mathrm{ET}_{24} = \left(\frac{-LE}{R_s}\right)\left(\frac{1000}{\rho_w \lambda}\right) R_{s24} \tag{2}$$

where R_s and R_{s24} are instantaneous (W m^{-2}) and daily (MJ m^{-2} d^{-1}) incoming solar radiation, respectively. They showed that for clear skies, R_{s24}/R_s could be closely approximated by:

$$\frac{R_{s24}}{R_s} = \frac{2N}{10^6 \pi \sin(\pi t / N)} \tag{3}$$

where N is the total time from sunrise to sunset (s), and t is the time elapsed since sunrise (s). Jackson et al. (1983), Allen et al. (1998), and Evett (2002) give equations to compute N and t. Combining equations 2 and 3 and converting LE to the average hourly ET (depth basis) gives:

$$\mathrm{ET}_{24} = \mathrm{ET}\frac{2N}{\pi \sin(\pi t/N)} \qquad (4)$$

where ET (mm h^{-1}) represents the instantaneous latent heat flux, and N and t now have units of h.

French et al. (2005) used a scaling method containing both EF and the ratio of net to incoming solar radiation (R_n/R_s):

$$\mathrm{ET}_{24} = \left(\frac{-LE}{R_n - G}\right)\left(\frac{R_n}{R_s}\right)\left(\frac{1000}{\rho_w \lambda}\right) R_{s24} \qquad (5)$$

where all units are as defined previously. The rationale for including R_n/R_s appears to be added stability during daytime hours, since R_n can be related to R_s by simple linear expressions for clear skies (Fritschen, 1967; Alados et al., 2003).

Allen et al. (2002, 2003) and Tasumi et al. (2005) used a scaling method based on the reference ET for alfalfa (ET_r):

$$\mathrm{ET}_{24} = \left(\frac{\mathrm{ET}}{\mathrm{ET}_r}\right)\mathrm{ET}_{r24} \qquad (6)$$

where ET is the average hourly ET of the surface (mm h^{-1}), and ET_r and ET_{r24} are the hourly (mm h^{-1}) and daily (mm d^{-1}) reference ET for alfalfa, respectively. Note that $\mathrm{ET}/\mathrm{ET}_r$ is the crop coefficient for the alfalfa reference (K_{c-r}), which has been found to be constant (similar to EF) during the daytime (Allen et al., 2002). Alternatively, the reference ET for grass (ET_o) may be used:

$$\mathrm{ET}_{24} = \left(\frac{\mathrm{ET}}{\mathrm{ET}_o}\right)\mathrm{ET}_{o24} \qquad (7)$$

Both ET_r and ET_o were computed according to the ASCE standardized equations for reference ET (Allen et al., 2005), and 0.5 h sums were used to compute ET_{r24} and ET_{o24}.

The purpose of this article is to evaluate the five scaling methods given by equations 1, 4, 5, 6, and 7 for several surfaces by scaling ET measured at one time of day (0.5 h period) to a daily (24 h) total, and to determine the relative performance of each method using one-time-of-day ET measurements from mid-morning to mid-afternoon.

Procedure

This study was conducted at Bushland, Texas (35° 11′ N, 102° 06′ W, 1,170 m elevation MSL). Crop surfaces included fully irrigated alfalfa (irrigated to meet the full ET requirement; 1997, 1998, and 1999 seasons; Evett et al., 2000; Tolk et al., 2006), dryland grain sorghum (1997, 1998, and 1999 seasons), partially irrigated cotton (irrigated to meet 50% of the full ET requirement; 2000 and 2001 seasons; Howell et al., 2004), and bare soil after tilling residue from a grain sorghum crop (1992 season; Evett, 2002). The climate is semi-arid with an evaporative demand of approximately 2600 mm year^{-1} (class A pan evaporation) and precipitation of 480 mm year^{-1} (66-year average). Strong advection of heat energy from the south and southwest is typical. The soil was a Pullman clay loam (fine, mixed, super active, thermic torrertic Paleustolls) with slow permeability, having a dense Bt2 layer from about 0.15 to 0.40 m depth and a calcic horizon that begins at the 1.1 m depth (Taylor et al., 1963; Unger and Pringle, 1981).

Crop water use (evapotranspiration, ET) was measured by four large precision weighing lysimeters, which have been in continuous operation since 1987. The four lysimeters are arranged in a square pattern in a 20 ha field, where each lysimeter is located in the center of a 5 ha quadrant. The east quadrants are irrigated with a hose-fed lateral-move sprinkler, and the west quadrants are dryland and not irrigated (except for a preplant and post-emergence irrigation in some years when preseason precipitation was inadequate for germination). The lysimeters have a 9-m^2 surface area and 2.3-m deep monolithic cores. Change in lysimeter mass was converted to ET on a depth basis with an accuracy of 0.05 mm and reported every 0.5 h (Marek et al., 1988; Howell et al., 1995). Standard micrometeorological parameters were recorded from instrumented masts adjacent to each lysimeter every 6 s and reported as 0.5 h averages. Net radiation was measured with a REBS Q*5.5 net radiometer (REBS, Inc., Seattle, Wash.). Soil heat flux was measured with four REBS HFT-1 heat flux plates buried at 5 cm in the lysimeter with parallel-wired averaging thermocouples at 2 and 4 cm over each plate, and surface soil heat flux was estimated using a single layer approach (Evett, 2002).

Agreement between daily (24 h) ET measured by weighing lysimeters and daily ET predicted using equations 1, 4, 5, 6, or 7 was assessed for each surface. Each equation requires a one-time-of-day measurement of latent heat flux (LE) or ET. In equations 4, 6, and 7, 0.5 h ET totals measured by weighing lysimeters were used, but in equations 1 and 5, the 0.5 h ET totals were converted to LE (0.5 h averages). The influence of time of day was also considered by using ET (or LE) measured at five periods during daylight hours (9:30-10:00, 11:00-11:30, 12:30-13:00, 14:00-14:30, and 15:30-16:00 CST). These times were approximately ±1.5 h and ±3.0 h from solar noon, which occurs at 12:45 to 12:55 CST at our location. Data were screened for days on which unmeasured or poorly measured changes in the soil water balance could potentially compromise the integrity of ET measurements (e.g., rainfall, irrigation, instrument maintenance and repair, plant measurements), and data were further restricted to clear days when measured incoming solar radiation closely matched theoretical clear sky radiation (Allen et al., 1998). This resulted in 304 days for alfalfa, 59 days for partially irrigated cotton, 124 days for dryland grain sorghum, and 66 days for bare soil.

