Chapter 7.

ENERGY BALANCE MODEL OF EVAPORATION: EXPERIMENT 3

Two improved versions of the EBM were demonstrated in Chapter 5. These were EBM2 and EBM3, and they differed only in that EBM3 used a separate empirically fitted transfer coefficient function for sensible heat flux from the reference dry soil. In this chapter validation of EBM2 and EBM3 is attempted using the data from Run 2 of Experiment 3. Also, a fourth and final form of the EBM (EBM4) is introduced. EBM4 features an empirical transfer coefficient function that was best fit using the Experiment 3 data set which was both larger and more precise than the Experiment 2 data set.

The loss of soil temperature data precluded validaton against data from Run 1. The data consisted of daily ML mass changes measured between 7 and 8 AM each day; meteorological data gathered on a 15 minute interval at weather stations situated at opposite ends of the field; soil temperature data recorded on a 15 minute basis at 0, 15 and 30 cm depth at a mid-field location; and ML and reference dry soil daily minimum and maximum temperatures measured by infrared thermometer. The 57 ML's were arranged in the field as shown in Figure 2-4. Irrigation was on day 328 and measurements were taken on days 329 through 338.

Validation.

Both evaporation models (EBM2 and EBM3) were numerically integrated on a 15 minute time step from 7:30 AM on each day until 7:30 AM on the next day (approximate time of ML weighing). For each ML, soil surface temperatures, T_d, were scaled from temperatures, FT, measured at 2 mid-field locations (thermistors #1 and #4) using the daily maximum and minimum IR temperatures. Equation 6-8 was used to scale the temperatures but the definition of FL_{min} was changed depending on time of day:

$$T_d = b_0 + b_1(FT) \quad [7\text{-}1]$$

where

$$b_1 = (MLIR_{max} - MLIR_{min})/(FL_{max} - FL_{min}) \quad [7\text{-}2]$$

$$b_0 = MLIR_{max} - b_1(FL_{max}) \quad [7\text{-}3]$$

and where FL_{max} was the maximum field soil temperature measured by thermistor. From 7:30 AM to 1:00 PM, FL_{min} was the minimum field soil temperature measured by thermistor on the current day. From 1:00 PM until 7:30 AM on the next day, FL_{min} was defined as the minimum temperature measured on the next day. This method gave better response to changing temperatures as cold or warm fronts moved in than did the method used in Chapter 5.

Reference dry soil surface temperatures were scaled using IR temperatures in the same fashion but, since no thermistor measurements were made of the reference temperature, the thermistor temperatures from the mid-field locations were used instead as the base for scaling. Only positive values of evaporation were summed since the dewpoint was never reached during Experiment 2.

To evaluate model output, regressions of actual, E_a, versus estimated evaporation, E_{est}, were performed. Results varied depending on which thermistor location (#1 or #2) was used for surface temperature data; and, depending on which model was used (Table 7-1). The r^2 value was lowest, at 0.67, for thermistor location #1 and EBM2, rising to 0.72 when thermistor #4 was used. This result indicated sensitivity to thermistor placement. Two problems were apparent in field use of the thermistors for surface temperature measurements. First, the thermistor provides nearly a point measurement whereas an areal average measurement might be more appropriate for use in the EBM. Second, it was difficult to place and maintain the thermistors just beneath the surface. Depending on placement the thermistors could give a measurement of temperature just below the surface or, if exposed to the sun, could give overestimates of surface temperature. When EBM3 was used, the difference in r^2 values was lower with values of 0.76 and 0.78 when thermistors #1 and #4 were used, respectively.

Table 7-1.

Equations for regression of actual evaporation versus that estimated by EBM2, EBM3 and EBM4 using either thermistor #1 or #4 for temperature data.

