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VAPOR PRESSURE DEFICIT CALCULATIONS AND THEIR EFFECT ON THE COMBINATION EQUATION

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ABSTRACT

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Of the several models used to calculate potential evapotranspiration (PET), many researchers use the combination method because of its theoretical basis. This model can be affected by random errors in the input parameters (net radiation, air temperature, wind speed, and daily average vapor pressure deficit, $\bar{V}$) and sensitivity analyses have described the impact of these errors. However, a more subtle non-random error may be introduced in PET estimates by changing the form by which the $\bar{V}$ term is specified. At least 12 different ways to present $\bar{V}$ have been published; the primary differences among them are the measured humidity parameter and the algebra used to compute $\bar{V}$. The effect of all applicable published computational methods on monthly and seasonal PET values for a range of locations differing in evaporative demand was examined in this study. Related methods of computing $\bar{V}$ resulted in little difference between PET values. The range of summer PET means obtained from the extreme methods was 8–17% of the best estimate method over all locations. Although this range approximates the expected accuracy of the combination method, it must be stressed that the net effect of the systematic and random errors may constitute a bias and, therefore, should be evaluated as such. Apparently innocuous computational differences can significantly affect PET results and, therefore, degrade confidence in the resulting values.

INTRODUCTION

Penman's (1948) combination method has been used extensively to calculate potential evapotranspiration (PET) for use as a reference value to characterize climate. The combination method has been criticized for being computationally difficult and data intensive. With the increased availability of weather data and computing power, these requirements are less restrictive, but the computations and data requirements remain somewhat extensive. Therefore, several opportunities exist for errors in computing PET using the Penman formula or one of its derivatives.

A particularly troublesome source of error in PET arises from the calculation of the average vapor pressure deficit in the aerodynamic term of the equation. Part of the problem with this precursor stems from the varied manners in which humidity may be measured and reported: dew point, relative humidity, vapor pressure, absolute humidity, vapor pressure deficit, mixing ratio, wet bulb temperature, etc. Second, different methods have been used to calculate the vapor pressure deficit terms in several benchmark papers (e.g. Penman, 1948; Van Bavel, 1966; Doorenbos and Pruitt, 1977). Finally, many reports are not sufficiently explicit for readers to determine the exact method used. As reported by Cuenca and Nicholson (1982), the choice ultimately depends upon the wind function used. Obviously, empirical wind functions (e.g. Penman, 1948) require the method used to derive the coefficients. The theoretically based wind functions appear to require the best estimate of $\bar{V}$. It is algebraically apparent that if $\bar{V}$ is dependent upon calculation method, then the corresponding wind functions are not comparable, and vice versa.

One further consideration is the availability of microprocessor-controlled data collectors, which can deliver humidity data in nearly any form and with temporal resolution from instantaneous to daily values. It can easily be shown that once humidity is averaged in one form, it may not be directly convertible to others. A prime example is average relative humidity, which is a complex combination of dew point and air temperature through the exponential saturation vapor pressure function.

Classical sensitivity analysis of the combination equation (Saxton, 1975) has indicated the dominance of the radiative term over the advective term. These results prompt the question of why it is necessary to concern oneself with a minor point. The answer is that the error associated with erroneous computation constitutes a bias rather than a random error. Preliminary calculations suggested that the bias could be about equal to literature values of the difference between calculated and measured PET (e.g. Jensen, 1974). There also is a fundamental need to follow a consistent and proper course toward accuracy in theory and calculation. The purpose of this work was to illustrate the sensitivity of combination equation PET to several published methods of calculating $\bar{V}$. If a real bias results, it would be a simple matter for modern data loggers to present humidity in the desired form.

Consideration of the final effect of changing any input to the combination equation necessitates a discussion of how the input was changed. In addition, the literature has most often discussed the variation of the input ($\bar{V}$) rather than the effect of that variation on resulting PET. As will be seen, the history of literature discussion of this topic matures from a brief discussion of $\bar{V}$ through a discussion of PET differences caused by $\bar{V}$. The current work is an extension of this historical course to cover more methods and sites.

To avoid conflicting numbering schemes in reference to literature methods, cross references to the definitions of the 15 methods in Table 1 have been added. These 15 methods are arranged into five general groups. Those in Group