Model assessment consisted of the standard statistical parameters (observed mean and standard deviation; predicted mean and standard deviation; slope; intercept; coefficient of determination, r^2; and root mean squared error, RMSE), as well as non-squared parameters described by Legates and McCabe (1999) (modified index of agreement, D; modified coefficient of efficiency, ε; and mean absolute error, MAE). The modified index of agreement (D) is:

$$D = 1.0 - \frac{\sum_{i=1}^{N}\left|O_i - P_i\right|}{\sum_{i=1}^{N}\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|} \qquad (8)$$

where O_i is observed data, $\overline{O}$ is mean of observed data, and P_i is model-predicted value. The modified index of agreement (D) is similar to r^2 in that $0 \le D \le 1$, with greater values of D indicating better agreement between observed and predicted values. However, Legates and McCabe (1999) argued that D is less sensitive to outliers because errors and ranges are not inflated by squared values; therefore, D is not as subject to artificially high values as r^2. The modified coefficient of efficiency (ε) is:

$$\varepsilon = 1.0 - \frac{\sum_{i=1}^{N} \left| O_i - P_i \right|}{\sum_{i=1}^{N} \left| O_i - \overline{O} \right|} \quad (9)$$

The modified coefficient of efficiency (ε) in interpreted differently from D or r^2, where $-\infty \le \varepsilon \le 1$, and = 0 indicates that the mean of all observed values is as good a predictor as the model (if $\varepsilon < 0$, then the mean of observed values is actually a better predictor than the model). In addition, $(1 - \varepsilon)$ indicates the absolute error between observed and predicted values as a percentage of the observed variance. The mean absolute error (MAE) is:

$$\text{MAE} = \sum_{i=1}^{N} \frac{\left| O_i - P_i \right|}{N} \quad (10)$$

The mean absolute error (MAE) should be used in conjunction with RMSE, where the extent that RMSE > MAE indicates the extent of outliers in the data, and poor model performance can be interpreted when MAE is greater than 50% of the observed standard deviation. Legates and McCabe (1999) strongly recommended that observed and modeled means and standard deviations, D, ε, MAE, and RMSE be reported as the minimum for appropriate model assessment.

Results and Discussion

As a first assessment of model performance, the modified coefficient of efficiency (ε) was plotted for each model and field surface for the five 0.5 h time periods (fig. 1). In this article, all times reported are at the midpoint of the 0.5 h period. For alfalfa (fig. 1a), the scaling model based on reference ET for alfalfa (ET/ET_r, eq. 6) resulted in the greatest ε until after solar noon (12:45), when it became nearly equal to the scaling model based on reference ET for grass (eq. 7). The scaling models based on incoming solar radiation (eq. 4) and evaporative fraction − net to incoming solar radiation ratio (eq. 5) resulted in considerably less ε except for solar noon (12:45) and mid-afternoon (14:15). The scaling model based solely on evaporative fraction (eq. 1) resulted in the lowest ε except for late afternoon (15:45). The ET/ET_o and ET/ET_r models appeared least sensitive to time of day. The additional parameters of model performance for alfalfa exhibited a similar pattern as ε, in that the most favorable performance (e.g., greatest r^2 and D and lowest MAE and RMSE) occurred for ET/ET_o and ET/ET_r during the afternoon (table 1). In addition, MAE for these cases were approximately 10% of the observed standard deviation (3.26 mm d^{-1}), indicating good model agreement, and