<u>EBM2:</u> $D_{H,o} = 0.0022\ u$

<u>Thermistor #1</u>

$E_a = -1.192 + 1.021\ E_{est}$, $r^2 = 0.667$

<u>Thermistor #4</u>

$E_a = -1.162 + 1.023\ E_{est}$, $r^2 = 0.720$

<u>EBM3:</u> $D_{H,o} = 0.00427$

<u>Thermistor #1</u>

$E_a = -1.555 + 1.232\ E_{est}$, $r^2 = 0.760$

<u>Thermistor #4</u>

$E_a = -1.462 + 1.219\ E_{est}$, $r^2 = 0.778$

<u>EBM4:</u> $D_{H,o} = 0.00383$

<u>Thermistor #1</u>

$E_a = -1.452 + 1.227\ E_{est}$, $r^2 = 0.767$

<u>Thermistor #4</u>

$E_a = -1.378 + 1.218\ E_{est}$, $r^2 = 0.780$

The difference between EBM2 and EBM3 was the use, in EBM3, of an empirically fitted function for the transfer coefficient for sensible heat flux from dry soil. The higher and more consistent r^2 values indicated both that the transfer coefficient function improved model performance and that its use tended to eliminate differences due to the different thermistors. Regardless of the thermistor used for temperature data, EBM3 explained more of the variability in evaporation than did the term $(T_{o,max} - T_{d,max})$. Regression of E_a versus $(T_{o,max} - T_{d,max})$ resulted in an r^2 value of 0.70.

Empirical Transfer Coefficients and
Fourth Improved Energy Balance Model.

The Experiment 3 data set was both larger (57 ML vs. 17 ML) and more precise (weighing of ML's was more precise for Experiment 3) than the Experiment 2 data set used in the fitting of parameters for the empirical transfer coefficient function developed in Chapter 6 (Equation 6-25). Therefore a second search was conducted for the "best" fit parameters in the function for the sensible heat flux transfer coefficient, $D_{h,o}$, for the reference dry soil. Recall that this function had the form:

$$D_{h,o} = c_0 + u^{c_1} \qquad [7\text{-}4]$$

where c_0 and c_1 were the parameters to be fitted. The values of c_0 and c_1 were varied from 0.005 to 0.002 and from 0.5 to -0.1, respectively. For every combination of c_0 and c_1, values of daily evaporation were estimated for the 57 ML's and 9 days and the sum of squared error (SSE) was calculated for measured vs. estimated evaporation. Temperature data from thermistor #4 were used. Values of c_0 and c_1 resulting in the lowest SSE were considered the best fit values. The best fit values were 0.00383 and -0.002 for c_0 and c_1, respectively. When the value of c_1 was fixed at zero the best fit value for c_0 was again 0.00383. Therefore the value of c_1 was left at zero.

The best fit transfer coefficient function was thus established as:

$$D_{h,o} = 0.00383 \qquad [7\text{-}5]$$

The r^2 value was 0.780 for regression of estimated vs. measured evaporation, only slightly better than that obtained when using Equation 6-25 for the transfer coefficient for dry soil (i.e. EBM3, Table 7-1). However, since the data set was judged better than that used previously, Equation 7-5 was adopted as the final form of the transfer coefficient function. The fourth improved energy balance model (call it EBM4) thus consisted of Equation 6-18 with dry and drying soil temperatures given by Equations 6-8 and 6-9, repectively, and with $D_{h,d}$ and $D_{h,o}$ given by Equations 6-12 and 7-5, respectively.

When temperature data from thermistor #1 were used with EBM4 to estimate evaporation the regression of E_a vs. E_{est} resulted in a regression relationship and r^2 value that were nearly identical to those found using thermistor #4 data (Table 7-1). Comparing the results using first EMB2, then EBM3 and finally EBM4 (Table 7-1), each with an improved function describing sensible heat flux, it is clear that the sensitivity to the source of soil temperature data decreases. Thus it appears that, with a proper function describing $D_{h,o}$, the model is nearly insensitive to the provenance of soil temperature data so long as those data are properly scaled using Equations 6-8 and 6-9.