TABLE 1

Methods to estimate average daily vapor pressure deficit

Group No.	Description
I. Temperature averaging methods	
1	Saturation ϵ at mean of maximum and minimum air temperature, minus ϵ at dew point measured at 0700 h LST (J-74 mth 1; C&N-82 mth 1) $\bar{V}(1) = Es(TAavg2) - Es(TD0700)$
2	As No. 1 above, but with minimum air temperature substituted for dew point (M&F-85) $\bar{V}(2) = Es(TAavg2) - Es(TAmin)$
3	As No. 1 above, but with mean of dew point maximum and minimum substituted for 0700 h LST value (D&P-77 mth 3, pg 16–17; C&N-82 mth 2) $\bar{V}(3) = Es(TAavg2) - Es(TDavg2)$
4	As No. 3 above, but with 24-point mean for both air temperature and dew point $\bar{V}(4) = Es(TAavg24) - Es(TDavg24)$
II. Temperature and relative humidity averaging methods	
5	Saturation ϵ at mean of maximum and minimum air temperature multiplied by one minus the mean relative humidity at the times of those two values (J-74 mth 2) $\bar{V}(5) = Es(TAavg2)(1. - RHavg2A)$
6	As 5 above, but with the mean of the maximum and minimum relative humidity (D&P-77 mth 1; C&N-82 mth 3) $\bar{V}(6) = Es(TAavg2)(1. - RHavg2)$
7	As 6 above, but with 24-point means for both parameters $\bar{V}(7) = Es(TAavg24)(1. - RHavg24)$
III. Vapor pressure averaging for saturation ϵ, temperature averaging for actual ϵ (hybrid method)	
8	Mean of saturation ϵ at maximum air temperature and saturation ϵ at minimum air temperature, minus saturation ϵ at the 0700 LST dew point (J-74 mth 3) $\bar{V}(8) = (Es(TAmax) + Es(TAmin))/2.0 - Es(TD0700)$
9	As 8 above, but with mean of maximum and minimum dew points substituted for 0700 h LST value (C&N-82 mth 4) $\bar{V}(9) = (Es(TAmax) + Es(TAmin))/2.0 - Es(TDavg2)$
IV. Vapor pressure deficit averaging methods	
10	Mean of ϵ deficit at time of maximum and minimum air temperatures (J-74 mth 4; D&P-77 mth 2 on pg 113; C&N-82 mth 5) $\bar{V}(10) = (Es(TAmax) - Es(TDmax1) + Es(TAmin) - Es(TDmin1))/2$
11	Calculate ϵ deficit assuming maximum temperature is paired with minimum relative humidity and vice versa, then average ϵ deficit (D&P-77 mth 4) $\bar{V}(11) = (Es(TAmax)(1. - RHmin) + Es(TAmin)(1. - RHmax))/2$
12	Mean of maximum and minimum ϵ deficit $\bar{V}(12) = (\delta max + \delta min)/2. (= \delta avg2)$
13	Mean of 24 hourly values of ϵ deficit (J-74 mth 5; H-85 mth 3) $\bar{V}(13) = \delta avg24$

TABLE 1 (*continued*)

Group No.	Description
V. Vapor pressure averaging methods	
14	As 8 above, but with 24-point mean actual ϵ substituted for saturation at the mean dew point (H-85, mth 1)
	$\bar{V}(14) = (Es(TAmax) + Es(TAmin))/2. - \epsilon avg24$
15	As 14 above, but with saturation ϵ taken at the mean of the maximum and minimum air temperatures (H-85, mth 2)
	$\bar{V}(15) = Es(TAavg2) - \epsilon avg24$

Explanations of abbreviations used:

avg2	average of maximum and minimum	avg24	average of 24 hourly values
avg2A	RH only: values at time of TAmax/min	$\bar{V}$	daily vapor pressure deficit (kPa)
Es	saturation vapor pressure func. (eq. 2)	max	maximum value
min	minimum value;	RH	relative humidity, 0–1.00
TA	temperature of the air (°C)	TD	dew point temperature (°C)
TD0700	value at 0700 h LST	TDmax1	TD only: values at time of TAmax/min
ϵ	vapor pressure (kPa)	δ	vapor pressure deficit (kPa)

Reference abbreviations used in Table 1:

C&N-82	Cuenca and Nicholson, 1982	D&P-77	Doorenbos and Pruitt, 1977
H-85	Heerman, 1985	J-74	Jensen, 1974
M&F-85	Merva and Fernandez, 1985		

I compute averages of both air temperature and dew point temperature prior to computing the exponential vapor pressure function. Group II similarly averages air temperature but uses relative humidity instead of dew point. Group III computes vapor pressure prior to averaging for the saturation vapor pressure but computes actual vapor pressure after averaging the dew point temperature. Group IV averages the vapor pressure deficit. Group V methods use the mean of 24 hourly vapor pressures for the actual vapor pressure term.

Jensen (1974, p. 71) tested five methods (M1, M5, M8, M10, and M13) on one day's data from southern Idaho and showed that method affected $\bar{V}$ by −26% to +3% from the average of 24 hourly vapor pressure deficit (δ) values. He cautioned against equating vapor pressure deficits calculated using mean air temperatures with the average daily deficit. Doorenbos and Pruitt (1977) listed five methods (three of which are M3, M6, and M8). They compared $\bar{V}$ for an air-temperature-averaging method (M6) and for a vapor-pressure-averaging method (M3) for 20 days' weather from Davis, CA. The air-temperature-averaging method resulted in $\bar{V}$ that was 8–54% less than the vapor-pressure-averaging method, with a mean of 32% less. They recommended using the simpler air-temperature-averaging method because the wind functions they used were developed using it.

Cuenca and Nicholson (1982) emphasized the dependence of method on choice of wind function. They presented details on the derivation of the original Penman formula, including examination of the method used in the Penman (1948) publication. Apparently, Penman used a 6-point (4-h interval) average air temperature and a correlation of a single local dew point measurement against a nearby station's dew point measurements, which themselves were on a 4-point (6-h) basis. It may be sufficient to say that the best estimate available was used for daily average air and dew point temperatures. In any case, the original Penman (1948) ∇ method was saturation vapor pressure at the average air temperature minus the saturation vapor pressure at the average dew point temperature (similar to M3 and M4).

Burman et al. (1983) listed three methods (M3, M6, and M9) for calculating ∇ and further noted that unreported studies indicated that a single dew point measurement at 0800 h (M1) represented a good daily average, and that it is becoming an accepted standard. Jensen (1974) used 0800 MDST as one method. Burman et al. (1983) cautioned that the ∇ calculation method used in applying a wind function must match the ∇ calculation method used in the determination of the wind function.