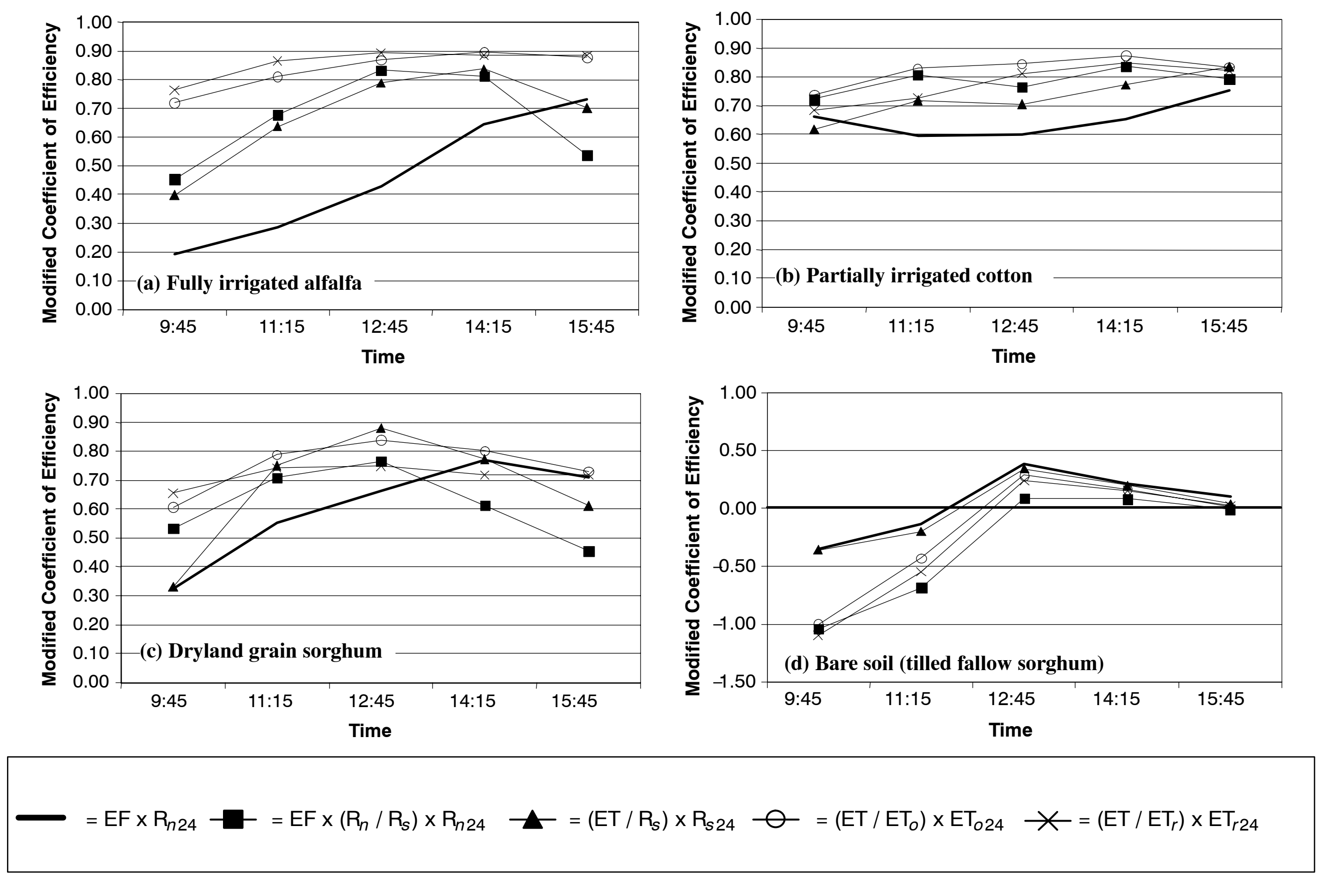


Figure 1. Modified coefficient of model efficiency (ε) of five models at five times of the day, where the times represent the midpoint of the 0.5 h period.

Table 1. Performance of five models at five times of the day for fully irrigated alfalfa (n = 304).

Model	Time	Observed (mm d^{-1}) Mean	Observed Std Dev	Predicted (mm d^{-1}) Mean	Predicted Std Dev	Slope	Intercept (mm d^{-1})	r^2	D	ε	MAE (mm d^{-1})	RMSE (mm d^{-1})
EF × R_{n24}	9:45	5.8	3.26	3.7	2.52	0.74[a]	−0.62[a]	0.92	0.61	0.19	2.14	2.40
EF × (R_n/R_s) × R_{n24}	9:45	5.8	3.26	4.4	2.88	0.84[a]	−0.48[a]	0.92	0.73	0.45	1.45	1.69
(ET/R_s) × R_{s24}	9:45	5.8	3.26	4.3	2.77	0.81[a]	−0.45[a]	0.91	0.70	0.40	1.59	1.85
(ET/ET$_o$) × ET$_{o24}$	9:45	5.8	3.26	5.3	3.22	0.96[a]	−0.28[a]	0.94	0.86	0.72	0.74	0.97
(ET/ET$_r$) × ET$_{r24}$	9:45	5.8	3.26	5.5	3.37	1.00	−0.28[a]	0.94	0.88	0.76	0.62	0.88
EF × R_{n24}	11:15	5.8	3.26	3.9	2.40	0.72[a]	−0.25[a]	0.95	0.64	0.29	1.89	2.16
EF × (R_n/R_s) × R_{n24}	11:15	5.8	3.26	5.0	2.80	0.84[a]	0.08	0.96	0.83	0.68	0.85	1.10
(ET/R_s) × R_{s24}	11:15	5.8	3.26	4.9	2.82	0.85[a]	−0.08	0.96	0.81	0.64	0.96	1.18
(ET/ET$_o$) × ET$_{o24}$	11:15	5.8	3.26	5.4	3.09	0.94[a]	−0.04	0.98	0.90	0.81	0.50	0.63
(ET/ET$_r$) × ET$_{r24}$	11:15	5.8	3.26	5.7	3.30	1.00	−0.09	0.98	0.93	0.87	0.36	0.46
EF × R_{n24}	12:45	5.8	3.26	4.3	2.55	0.76[a]	−0.14[a]	0.96	0.70	0.43	1.51	1.77
EF × (R_n/R_s) × R_{n24}	12:45	5.8	3.26	5.5	2.98	0.90[a]	0.28[a]	0.98	0.91	0.83	0.44	0.63
(ET/R_s) × R_{s24}	12:45	5.8	3.26	5.4	3.03	0.91[a]	0.05	0.97	0.89	0.79	0.56	0.75
(ET/ET$_o$) × ET$_{o24}$	12:45	5.8	3.26	5.6	3.16	0.96[a]	−0.03	0.99	0.93	0.87	0.35	0.46
(ET/ET$_r$) × ET$_{r24}$	12:45	5.8	3.26	5.9	3.35	1.02[a]	−0.08	0.99	0.95	0.89	0.29	0.38
EF × R_{n24}	14:15	5.8	3.26	4.9	2.86	0.85[a]	−0.06	0.95	0.82	0.64	0.94	1.21
EF × (R_n/R_s) × R_{n24}	14:15	5.8	3.26	6.1	3.29	0.99	0.36[a]	0.97	0.91	0.81	0.50	0.63
(ET/R_s) × R_{s24}	14:15	5.8	3.26	5.9	3.30	1.00	0.10	0.97	0.92	0.84	0.43	0.58
(ET/ET$_o$) × ET$_{o24}$	14:15	5.8	3.26	5.8	3.32	1.01	−0.13[a]	0.99	0.95	0.90	0.28	0.38
(ET/ET$_r$) × ET$_{r24}$	14:15	5.8	3.26	5.9	3.44	1.05[a]	−0.18[a]	0.99	0.94	0.89	0.30	0.44
EF × R_{n24}	15:45	5.8	3.26	6.1	3.31	0.97	0.46[a]	0.92	0.87	0.73	0.71	0.99
EF × (R_n/R_s) × R_{n24}	15:45	5.8	3.26	7.0	3.61	1.09[a]	0.71[a]	0.96	0.78	0.54	1.22	1.43
(ET/R_s) × R_{s24}	15:45	5.8	3.26	6.6	3.58	1.08[a]	0.28[a]	0.97	0.86	0.70	0.79	1.02
(ET/ET$_o$) × ET$_{o24}$	15:45	5.8	3.26	6.0	3.39	1.03[a]	−0.02	0.99	0.94	0.88	0.33	0.44
(ET/ET$_r$) × ET$_{r24}$	15:45	5.8	3.26	5.9	3.39	1.03[a]	−0.11[a]	0.99	0.94	0.88	0.31	0.41

[a] Slope or intercept is not significantly different from one or zero, respectively (two−tailed Student t test, α = 0.05).

Table 2. Performance of five models at five times of the day for partially irrigated cotton (n = 59).