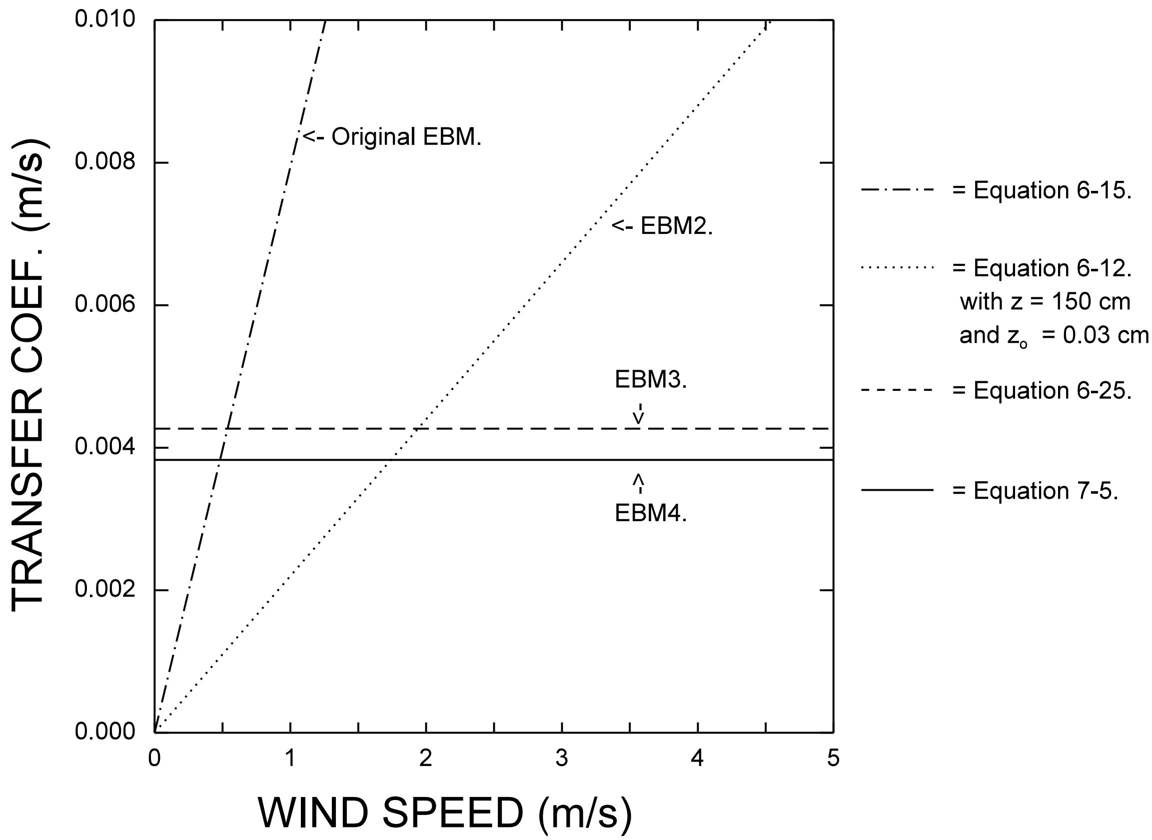

Figure 7-1. Transfer coefficient for sensible heat flux as predicted by two functions from the literature and by the best fit functions obtained using data from Experiment 2 (Equation 6-25) and Experiment 3 (Equation 7-5).

Despite the small difference between Equations 6-25 and 7-5, both of these best fit functions predict transfer coefficient values which are quite similar and much different from values predicted by Equation 6-15, which was used in the original EBM, and Equation 6-12 which was used in EBM2 (Figure 7-1). The fact that the best fit exponent was practically zero, when Experiment 3 data were used, supports the idea that wind speed was not important in determining the sensible heat flux from the reference dry soil. Clearly sensible heat flux from the reference was dominated by free convection.

Consideration of Additional Terms.

EBM4 underestimated evaporation on the first day after irrigation and overestimated on subsequent days (Figure 7-2). Although data from the first day plotted somewhat apart from that for later days there was no reason to omit the first day data.

The shortwave radiation and soil heat flux terms in the L.H.S. of Equation 5-7 were neglected in EBM4 as in all previous versions of the EBM. In Chapter 6 these terms were found to be important and corrective if included in the model. Thus the L.H.S. was estimated on a daily basis for the Run 2, Experiment 3 data in order to see if its inclusion would improve model estimates.