Heermann (1985) extended these analyses to show the effect on the resulting evapotranspiration values for three methods (M13, M14, and M15). He used 24-point averages of actual vapor pressure as the second term in the ∇ calculation for all three methods. Average daily differences between the three methods were shown for 14 site-years (of 13–61 days each) between 1978 and 1980; Akron, CO, Albin, WY, Garden City, Mankato, and Tribune, KS, Medford, OK, and Paxton, NE. The vapor-pressure-averaging method (M14) was in all cases significantly different (5% level) than the temperature-averaging method (M15). The mean yearly differences were 0.33–0.90 mm day^{-1}, or about 11–24%, with M14 consistently higher. Results of the comparison of M14 to M13, a 24-point average of δ, showed similar but not as consistent differences. Heermann noted that hourly data could provide additional confusion in the application of the Penman equation, and that calibration was necessary to properly use these data from automatic weather stations.

In summary, the literature has presented several examples of cases in which ∇ significantly depended upon method of calculation (Jensen, 1974; Doorenbos and Pruitt, 1977). Doorenbos and Pruitt (1977) further demonstrated the effect of calculation method on the magnitude and shape of the wind function. Heermann (1985) extended this analysis to show the effect of three methods on the resultant PET value for seven Central Plains locations.

METHODS

The current work further extends this analysis of PET to 15 methods, for the summer months (April–September), for a range of U.S. geographic regions differing in humidity. These data are used to determine the effect the choice of method has on PET and to determine whether the effect depends upon climate.

Standard sensitivity analysis techniques are not well suited to the evaluation of $\bar{V}$ method on combination PET values, because the errors obtained for $\bar{V}$ are not necessarily random. In fact, for given diurnal patterns of temperature and dew point, many can be shown algebraically to be consistently related. It remained to be shown how $\bar{V}$ from the methods were related for real data, and further how PET, the variable of interest, was affected. The data used for this study were taken from the Typical Meteorological Year (TMY) data set compiled for the study of energy loads on buildings (National Climatic Center, 1981). These data were developed to provide a year of actual hourly data that was representative of long-term weather at a given location. Details of the collection and selection of the TMY data can be obtained from the National Climatic Data Center. Briefly, data were examined to determine the best match for each month to long-term normals for monthly average air temperature, dew point, wind velocity, and solar radiation. The best matches for each of the 12 months were linked to form the TMY data set. Data pertinent to this study included solar radiation, air temperature, air dew point, wind speed, and air pressure.

The TMY data for 12 stations (Table 2) were transferred to a minicomputer and manipulated using FORTRAN-77 and SAS* (SAS, 1985). Daily descrip-

TABLE 2

List of stations used in the analysis of vapor pressure deficit on PET calculations by the combination equation. Elevations and locations were taken from NOAA station notes. The empirical coefficients *A* and *B* are used in the relationship to compute net radiation, and depend upon humidity classification for the site

Location	Abbreviation	Latitude (°N)	Longitude (°W)	Elevation (m)	*A*	*B*
Apalachicola, FL	ACFL	29.73	85.03	6	1.0	0.0
Bismarck, ND	BKND	46.78	100.75	502	1.1	−0.1
Charleston, SC	CHSC	32.88	80.03	12	1.0	0.0
Columbia, MO	COMO	38.82	92.22	270	1.0	0.0
Dodge City, KS	DCKS	37.77	99.97	787	1.1	−0.1
Fresno, CA	FRCA	36.77	119.72	100	1.2	−0.2
Fort Worth, TX	FWTX	32.22	98.18	168	1.0	0.0
Lake Charles, LA	LCLA	30.12	93.22	3	1.0	0.0
Madison, WI	MDWI	43.13	89.33	262	1.0	0.0
Omaha, NE	OMNE	41.37	96.02	399	1.1	−0.1
Phoenix, AZ	PXAZ	33.43	112.00	338	1.2	−0.2
Washington, DC	WADC	38.95	77.35	88	1.0	0.0

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tive statistics (average, max., min., total, etc.) for air temperature, dew point, vapor pressure, relative humidity, vapor pressure deficit, wind run, solar radiation, and air pressure were computed and used to compute daily average vapor pressure deficit by the methods listed in Table 1. The resulting array of $\bar{V}$ values then was 15 values day^{-1} for 183 days, April–September.

It was assumed that the series of 24 hourly temperatures, dew points, and air pressure could be used to compute the corresponding daily extremes, totals, and means. Wind and radiation hourly values represented hourly totals, so daily sums of these were also considered representative of daily totals. For each hour, vapor pressure was calculated from dew point, saturation vapor pressure was calculated from air temperature, relative humidity was calculated from the ratio, and vapor pressure deficit was calculated from the difference. Daily averages and extremes from these values were also required as were dew point and relative humidity at the times of the extreme air temperatures.