Model	Time	Observed (mm d^{-1}) Mean	Observed Std Dev	Predicted (mm d^{-1}) Mean	Predicted Std Dev	Slope	Intercept (mm d^{-1})	r^2	D	ε	MAE (mm d^{-1})	RMSE (mm d^{-1})
EF × R_{n24}	9:45	3.9	1.93	3.4	1.75	0.87[a]	−0.01	0.91	0.83	0.66	0.56	0.78
EF × (R_n/R_s) × R_{n24}	9:45	3.9	1.93	3.8	1.93	0.95	0.15	0.90	0.86	0.72	0.46	0.61
(ET/R_s) × R_{s24}	9:45	3.9	1.93	3.3	1.80	0.90[a]	−0.22	0.92	0.81	0.62	0.64	0.82
(ET/ET$_o$) × ET$_{o24}$	9:45	3.9	1.93	4.1	2.15	1.08[a]	−0.13	0.94	0.88	0.74	0.44	0.57
(ET/ET$_r$) × ET$_{r24}$	9:45	3.9	1.93	4.2	2.23	1.12[a]	−0.12	0.93	0.85	0.68	0.53	0.69
EF × R_{n24}	11:15	3.9	1.93	3.2	1.60	0.81[a]	0.10	0.95	0.78	0.59	0.68	0.83
EF × (R_n/R_s) × R_{n24}	11:15	3.9	1.93	3.8	1.75	0.89[a]	0.39[a]	0.96	0.90	0.81	0.32	0.42
(ET/R_s) × R_{s24}	11:15	3.9	1.93	3.4	1.76	0.89[a]	−0.03	0.97	0.85	0.72	0.47	0.58
(ET/ET$_o$) × ET$_{o24}$	11:15	3.9	1.93	4.0	2.02	1.03	0.05	0.97	0.92	0.83	0.29	0.39
(ET/ET$_r$) × ET$_{r24}$	11:15	3.9	1.93	4.3	2.14	1.09[a]	0.03	0.97	0.87	0.73	0.45	0.58
EF × R_{n24}	12:45	3.9	1.93	3.3	1.61	0.81[a]	0.13	0.93	0.79	0.60	0.67	0.85
EF × (R_n/R_s) × R_{n24}	12:45	3.9	1.93	3.8	1.72	0.87[a]	0.46[a]	0.95	0.87	0.77	0.39	0.47
(ET/R_s) × R_{s24}	12:45	3.9	1.93	3.4	1.76	0.89[a]	−0.05	0.95	0.85	0.70	0.49	0.64
(ET/ET$_o$) × ET$_{o24}$	12:45	3.9	1.93	3.8	1.93	0.99	−0.01	0.97	0.92	0.85	0.26	0.33
(ET/ET$_r$) × ET$_{r24}$	12:45	3.9	1.93	4.0	2.04	1.04	−0.01	0.97	0.91	0.81	0.31	0.38
EF × R_{n24}	14:15	3.9	1.93	3.3	1.75	0.89[a]	−0.13	0.95	0.82	0.65	0.58	0.72
EF × (R_n/R_s) × R_{n24}	14:15	3.9	1.93	3.8	1.85	0.94[a]	0.18	0.97	0.92	0.84	0.27	0.36
(ET/R_s) × R_{s24}	14:15	3.9	1.93	3.6	1.84	0.93[a]	−0.04	0.96	0.88	0.77	0.38	0.50
(ET/ET$_o$) × ET$_{o24}$	14:15	3.9	1.93	3.8	1.96	1.01	−0.09	0.98	0.94	0.88	0.21	0.28
(ET/ET$_r$) × ET$_{r24}$	14:15	3.9	1.93	4.0	2.05	1.05[a]	−0.14	0.98	0.93	0.85	0.25	0.32
EF × R_{n24}	15:45	3.9	1.93	3.7	1.88	0.94	0.02	0.93	0.88	0.76	0.41	0.55
EF × (R_n/R_s) × R_{n24}	15:45	3.9	1.93	4.0	1.95	0.98	0.20	0.95	0.90	0.79	0.35	0.46
(ET/R_s) × R_{s24}	15:45	3.9	1.93	3.9	1.86	0.95	0.18	0.97	0.92	0.84	0.27	0.36
(ET/ET$_o$) × ET$_{o24}$	15:45	3.9	1.93	3.9	1.96	0.99	−0.01	0.96	0.92	0.83	0.28	0.38
(ET/ET$_r$) × ET$_{r24}$	15:45	3.9	1.93	3.8	2.00	1.01	−0.11	0.96	0.91	0.82	0.30	0.41

[a] Slope or intercept is not significantly different from one or zero, respectively (two−tailed Student t test, α = 0.05).

RMSE was not greater than 50% of MAE, indicating a general absence of outliers (Legates and McCabe, 1999).

The ET/ET$_o$ model resulted in the greatest ε for all five time periods for the partially irrigated cotton (fig. 1b).

Similar to alfalfa, the EF model resulted in the lowest ε (except for 9:45); however, the ε for the EF model was greater for cotton than for alfalfa. The EF, EF × R_n/R_s, and ET/R_s models appeared less sensitive to time of day for cotton than for alfalfa. The D, r^2, MAE, and RMSE parameters also suggested that the ET/ET_o model performed best for cotton, especially during the afternoon (table 2). The MAE for these cases were less than 15% of the observed standard deviation (1.93 mm d^{-1}), also indicating good model agreement, and RMSE was not greater than 30% of MAE, also indicating the data were mostly free of outliers.

The ε values for the dryland grain sorghum were less consistent during the day than for alfalfa or cotton, although the ET/ET_o model resulted in the largest ε three out of five times (fig. 1c). Interestingly, the ET/R_s model had the largest ε at solar noon (12:45), followed by the ET/ET_o model. All models for grain sorghum (except the EF model) had the best performance at solar noon, when peak energy exchange mostly likely occurred (table 3). As a general recommendation for cropped surfaces, the ET/ET_o scaling model would, in most cases, result in the best prediction of daily ET, where the one-time-of-day ET measurement around solar noon was used. Both the ET/ET_o and ET/ET_r scaling models appeared more stable throughout the day than the other models, an important consideration because the time of a remote sensing platform overpass may vary.

Model performance for bare soil (following tillage of grain sorghum stubble) was poor according to values of ε (fig. 1d) and other parameters (table 4) throughout the day. For all models, ε was less than zero during the morning and late afternoon (except EF), indicating that the observed mean of daily ET (1.4 mm d^{-1}) was a better predictor than any model at these times. All models had the greatest ε at solar noon. Although all ε values were greater than zero, the greatest ε (0.38 for the EF model) was much lower than for all other surfaces, and MAE (0.37 mm d^{-1}) was almost 50% of the observed standard deviation (0.76 mm d^{-1}). Unlike the other surfaces, the EF model appeared to have the least poor performance, but similar to the other surfaces, the bare soil data appeared free of outliers because RMSE was not greater than 50% of MAE.