Net daily shortwave radiation was calculated using albedo values for the Avondale clay loam at Phoenix in early December for the days immediately after an irrigation of 25 cm (Idso et al. 1974). Though the Run 2 irrigation was only 2.4 cm it was preceded by an irrigation of 2.3 cm and 2 rains in the previous month and the soil was near saturation to at least the 30 cm depth after irrigation. Therefore the rate of

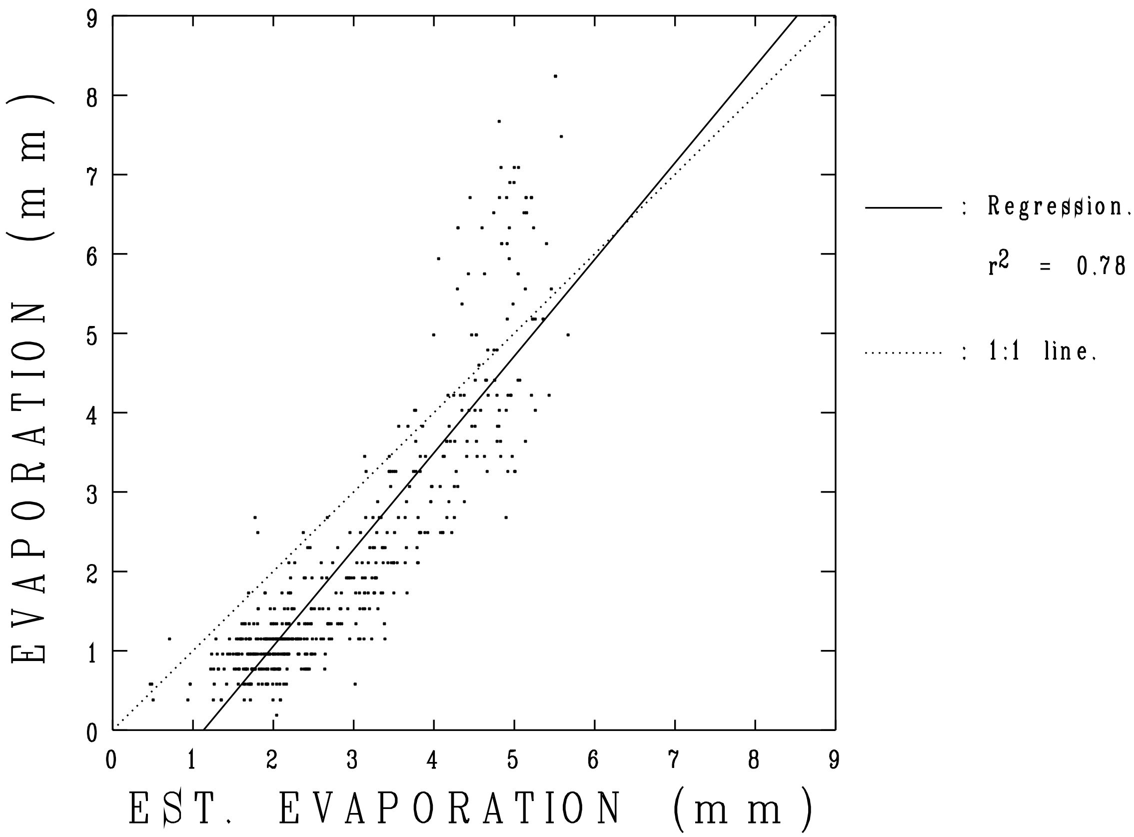

Figure 7-2. Regression of measured versus estimated (EBM4) evaporation for Run 2, Experiment 3.

change of albedo observed in Phoenix was assumed to be close to that occurring for Run 2. The albedo for dry Avondale soil was 0.30. Daily albedos assumed for the drying soil are shown in Table 7-3. Net daily shortwave radiation was calculated from solar radiation, measured on a 15 minute interval, by numerically integrating over 24 hours starting at 7:30 AM.

Table 7-2.

Apparent thermal diffusivities from harmonic analysis on 7:30 AM to 7:30 AM data and on midnight to midnight data. Second run 1986.