The procedure used for this study was to select a form of the combination equation, including a suitable wind function, and by reason of its development,

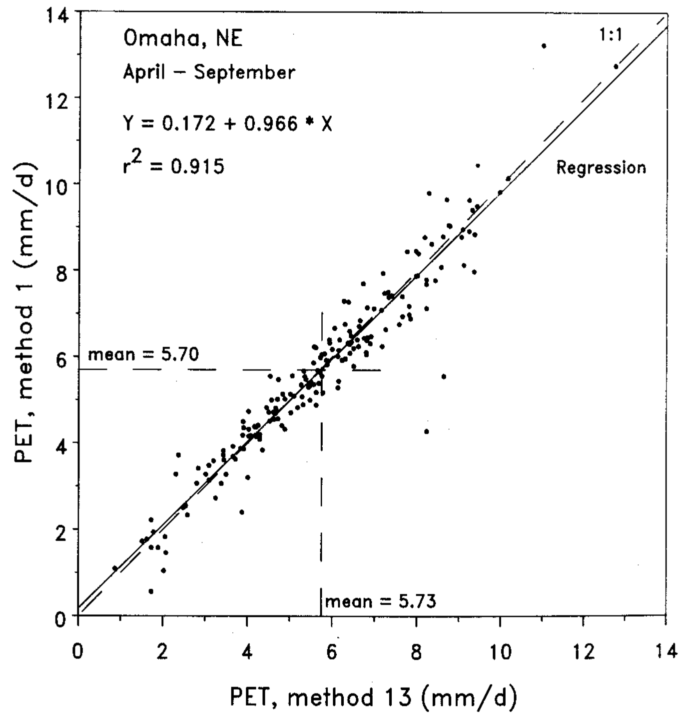

Fig. 1. Comparison of daily PET values for the April–September period at Omaha, NE, as calculated by Methods M1 and M13. Results of linear regression of M1 values on M13 are given as well as the mean values for each method. For reference, the line of equality is also shown.

an associated "best" method to compute V. The form of the combination equation used was given by Van Bavel (1966) with the theoretically based wind function (Businger, 1956; Van Bavel, 1966). The best estimate of V was chosen to be M13, or the mean of 24 hourly values of vapor pressure deficit. Method 13 weights the 24 hourly vapor pressure deficit values equally and has been criticized as being unable to account for the evaporative flux being heavily weighted to the daytime. This has been used to support the choice of a 2-point mean, such as M6. Since the objective is not to prove one method superior but to document differences between methods, the question of daytime/night-time weighting does not affect the conclusions.

This single form of the combination equation was evaluated for PET using V computed using each of the 15 methods. In this way, the effect of choosing the wrong method can be examined. For this analysis, the choice of the form of the combination equation, wind function, and best V method is arbitrary. This is because if Method X gives PET values appreciably different from those of Method Y in eq. Y, then Method Y is likewise expected to give PET values different from those of Method X in eq. X.

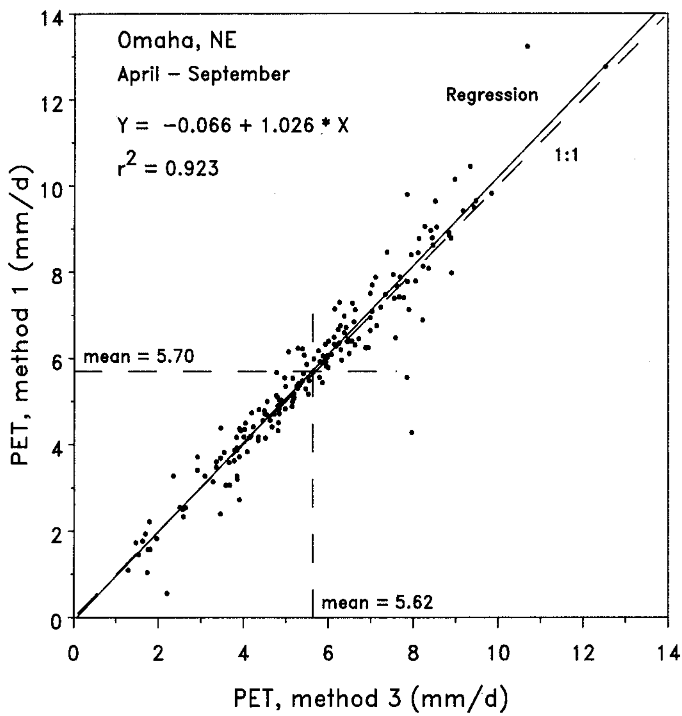

Fig. 2. Comparison of daily PET values for the April–September period at Omaha, NE, as calculated by Methods M1 and M3. Results of linear regression of M1 values on M3 are given as well as the mean values for each method. For reference, the line of equality is also shown.

Once PET values corresponding to the 15 methods of calculating $\bar{V}$ were calculated, evaluation of the effect of method on PET was performed. Scatter plots of PET by one method against another gave a visual indication of fit between methods. Regression of values from one method on another gave an indication of agreement by reason of slopes and intercepts approaching the nominal values of 1 and 0, and an indication of the systematic nature of the trend by r^2 values near 1. Analysis of variance was performed on the PET values and the Waller–Duncan test was used to compare means for the season and by month. An additional indication of variation was made by scaling PET values to those from M13 and examining means, extremes, and coefficients of variation for these ratios.