The disparity in model performance between the cropped surfaces and bare soil was mostly related to signal-to-noise ratios of measured ET. The magnitude of the relative model error increased as ET decreased (fig. 2), where relative error was defined as $[(O_i - P_i)/O_i] \times 100\%$, and O_i and P_i are observed and predicted daily ET, respectively. The predicted daily ET (P_i) in figure 2 was computed using ET/ET_o for the crops and EF for the bare soil during the solar noon time period (12:45). Relative error was within 10% for daily ET greater than 6 mm d^{-1} and within 20% for daily ET greater than 3 mm d^{-1}. Most relative error greater than 20% only occurred for the bare soil, which had daily ET values ranging from only 0.42 to 3.16 mm d^{-1}. This result would be expected, since for a given measurement precision, relative error between a measured value and simulated values increases as the measured value decreases.

The effect of other variables on model performance were investigated, including the proportion of nighttime ET to daily ET, wind speed, variance of scaling factors during the daytime, and correlation between measured ET and quasi-sinusoidal parameters (i.e., ET_o, ET_r, R_s, and $R_n - G$) during the daytime. These variables conceivably could have also influenced the poor model performance observed for bare soil.

Table 3. Performance of five models at five times of the day for dryland grain sorghum (n = 124).

Model	Time	Observed (mm d^{-1}) Mean	Observed Std Dev	Predicted (mm d^{-1}) Mean	Predicted Std Dev	Slope	Intercept (mm d^{-1})	r^2	D	ε	MAE (mm d^{-1})	RMSE (mm d^{-1})
$EF \times R_{n24}$	9:45	4.1	1.84	3.1	1.51	0.74[a]	0.05	0.82	0.65	0.32	1.08	1.27
$EF \times (R_n/R_s) \times R_{n24}$	9:45	4.1	1.84	3.6	1.68	0.82[a]	0.23	0.81	0.76	0.53	0.75	0.93
$(ET/R_s) \times R_{s24}$	9:45	4.1	1.84	3.1	1.48	0.76[a]	−0.05	0.90	0.65	0.33	1.07	1.21
$(ET/ET_o) \times ET_{o24}$	9:45	4.1	1.84	3.6	1.66	0.86[a]	0.06	0.90	0.80	0.61	0.63	0.79
$(ET/ET_r) \times ET_{r24}$	9:45	4.1	1.84	3.7	1.69	0.87[a]	0.12	0.90	0.82	0.65	0.55	0.71
$EF \times R_{n24}$	11:15	4.1	1.84	3.4	1.64	0.84[a]	−0.01	0.89	0.77	0.55	0.72	0.88
$EF \times (R_n/R_s) \times R_{n24}$	11:15	4.1	1.84	4.2	1.87	0.96	0.26	0.89	0.86	0.71	0.47	0.61
$(ET/R_s) \times R_{s24}$	11:15	4.1	1.84	3.7	1.77	0.94[a]	−0.09	0.96	0.87	0.75	0.40	0.50
$(ET/ET_o) \times ET_{o24}$	11:15	4.1	1.84	4.0	1.87	0.99	0.00	0.95	0.90	0.79	0.34	0.44
$(ET/ET_r) \times ET_{r24}$	11:15	4.1	1.84	4.3	1.96	1.04	0.04	0.94	0.88	0.74	0.41	0.52
$EF \times R_{n24}$	12:45	4.1	1.84	3.6	1.76	0.93[a]	−0.23[a]	0.95	0.83	0.67	0.54	0.64
$EF \times (R_n/R_s) \times R_{n24}$	12:45	4.1	1.84	4.4	1.99	1.06[a]	0.03	0.96	0.89	0.77	0.38	0.50
$(ET/R_s) \times R_{s24}$	12:45	4.1	1.84	4.1	1.95	1.05[a]	−0.19[a]	0.98	0.94	0.88	0.19	0.27
$(ET/ET_o) \times ET_{o24}$	12:45	4.1	1.84	4.2	1.96	1.05[a]	−0.11	0.98	0.92	0.84	0.26	0.34
$(ET/ET_r) \times ET_{r24}$	12:45	4.1	1.84	4.4	2.05	1.10[a]	−0.10	0.97	0.88	0.75	0.40	0.51
$EF \times R_{n24}$	14:15	4.1	1.84	3.9	1.90	1.01	−0.16	0.95	0.89	0.77	0.37	0.45
$EF \times (R_n/R_s) \times R_{n24}$	14:15	4.1	1.84	4.7	2.09	1.12[a]	0.10	0.96	0.82	0.61	0.62	0.74
$(ET/R_s) \times R_{s24}$	14:15	4.1	1.84	4.4	2.04	1.10[a]	−0.12	0.98	0.89	0.77	0.36	0.45
$(ET/ET_o) \times ET_{o24}$	14:15	4.1	1.84	4.3	2.02	1.08[a]	−0.12	0.97	0.91	0.80	0.32	0.42
$(ET/ET_r) \times ET_{r24}$	14:15	4.1	1.84	4.5	2.11	1.13[a]	−0.15	0.97	0.87	0.72	0.45	0.59
$EF \times R_{n24}$	15:45	4.1	1.84	4.4	2.03	1.06	0.09	0.92	0.86	0.71	0.47	0.69
$EF \times (R_n/R_s) \times R_{n24}$	15:45	4.1	1.84	4.9	2.16	1.14[a]	0.26	0.94	0.75	0.45	0.87	1.02
$(ET/R_s) \times R_{s24}$	15:45	4.1	1.84	4.6	2.09	1.12[a]	0.08	0.96	0.82	0.61	0.62	0.72
$(ET/ET_o) \times ET_{o24}$	15:45	4.1	1.84	4.4	2.03	1.08[a]	−0.03	0.95	0.87	0.73	0.43	0.54
$(ET/ET_r) \times ET_{r24}$	15:45	4.1	1.84	4.3	2.07	1.09[a]	−0.12	0.94	0.87	0.72	0.45	0.58

[a] Slope or intercept is not significantly different from one or zero, respectively (two-tailed Student t test, α = 0.05).

Table 4. Performance of five models at five times of the day for bare soil (tilled fallow sorghum) (n = 66).