	Temperature					Temp.			
Day	Surface	15cm	D @ 15cm	r^2	net G	30cm	D @ 30cm	r^2	net G
7:30 to 7:30.									
327	10.46	14.27	0.002383	0.67	-0.509	15.91	0.001903	0.70	-0.329
328	9.59	13.24	0.002697	0.82	-0.787	15.11	0.001999	0.67	-0.555
329	8.30	11.69	0.002559	0.88	-0.554	13.99	0.000370	0.44	0.044
330	7.32	11.09	0.002971	0.95	-0.630	13.17	0.002759	0.31	-0.723
331	8.33	11.23	0.002954	0.98	-0.462	12.87	0.003549	0.70	-0.480
332	9.85	11.51	0.002967	0.98	-0.209	12.83	0.003769	0.81	-0.194
333	9.70	11.81	0.002818	0.94	-0.378	12.98	0.003568	0.71	-0.389
334	7.07	10.94	0.002712	0.75	-0.625	12.69	0.002605	0.29	-0.489
335	7.77	10.51	0.002821	0.96	-0.357	12.19	0.003287	0.66	-0.359
336	8.26	10.58	0.002849	0.96	-0.342	12.03	0.003482	0.73	-0.335
337	9.78	10.90	0.002855	0.97	-0.017	12.06	0.003728	0.86	0.000
338	12.44	11.52	0.003133	0.70	0.424	12.28	0.004254	0.60	0.493
0 to 24 hours.									
327	-	-	-	-	-	-	-	-	-0.442
328	-	-	-	-	-	-	-	-	-0.926
329	8.39	12.22	0.001931	0.83	-	14.51	0.002970	0.52	-0.607
330	7.31	11.28	0.002785	0.99	-	13.51	0.003575	0.73	-0.603
331	8.36	11.30	0.003024	0.98	-	13.04	0.003623	0.99	-0.406
332	9.41	11.46	0.003091	0.95	-	12.95	0.003673	0.94	-0.155
333	10.12	11.93	0.002895	0.97	-	13.08	0.003537	0.87	-0.260
334	7.67	11.42	0.002296	0.89	-	12.98	0.003273	0.90	-0.676
335	7.52	10.64	0.002750	0.97	-	12.42	0.003522	0.96	-0.398
336	8.17	10.63	0.002880	0.96	-	12.19	0.003572	0.98	-0.258
337	9.03	10.88	0.002919	0.96	-	12.14	0.003571	0.89	-0.206
338	10.30	11.30	0.003134	0.93	-	12.34	0.003708	0.84	0.058

Prior to calculating soil heat flux, the apparent soil thermal diffusivity was calculated by the harmonic analysis method described in Chapter 4. Diffusivities were found for the 0 to 24 hour period of each day and also for the 24 hour period starting at 7:30 AM each day. Apparent diffusivities (Figure 7-3) were sensitive to three factors: 1) depth of the layer, whether 0 to 15 cm or 0 to 30 cm; 2) the starting time of the 24 hour period used in the analysis; and 3) large changes in average soil temperature from day to day (Figure 3-26).

Diffusivities for the surface to 15 cm layer showed better correlation between actual and predicted temperatures than did those for the surface to 30 cm layer (Table 7-2). Low correlations also occurred when there were large shifts in air and soil surface temperature, e.g. days 333-334. These problems were a direct result of the fact that the harmonic method assumed no net daily soil heat flux while in fact the net flux was not only non-zero but varied considerably from day to day. Apparent diffusivities calculated using data for the 0 to 15 cm layer over the 7:30 to 7:30 period showed the least variability and reasonably high correlation coefficients for the harmonic method. Therefore these diffusivities were used in the heat flux calculations.

Net daily soil heat flux was calculated as in Chapter 5 using an implicit finite difference scheme and numerically integrating over 24 hours starting at 7:30 AM. The dry soil net daily heat flux was assumed to be negligible (see Equation 6-31 results, Chapter 6). Net G_o could not be calculated directly since no temperature measurements were made in the reference dry soils.