RESULTS

There are 105 comparisons that can be made between results from any two methods for each location. For illustration of the type and degree of fit, three comparisons for Omaha, NE, are given in Figs. 1, 2 and 3. Figure 1 compares

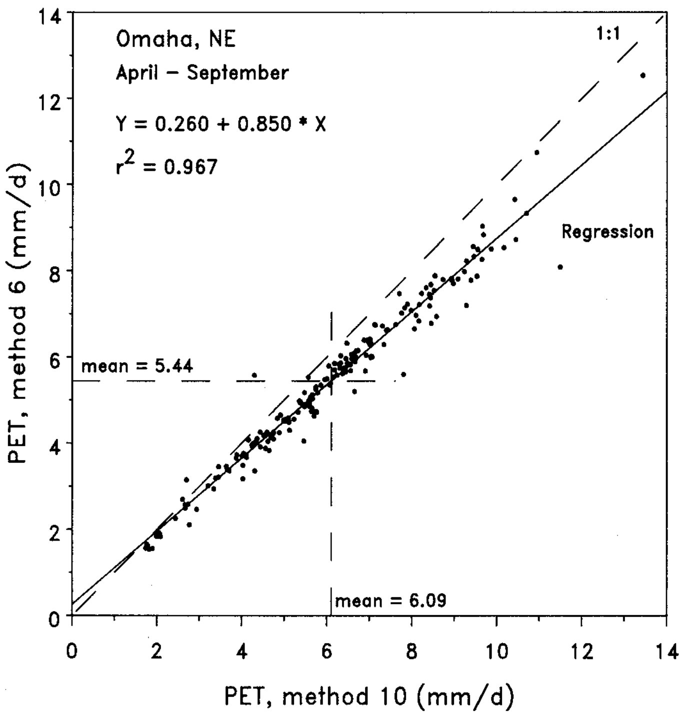

Fig. 3. Comparison of daily PET values for the April–September period at Omaha, NE, as calculated by Methods M6 and M10. Results of linear regression of M6 values on M10 are given as well as the mean values for each method. For reference, the line of equality is also shown.

TABLE 3

Regression coefficients for all combinations of methods. Dependent variable is listed in first column. Independent variable is listed on top row. Data are for Charleston, SC

		M1	M2	M3	M4	M5	M6	M7
M1	Intercept		−0.176	0.132	0.121	0.047	−0.110	0.053
	Slope		1.041	0.972	1.007	1.001	1.039	1.046
	R^2		0.797	0.897	0.882	0.875	0.891	0.890
M2	Intercept	1.102		0.803	0.748	0.692	0.507	0.713
	Slope	0.766		0.827	0.868	0.860	0.904	0.896
	R^2	0.797		0.884	0.890	0.879	0.917	0.888
M3	Intercept	0.374	−0.300		0.037	−0.066	−0.219	−0.012
	Slope	0.923	1.068		1.026	1.025	1.063	1.062
	R^2	0.897	0.884		0.964	0.967	0.982	0.965
M4	Intercept	0.442	−0.255	0.132		0.023	−0.137	−0.040
	Slope	0.876	1.025	0.940		0.973	1.012	1.033
	R^2	0.882	0.890	0.964		0.952	0.972	0.998
M5	Intercept	0.553	−0.134	0.218	0.206		−0.054	0.158
	Slope	0.874	1.022	0.943	0.978		1.017	1.012
	R^2	0.875	0.879	0.967	0.952		0.976	0.953
M6	Intercept	0.609	−0.122	0.287	0.262	0.165		0.214
	Slope	0.858	1.014	0.924	0.961	0.960		0.994
	R^2	0.891	0.917	0.982	0.972	0.976		0.974
M7	Intercept	0.452	−0.198	0.168	0.047	0.062	−0.094	
	Slope	0.851	0.991	0.909	0.966	0.942	0.980	
	R^2	0.890	0.888	0.965	0.998	0.953	0.974	
M8	Intercept	0.077	−0.243	0.180	0.144	0.083	−0.080	0.086
	Slope	1.037	1.108	1.015	1.057	1.046	1.086	1.095
	R^2	0.993	0.834	0.903	0.897	0.883	0.900	0.900
M9	Intercept	0.451	−0.368	0.048	0.060	−0.029	−0.190	0.020
	Slope	0.959	1.135	1.043	1.076	1.071	1.110	1.110
	R^2	0.885	0.911	0.993	0.967	0.963	0.978	0.964
M10	Intercept	0.534	−0.350	0.141	0.098	−0.084	−0.161	0.069
	Slope	0.970	1.159	1.051	1.096	1.110	1.132	1.129
	R^2	0.858	0.902	0.957	0.953	0.983	0.966	0.946
M11	Intercept	0.640	−0.299	0.245	0.183	0.103	−0.074	0.156
	Slope	0.951	1.152	1.033	1.082	1.075	1.118	1.114
	R^2	0.862	0.930	0.965	0.968	0.961	0.981	0.960
M12	Intercept	0.589	−0.339	0.207	0.146	0.057	−0.114	0.118
	Slope	0.958	1.157	1.037	1.085	1.080	1.122	1.118
	R^2	0.868	0.930	0.965	0.968	0.964	0.982	0.960
M13	Intercept	0.407	−0.327	0.104	−0.035	0.002	−0.171	−0.073
	Slope	0.902	1.060	0.965	1.027	0.997	1.039	1.061
	R^2	0.886	0.899	0.961	0.998	0.945	0.969	0.995
M14	Intercept	0.230	−0.412	−0.030	−0.053	−0.113	−0.294	−0.097
	Slope	0.996	1.135	1.049	1.090	1.079	1.123	1.126
	R^2	0.930	0.888	0.980	0.968	0.953	0.975	0.967
M15	Intercept	0.153	−0.345	−0.078	−0.075	−0.149	−0.323	−0.130
	Slope	0.959	1.068	1.007	1.040	1.033	1.075	1.078
	R^2	0.935	0.853	0.978	0.957	0.948	0.970	0.960