Model	Time	Observed (mm d^{-1}) Mean	Observed (mm d^{-1}) Std Dev	Predicted (mm d^{-1}) Mean	Predicted (mm d^{-1}) Std Dev	Slope	Intercept (mm d^{-1})	r^2	D	ε	MAE (mm d^{-1})	RMSE (mm d^{-1})
EF × R_{n24}	9:45	1.4	0.76	1.8	1.40	1.36	−0.10	0.53	0.52	−0.35	0.82	1.07
EF × (R_n/R_s) × R_{n24}	9:45	1.4	0.76	2.3	1.73	1.62[a]	0.02	0.50	0.39	−1.04	1.24	1.57
(ET/R_s) × R_{s24}	9:45	1.4	0.76	1.8	1.41	1.38[a]	−0.15	0.54	0.51	−0.36	0.83	1.06
(ET/ET_o) × ET_{o24}	9:45	1.4	0.76	2.2	1.74	1.64[a]	−0.07	0.51	0.39	−1.00	1.22	1.54
(ET/ET_r) × ET_{r24}	9:45	1.4	0.76	2.3	1.80	1.69[a]	−0.07	0.50	0.38	−1.10	1.28	1.62
EF × R_{n24}	11:15	1.4	0.76	1.8	1.27	1.11	0.29	0.43	0.52	−0.14	0.69	1.05
EF × (R_n/R_s) × R_{n24}	11:15	1.4	0.76	2.3	1.50	1.27	0.52	0.41	0.40	−0.69	1.03	1.47
(ET/R_s) × R_{s24}	11:15	1.4	0.76	1.9	1.27	1.09	0.36	0.42	0.49	−0.20	0.73	1.08
(ET/ET_o) × ET_{o24}	11:15	1.4	0.76	2.1	1.34	1.06	0.63	0.36	0.44	−0.43	0.87	1.28
(ET/ET_r) × ET_{r24}	11:15	1.4	0.76	2.2	1.41	1.11	0.65	0.35	0.42	−0.55	0.94	1.39
EF × R_{n24}	12:45	1.4	0.76	1.5	0.84	0.93	0.18	0.69	0.70	0.38	0.37	0.47
EF × (R_n/R_s) × R_{n24}	12:45	1.4	0.76	1.8	0.97	1.03	0.37[a]	0.64	0.60	0.09	0.56	0.71
(ET/R_s) × R_{s24}	12:45	1.4	0.76	1.5	0.81	0.85	0.33[a]	0.63	0.68	0.35	0.40	0.52
(ET/ET_o) × ET_{o24}	12:45	1.4	0.76	1.6	0.78	0.78[a]	0.50[a]	0.56	0.65	0.29	0.43	0.57
(ET/ET_r) × ET_{r24}	12:45	1.4	0.76	1.7	0.82	0.81	0.52[a]	0.56	0.63	0.24	0.46	0.62
EF × R_{n24}	14:15	1.4	0.76	1.3	0.90	0.84	0.15	0.50	0.64	0.21	0.48	0.64
EF × (R_n/R_s) × R_{n24}	14:15	1.4	0.76	1.6	1.02	0.91	0.29	0.46	0.61	0.08	0.56	0.77
(ET/R_s) × R_{s24}	14:15	1.4	0.76	1.3	0.89	0.78	0.27	0.43	0.63	0.20	0.49	0.69
(ET/ET_o) × ET_{o24}	14:15	1.4	0.76	1.3	0.87	0.70[a]	0.38	0.37	0.60	0.17	0.51	0.72
(ET/ET_r) × ET_{r24}	14:15	1.4	0.76	1.4	0.89	0.73[a]	0.39	0.38	0.60	0.15	0.52	0.72
EF × R_{n24}	15:45	1.4	0.76	1.3	1.25	1.14	−0.31	0.48	0.63	0.11	0.54	0.91
EF × (R_n/R_s) × R_{n24}	15:45	1.4	0.76	1.4	1.41	1.20	−0.22	0.41	0.60	−0.01	0.61	1.09
(ET/R_s) × R_{s24}	15:45	1.4	0.76	1.2	1.29	1.03	−0.18	0.36	0.60	0.04	0.58	1.03
(ET/ET_o) × ET_{o24}	15:45	1.4	0.76	1.2	1.28	0.93	−0.08	0.30	0.57	0.01	0.60	1.08
(ET/ET_r) × ET_{r24}	15:45	1.4	0.76	1.2	1.27	0.92	−0.08	0.30	0.57	0.02	0.60	1.07

[a] Slope or intercept is not significantly different from one or zero, respectively (two−tailed Student t test, α = 0.05).

The scaling models described herein assume that most ET occurs during daylight hours with little contribution of nighttime ET to daily totals. This appears to be a valid assumption for the present data set (fig. 3). The average nighttime to daily ET ratios for alfalfa, cotton, grain sorghum, and bare soil were 0.07, 0.07, 0.04, and 0.16, respectively, although much of the data ranges almost to 0.2 for ET rates less than approximately 7 mm d^{-1}. Negative ratios indicate nighttime condensation. The amount of nighttime ET depends on climate (e.g., vapor pressure deficit, wind speed, sensible heat flux gain), irrigation practices, and type of surface (Jackson et al., 1983; Tolk et al., 2006). Nighttime ET at our location was generally less than 1 mm d^{-1}, and ratios greater than 0.10 usually occurred only when daily ET was less than about 6 mm d^{-1}. Attempts to correct for nighttime ET by multiplying daily totals by a factor (Jackson et al., 1983) did not improve model performance, and we observed no correlation between the proportion of nighttime ET to daily ET and model performance for any surface.