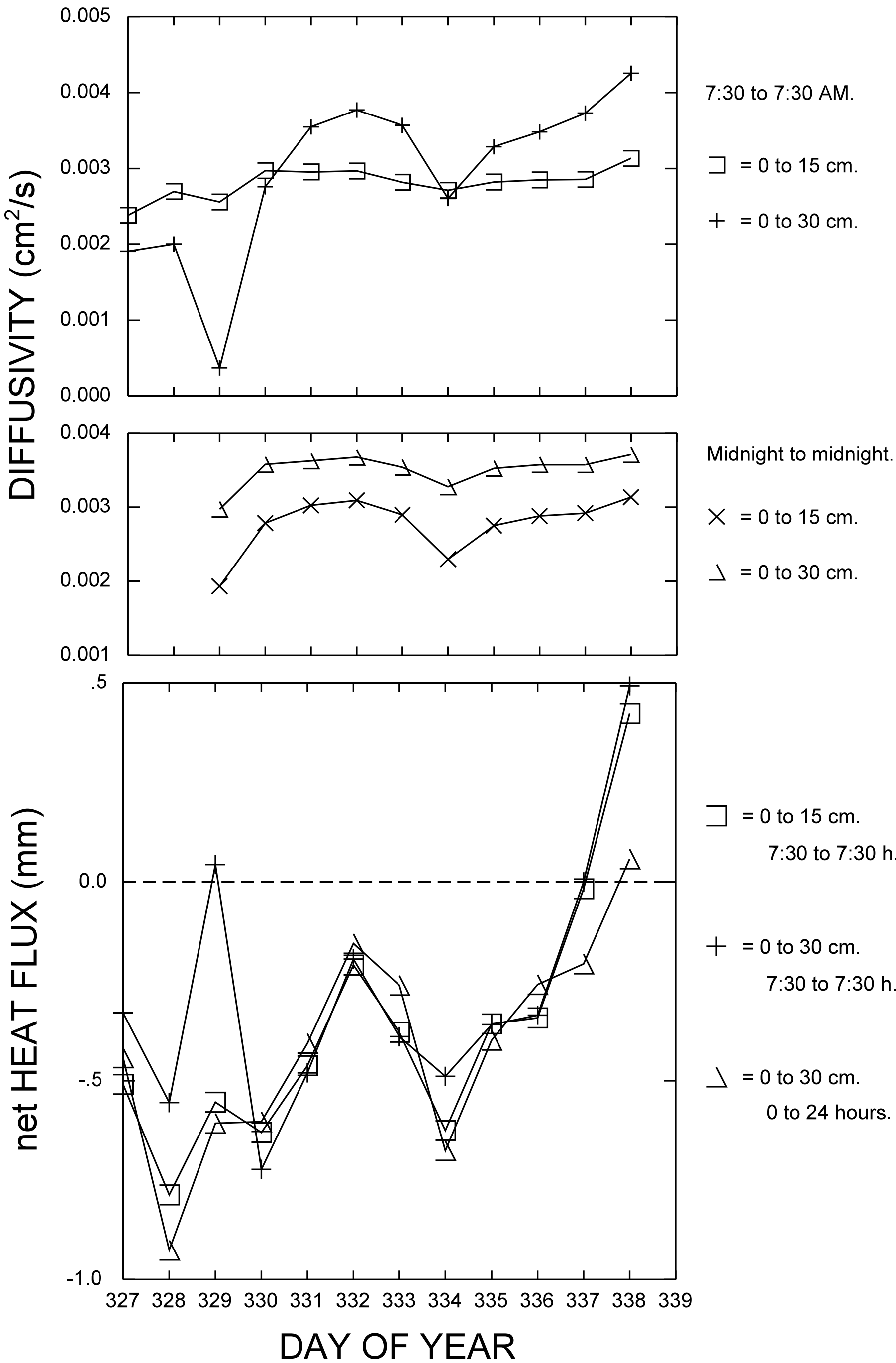

Figure 7-3. Diffusivities calculated by the harmonic method for 24 hour periods starting at 7:30 AM [top] and at midnight [middle]. Net daily soil heat flux calculated with finite difference program using these diffusivities, for surface to 15 cm and surface to 30 cm layers (bottom).