M8	M9	M10	M11	M12	M13	M14	M15
−0.038	0.135	0.206	0.083	0.102	0.149	0.121	0.160
0.958	0.923	0.885	0.906	0.906	0.982	0.934	0.975
0.993	0.885	0.858	0.862	0.868	0.886	0.930	0.935
0.973	0.718	0.739	0.576	0.607	0.760	0.857	0.979
0.753	0.803	0.779	0.807	0.804	0.848	0.783	0.799
0.834	0.911	0.902	0.930	0.930	0.899	0.888	0.853
0.308	−0.010	0.076	−0.059	−0.024	0.083	0.123	0.180
0.890	0.952	0.911	0.934	0.931	0.996	0.934	0.972
0.903	0.993	0.957	0.965	0.965	0.961	0.980	0.978
0.357	0.098	0.131	−0.016	0.019	0.042	0.194	0.270
0.848	0.899	0.870	0.895	0.892	0.972	0.888	0.920
0.897	0.967	0.953	0.968	0.968	0.998	0.968	0.957
0.482	0.200	0.153	0.094	0.121	0.259	0.322	0.383
0.844	0.900	0.886	0.894	0.892	0.948	0.884	0.918
0.883	0.963	0.983	0.961	0.964	0.945	0.953	0.948
0.540	0.270	0.298	0.152	0.184	0.306	0.373	0.432
0.828	0.881	0.853	0.878	0.875	0.933	0.869	0.902
0.900	0.978	0.966	0.981	0.982	0.969	0.975	0.970
0.380	0.146	0.187	0.047	0.079	0.091	0.234	0.297
0.822	0.868	0.838	0.862	0.859	0.938	0.859	0.891
0.900	0.964	0.946	0.960	0.960	0.995	0.967	0.960
	0.145	0.200	0.066	0.089	0.163	0.157	0.234
	0.971	0.935	0.958	0.957	1.032	0.977	1.013
	0.905	0.885	0.890	0.895	0.904	0.940	0.932
0.346		0.071	−0.076	−0.037	0.097	0.159	0.255
0.932		0.961	0.986	0.982	1.047	0.977	1.009
0.905		0.972	0.981	0.981	0.969	0.980	0.963
0.409	0.072		−0.083	−0.051	0.138	0.221	0.337
0.946	1.012		1.012	1.010	1.066	0.991	1.020
0.885	0.972		0.983	0.986	0.954	0.957	0.934
0.512	0.174	0.169		0.041	0.217	0.313	0.431
0.929	0.996	0.971		0.996	1.053	0.977	1.004
0.890	0.981	0.983		0.999	0.971	0.969	0.944
0.463	0.137	0.125	−0.035		0.179	0.272	0.388
0.935	0.999	0.976	1.003		1.057	0.981	1.009
0.895	0.981	0.986	0.999		0.971	0.970	0.946
0.310	0.058	0.095	−0.062	−0.028		0.154	0.242
0.876	0.925	0.895	0.922	0.919		0.915	0.945
0.904	0.969	0.954	0.971	0.971		0.971	0.955
0.147	−0.059	0.000	−0.154	−0.121	−0.018		0.075
0.962	1.002	0.966	0.992	0.989	1.061		1.038
0.940	0.980	0.957	0.969	0.970	0.971		0.993
0.108	−0.069	0.006	−0.137	−0.108	−0.032	−0.036	
0.920	0.955	0.916	0.940	0.938	1.011	0.957	
0.932	0.963	0.934	0.944	0.946	0.955	0.993	

TABLE 4

Regression coefficients for all combinations of methods. Dependent variable is listed in first column. Independent variable is listed on top row. Data are for Omaha, NE