Wind speed is directly related to the standard deviation of mass measured by the weighing lysimeters, and standard deviations were greater for bare soil than for crops, since turbulent mixing inside the crop canopy will dissipate some of the momentum transferred to the lysimeter surface (Howell et al., 1995; Evett, 2002). The high winds typical for our location would be expected to degrade the precision of lysimeter measurements and hence degrade model agree−

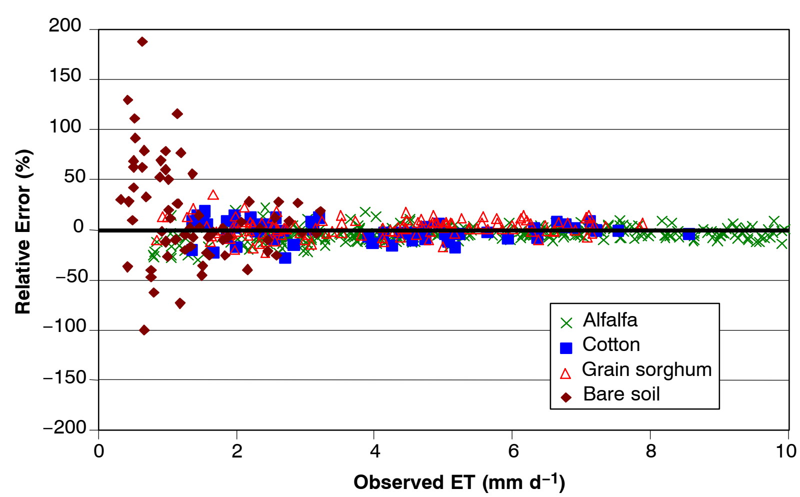


Figure 2. Relative model error [(P_i – O_i)/O_i, where O_i and P_i are observed and predicted daily ET, respectively] vs. observed daily (24 h) ET.

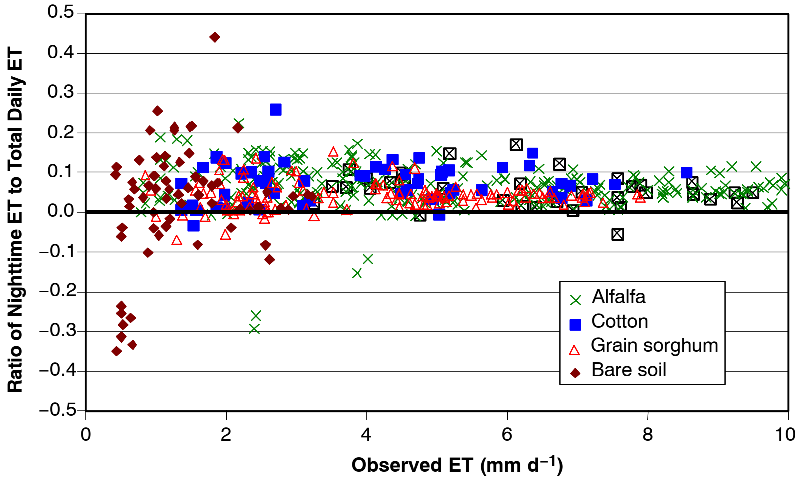


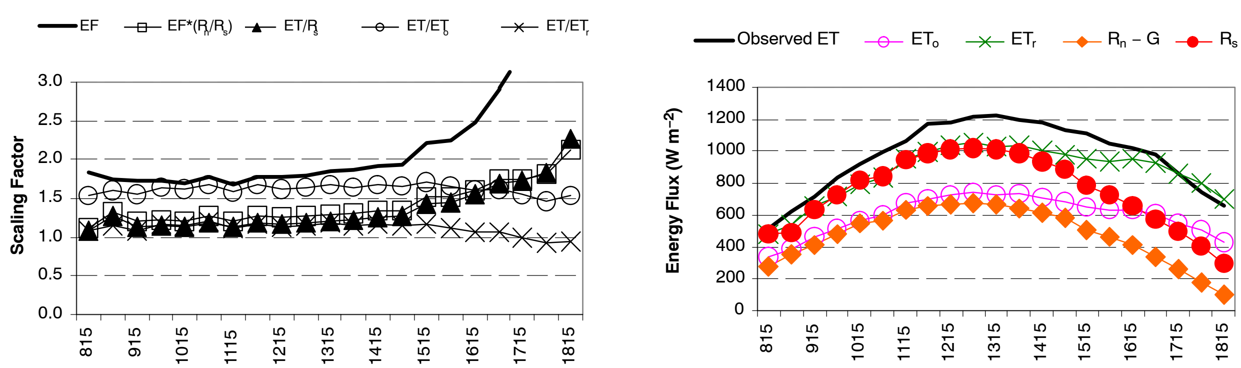
Figure 3. Ratio of observed nighttime ET to observed daily (24 h) ET vs. observed daily ET.

ment (especially for bare soil, where ET values were relatively small); however, we observed no relation between wind speed and model performance for any surface, considering all days.

The extent that daytime ET follows a quasi-sinusoidal shape has direct bearing on how constant the scaling factor is during the daytime, which is a basic assumption of each scaling model. Therefore, we checked for relationships between model performance and the variance of daytime scaling factors, and relationships between model performance and the correlation between daytime ET and quasi-sinusoidal parameters (i.e., ET_o, ET_r, R_s, and $R_n - G$). Although no relationships were observed, the following examples illustrate the daytime behavior of scaling factors and energy flux components for alfalfa during highly advective conditions (i.e., high wind speed), alfalfa during relatively low advection (i.e., low wind speed), and bare soil during moderate wind speeds.

The scaling factors for fully irrigated alfalfa under strong regional advection were observed as fairly constant from 8:00 to around 15:00 (fig. 4a). Wind speed at the 2 m height exceeded 11 m s^{-1} at solar noon. Measured ET appeared quasi-sinusoidal, as were each scaling parameter (ET, ET_o, and ET_r were converted to energy flux for plotting with $R_n - G$ and R_s) (fig. 4b). Sensible heat flux contributed significantly to the energy balance (not shown), and measured ET exceeded both $R_n - G$ and R_s all day. Measured and predicted daily ET (using the ET/ET_o model at solar noon) was 18.1 and 17.8 mm d^{-1}, respectively, which agreed very well. On another day with much less advection (i.e., midday wind speeds at the 2 m height were around 3.0 m s^{-1}), daytime scaling factors were also fairly constant (fig. 5a) and somewhat less than those in figure 4a. Measured ET and scaling parameters (converted to energy flux where necessary) also appeared quasi-sinusoidal (fig. 5b), but measured ET flux was much less compared with figure 4b and was very similar in value to $R_n - G$ and ET_r. Measured and predicted daily ET was 9.5 and 8.4 mm d^{-1}, respectively.

The measured ET values for bare soil, on the other hand, were relatively small (0.00 to 0.13 mm per 0.5 h) and similar to the noise levels expected for measured changes in lysimeter mass (0.05 mm), resulting a rather non-sinusoidal shape (fig. 6b). Consequently, the scaling factors for bare soil were often variable during the daytime (fig. 6a). Measured and predicted daily ET (using the EF model at solar noon) were 0.97 and 1.73 mm d^{-1}, respectively. The overestimation of daily ET was likely because EF was at a local maximum (0.38) at solar noon; underestimation would have resulted if EF at 13:15 or 16:45 had been used. Comparison of figures 4, 5, and 6 further illustrates why daily ET scaling models performed relatively well for transpiring crops but poorly for bare soil.