The sum of the shortwave and soil heat flux terms ranged from 1.5 mm on the second day after irrigation to -0.2 mm on the 10th day (Table 7-3). The daily ML evaporation estimated by EBM4 was corrected by adding the sum of shortwave and heat flux terms to the evaporation estimated for each ML. This procedure caused the r^2 value to decrease to 0.79 and caused the model to deviate further from the 1:1 line.

Contrary to the results in Chapter 6, addition of estimated L.H.S. values on a daily basis did not improve model results. This may be due to errors in the L.H.S. values. As in Chapter 6, the heat flux in the reference dry soil could not be calculated since temperatures were not measured in the reference. The lack of improvement may also be due to the fact that the estimated L.H.S. values could not be calculated for individual locations but only as a general value for the field as whole. Applying the same corrective value to all ML's for each day may cause some evaporation estimates to be undercorrected while others are overcorrected.

Plotting E_a versus E_{est} and E_a vs. $(T_{o,max} - T_{d,max})$ on a daily basis was revealing in this regard (Figure 7-4). For four of the first five days the regression lines exhibited a large negative intercept. The smaller intercept for day 329 appears to be caused by only two outliers. As the soil dried the intercept approached zero. This is a clear example of the need for inclusion of the shortwave radiation and soil heat

Table 7-3.

Estimated daily values (mm) of shortwave radiation and soil heat flux terms neglected in the energy balance model, and percentage of average evaporation that is represented by these terms.

Day	α_o	α_d	Net R_s	Net G_d	G_o-G_d	Net (R_s+G)	% of Ave. E_a
329	0.3	0.140	0.883	-0.554	0.554	1.44	25
330	0.3	0.140	0.860	-0.630	0.630	1.49	44
331	0.3	0.140	0.861	-0.462	0.462	1.32	60
332	0.3	0.145	0.798	-0.209	0.209	1.01	37
333	0.3	0.155	0.676	-0.378	0.378	1.05	66
334	0.3	0.160	0.721	-0.625	0.625	1.35	113
335	0.3	0.165	0.727	-0.357	0.357	1.08	90
336	0.3	0.170	0.565	-0.342	0.342	0.91	101
337	0.3	0.185	0.598	-0.017	0.017	0.62	62

flux terms, net (R_s + G) on an individual basis for each ML. Examination of the point cloud for any of the first five days shows that inclusion of net (R_s + G) would tend to transform the cloud so that it's long axis would more nearly parallel the 1:1 line. This is because the value of net (R_s + G) is larger for the wetter ML's, which show higher evaporation and plot at the upper end of the cloud, while it is smaller for the drier ML's (See Table 7-3).