		M1	M2	M3	M4	M5	M6	M7
M1	Intercept		−0.231	−0.066	0.159	−0.054	−0.185	0.105
	Slope		1.170	1.026	0.992	1.048	1.082	1.025
	R^2		0.791	0.923	0.909	0.906	0.930	0.919
M2	Intercept	1.217		0.932	1.078	0.880	0.843	1.074
	Slope	0.676		0.737	0.715	0.763	0.777	0.732
	R^2	0.791		0.823	0.817	0.831	0.831	0.812
M3	Intercept	0.493	−0.044		0.246	0.065	−0.020	0.229
	Slope	0.899	1.117		0.962	1.011	1.037	0.988
	R^2	0.923	0.823		0.975	0.963	0.974	0.973
M4	Intercept	0.361	−0.209	−0.112		−0.110	−0.197	−0.018
	Slope	0.917	1.143	1.014		1.037	1.064	1.027
	R^2	0.909	0.817	0.975		0.961	0.972	0.998
M5	Intercept	0.564	−0.031	0.141	0.318		0.003	0.293
	Slope	0.865	1.090	0.952	0.926		1.010	0.953
	R^2	0.906	0.831	0.963	0.961		0.981	0.962
M6	Intercept	0.538	0.021	0.157	0.332	0.102		0.300
	Slope	0.860	1.069	0.940	0.914	0.972		0.941
	R^2	0.930	0.831	0.974	0.972	0.981		0.976
M7	Intercept	0.347	−0.161	−0.080	0.029	−0.087	−0.179	
	Slope	0.897	1.108	0.986	0.972	1.010	1.037	
	R^2	0.919	0.812	0.973	0.998	0.962	0.976	
M8	Intercept	−0.060	−0.406	−0.154	0.083	−0.132	−0.261	0.040
	Slope	1.078	1.280	1.110	1.074	1.132	1.167	1.107
	R^2	0.993	0.810	0.924	0.912	0.904	0.925	0.917
M9	Intercept	0.433	−0.219	−0.088	0.170	−0.013	−0.095	0.163
	Slope	0.977	1.227	1.084	1.044	1.095	1.121	1.070
	R^2	0.921	0.839	0.993	0.971	0.955	0.963	0.965
M10	Intercept	0.510	−0.298	0.015	0.219	−0.083	−0.093	0.215
	Slope	0.979	1.260	1.081	1.051	1.124	1.137	1.077
	R^2	0.902	0.864	0.964	0.961	0.981	0.967	0.954
M11	Intercept	0.494	−0.243	−0.001	0.195	−0.027	−0.116	0.193
	Slope	0.984	1.252	1.087	1.057	1.116	1.144	1.083
	R^2	0.911	0.852	0.973	0.972	0.967	0.977	0.965
M12	Intercept	0.518	−0.239	0.031	0.221	−0.013	−0.093	0.217
	Slope	0.976	1.246	1.077	1.048	1.109	1.135	1.074
	R^2	0.910	0.857	0.970	0.971	0.970	0.978	0.964
M13	Intercept	0.323	−0.295	−0.144	−0.026	−0.131	−0.226	−0.041
	Slope	0.948	1.187	1.044	1.029	1.066	1.094	1.056
	R^2	0.915	0.830	0.974	0.998	0.956	0.969	0.995
M14	Intercept	0.317	−0.316	−0.140	0.073	−0.104	−0.199	0.063
	Slope	0.990	1.237	1.085	1.053	1.104	1.132	1.080
	R^2	0.935	0.845	0.985	0.979	0.960	0.972	0.974
M15	Intercept	0.377	−0.141	−0.052	0.149	−0.027	−0.124	0.129
	Slope	0.912	1.127	1.001	0.971	1.020	1.048	0.998
	R^2	0.936	0.827	0.990	0.982	0.967	0.982	0.981

M8	M9	M10	M11	M12	M13	M14	M15
0.092	0.045	0.087	0.049	0.033	0.172	0.072	−0.024
0.922	0.942	0.922	0.926	0.932	0.966	0.945	1.027
0.993	0.921	0.902	0.911	0.910	0.915	0.935	0.936
1.222	0.967	0.896	0.917	0.888	1.068	1.003	0.981
0.633	0.684	0.685	0.680	0.688	0.699	0.683	0.734
0.810	0.839	0.864	0.852	0.857	0.830	0.845	0.827
0.557	0.121	0.187	0.152	0.140	0.279	0.210	0.110
0.832	0.916	0.892	0.896	0.901	0.933	0.908	0.988
0.924	0.993	0.964	0.973	0.970	0.974	0.985	0.990
0.421	0.003	0.018	−0.025	−0.042	0.037	0.050	−0.048
0.849	0.930	0.914	0.920	0.926	0.970	0.930	1.011
0.912	0.971	0.961	0.972	0.971	0.998	0.979	0.982
0.633	0.261	0.174	0.203	0.175	0.360	0.312	0.209
0.799	0.872	0.873	0.867	0.875	0.897	0.870	0.948
0.904	0.955	0.981	0.967	0.970	0.956	0.960	0.967
0.617	0.284	0.260	0.222	0.202	0.367	0.323	0.213
0.793	0.859	0.850	0.855	0.861	0.886	0.859	0.937
0.925	0.963	0.967	0.977	0.978	0.969	0.972	0.982
0.419	0.043	0.060	0.019	0.002	0.068	0.086	−0.020
0.828	0.902	0.886	0.891	0.898	0.942	0.902	0.983
0.917	0.965	0.954	0.965	0.964	0.995	0.974	0.981
	−0.076	−0.037	−0.080	−0.092	0.082	−0.038	−0.099
	1.026	1.005	1.010	1.016	1.049	1.028	1.109
	0.934	0.918	0.927	0.924	0.923	0.946	0.934
0.465		0.062	0.023	0.014	0.189	0.100	0.035
0.910		0.975	0.980	0.985	1.016	0.991	1.071
0.934		0.974	0.984	0.979	0.976	0.991	0.981
0.535	0.094		0.025	−0.004	0.236	0.154	0.094
0.913	0.999		0.994	1.003	1.023	0.996	1.076
0.918	0.974		0.988	0.990	0.966	0.979	0.967
0.518	0.077	0.047		−0.016	0.213	0.135	0.076
0.918	1.004	0.994		1.007	1.029	1.002	1.082
0.927	0.984	0.988		0.998	0.977	0.989	0.977
0.547	0.112	0.063	0.030		0.237	0.161	0.097
0.909	0.994	0.988	0.991		1.021	0.993	1.073
0.924	0.979	0.990	0.998		0.976	0.988	0.977
0.372	−0.042	−0.029	−0.073	−0.091		0.004	−0.080
0.880	0.961	0.945	0.950	0.957		0.960	1.041
0.923	0.976	0.966	0.977	0.976		0.984	0.981
0.358	−0.048	−0.026	−0.067	−0.086	0.090		−0.075
0.920	1.001	0.982	0.987	0.994	1.025		1.082
0.946	0.991	0.979	0.989	0.988	0.984		0.993
0.450	0.074	0.098	0.062	0.040	0.180	0.109	
0.842	0.916	0.899	0.903	0.910	0.942	0.917	
0.934	0.981	0.967	0.977	0.977	0.981	0.993	