(a) (b)

Figure 4. (a) Daytime scaling factors, and (b) energy flux components for alfalfa (LAI = 2.4) at the southeast lysimeter on DOY 164, 1998, during strong regional advection. Observed and predicted daily ET was 18.1 and 17.8 mm d^{-1}, respectively, and wind speed measured at the 2 m height was 11.2 m s^{-1} at solar noon.

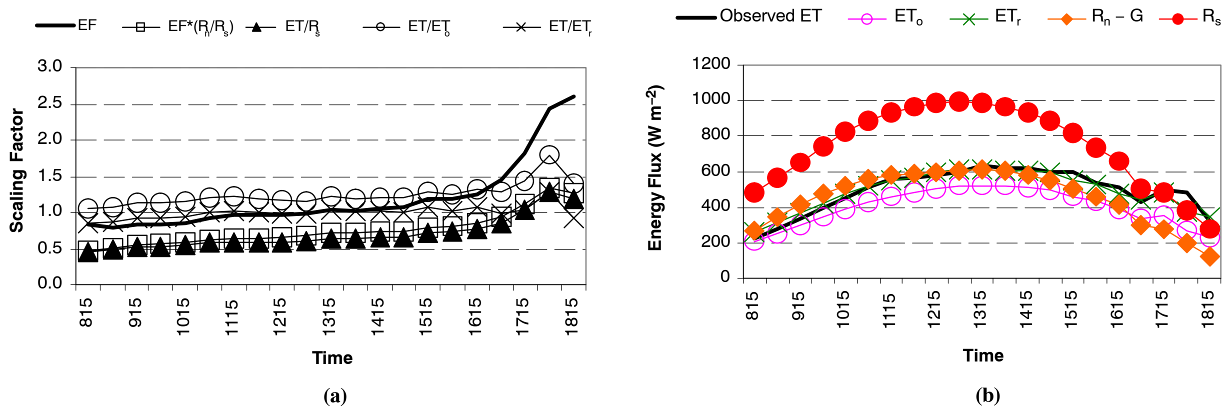


Figure 5. (a) Daytime scaling factors, and (b) energy flux components for alfalfa (LAI = 2.9) at the southeast lysimeter on DOY 172, 1998, with relatively low advection. Observed and predicted daily ET was 9.5 and 8.4 mm d^{-1}, respectively, and wind speed measured at the 2 m height was 3.0 m s^{-1} at solar noon.

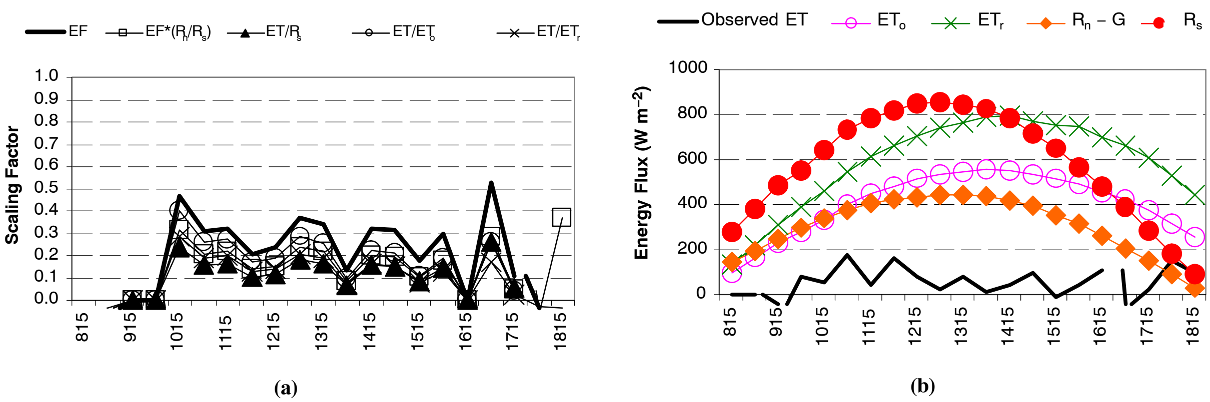


Figure 6. (a) Daytime scaling factors, and (b) energy flux components for bare soil (tilled fallow sorghum) at the northwest lysimeter on DOY 261, 1992. Observed and predicted daily ET was 0.97 and 1.73 mm d^{-1}, respectively.

Conclusion

Five scaling models that estimate daily ET given a one-time-of-day measurement of ET were evaluated for fully irrigated alfalfa, partially irrigated cotton, dryland grain sorghum, and bare soil during clear days. The five scaling models used the evaporative fraction, incoming solar radiation, ratio of net to incoming solar radiation, reference ET for grass, or reference ET for alfalfa as the daytime quasi-sinusoidal parameter. For transpiring crops (alfalfa, cotton, and grain sorghum), the model based on reference ET for grass resulted in the best model agreement in most cases. For bare soil, the model based on evaporative fraction resulted in the best agreement. Model agreement was usually best for crops when the one-time-of-day ET measurement was used within 1 or 2 h of solar noon, when energy flux components were at daily maxima.

Relative error between observed and predicted daily ET was directly related to observed daily ET. Observed and predicted daily ET agreed well for the transpiring crops (RMSE of 0.33 to 0.46 mm d^{-1} for mean daily ET of 3.9 to 5.8 mm d^{-1}) but poorly for bare soil (RMSE of 0.47 mm d^{-1} for mean daily ET of 1.4 mm d^{-1}). We therefore recommend using the model based on the grass reference ET, where the one-time-of-day ET measurement occurs within 1 or 2 h of solar noon, to estimate daily ET for transpiring vegetation. For bare soil or other surfaces having low ET rates (i.e., $\leq$3 mm d^{-1}), the scaling model based on evaporative fraction at solar noon may give slightly better estimates than seasonal means. Regardless of the scaling model used, the resulting daily ET values should be verified for reasonable values.

Finally, we emphasize that the one-time-of-day ET measurements used in this study were 0.5 h averages, and these were intended to represent instantaneous latent heat flux estimated by remotely sensed surface temperature. Consequently, agreement between observed daily ET and ET predicted with instantaneous flux may not be as good as the results reported here. The next step in this research is to apply remote sensing algorithms to estimate daily ET.

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