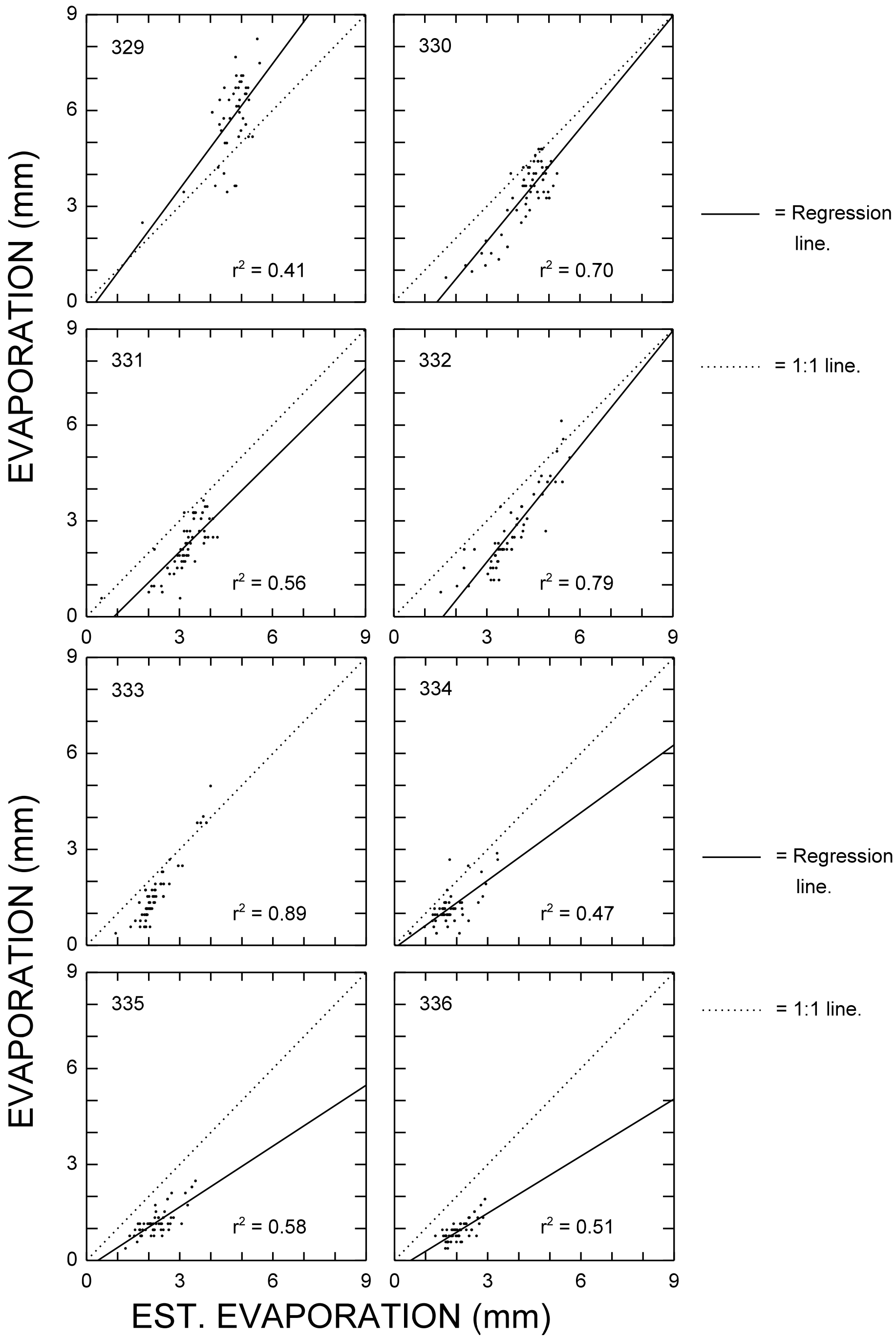

Figure 7-4. Day by day regressions of measured evaporation vs. that estimated with EBM4.

Summary.

The fourth improved energy balance model (EBM4) proved to be a reasonably good estimator of evaporation and was better than all previous versions though not much different from EBM3. Regression of measured against estimated evaporation resulted in an r^2 value of 0.78 vs. $r^2 = 0.70$ for regression of measured evaporation against the quantity ($T_{o,max} - T_{d,max}$). A "best fit" function, for the transfer coefficient for sensible heat flux from the reference dry soil, improved model performance and supported the idea that sensible heat flux from the reference was dominated by free convection and was little influenced by wind speed. The model was shown to be fairly insensitive to the exact location of soil temperature measurements, a result which should make future use of the model less problematic.

It was shown that inclusion of soil heat flux and shortwave radiation terms on a daily basis, i.e. the same correction for each ML on a given day, did nothing to improve the model. Even so, it was clear that inclusion of soil heat flux and shortwave radiation terms would improve estimation by the model if these terms could be calculated for individual ML's or field sites since the combined terms could equal as much as 113% of daily evaporation.

Performance of EBM4 should improve under conditions of high evaporative demand during which the dry and drying soil albedos would quickly become similar. Performance should also improve if soil heat flux is small and is constant from day to day. Conditions such as these would most likely be found in summer in Arizona, a time when closed crop canopies are more prevalent than is bare field soil. Work on estimation of soil heat flux and soil albedo in both the reference dry soil and drying soils is necessary for further model improvements.