TABLE 5

Regression coefficients for all combinations of methods. Dependent variable is listed in first column. Independent variable on top row. Data are for Phoenix, AZ

		M1	M2	M3	M4	M5	M6	M7
M1	Intercept		−1.198	0.146	−0.003	0.350	0.162	0.019
	Slope		1.583	0.962	0.963	0.962	0.987	0.973
	R^2		0.698	0.969	0.957	0.962	0.981	0.964
M2	Intercept	2.268		2.210	2.034	2.393	2.317	2.095
	Slope	0.441		0.439	0.453	0.428	0.438	0.451
	R^2	0.698		0.726	0.760	0.683	0.694	0.745
M3	Intercept	0.100	−1.438		−0.102	0.243	0.108	−0.037
	Slope	1.008	1.653		0.995	0.996	1.015	1.000
	R^2	0.969	0.726		0.974	0.984	0.989	0.971
M4	Intercept	0.359	−1.436	0.312		0.568	0.406	0.059
	Slope	0.993	1.678	0.979		0.973	0.995	1.006
	R^2	0.957	0.760	0.974		0.954	0.967	0.998
M5	Intercept	−0.047	−1.325	−0.115	−0.198		−0.069	−0.147
	Slope	1.000	1.597	0.988	0.981		1.010	0.987
	R^2	0.962	0.683	0.984	0.954		0.988	0.955
M6	Intercept	−0.012	−1.263	−0.019	−0.131	0.158		−0.096
	Slope	0.994	1.584	0.975	0.971	0.978		0.979
	R^2	0.981	0.694	0.989	0.967	0.988		0.970
M7	Intercept	0.277	−1.381	0.270	−0.046	0.511	0.336	
	Slope	0.990	1.650	0.971	0.993	0.967	0.991	
	R^2	0.964	0.745	0.971	0.998	0.955	0.970	
M8	Intercept	0.175	−1.354	0.333	0.103	0.563	0.366	0.137
	Slope	1.032	1.684	0.992	1.002	0.989	1.016	1.011
	R^2	0.989	0.734	0.957	0.962	0.944	0.964	0.966
M9	Intercept	0.275	−1.594	0.187	0.005	0.456	0.313	0.080
	Slope	1.040	1.754	1.030	1.034	1.023	1.043	1.038
	R^2	0.962	0.763	0.989	0.981	0.969	0.975	0.976
M10	Intercept	0.257	−1.596	0.177	−0.003	0.363	0.277	0.072
	Slope	1.041	1.753	1.030	1.034	1.034	1.047	1.038
	R^2	0.955	0.755	0.980	0.972	0.980	0.972	0.967
M11	Intercept	0.317	−1.520	0.270	0.072	0.512	0.355	0.138
	Slope	1.035	1.742	1.020	1.026	1.017	1.038	1.031
	R^2	0.967	0.763	0.984	0.980	0.970	0.979	0.977
M12	Intercept	0.276	−1.553	0.244	0.042	0.474	0.321	0.106
	Slope	1.039	1.746	1.022	1.029	1.020	1.041	1.034
	R^2	0.969	0.762	0.982	0.979	0.971	0.979	0.977
M13	Intercept	0.437	−1.501	0.412	0.064	0.681	0.506	0.125
	Slope	1.006	1.719	0.988	1.013	0.981	1.005	1.019
	R^2	0.952	0.775	0.964	0.997	0.941	0.956	0.995
M14	Intercept	0.253	−1.594	0.202	0.002	0.467	0.312	0.070
	Slope	1.041	1.752	1.026	1.033	1.020	1.042	1.038
	R^2	0.969	0.765	0.987	0.983	0.967	0.976	0.980
M15	Intercept	0.078	−1.438	0.015	−0.105	0.254	0.107	−0.047
	Slope	1.009	1.651	0.997	0.994	0.993	1.013	1.000
	R^2	0.977	0.728	0.998	0.977	0.983	0.991	0.976

M8	M9	M10	M11	M12	M13	M14	M15
−0.077	0.044	0.120	−0.033	−0.008	−0.032	0.012	0.109
0.958	0.926	0.917	0.934	0.932	0.947	0.931	0.968
0.989	0.962	0.955	0.967	0.969	0.952	0.969	0.977
2.125	2.059	2.101	2.032	2.049	1.974	2.053	2.202
0.436	0.435	0.430	0.438	0.436	0.451	0.436	0.441
0.734	0.763	0.755	0.763	0.762	0.775	0.765	0.728
0.030	−0.091	−0.006	−0.130	−0.089	−0.108	−0.088	−0.001
0.965	0.961	0.951	0.965	0.961	0.975	0.962	1.002
0.957	0.989	0.980	0.984	0.982	0.964	0.987	0.998
0.217	0.150	0.236	0.094	0.131	−0.039	0.135	0.293
0.960	0.949	0.940	0.956	0.952	0.984	0.952	0.983
0.962	0.981	0.972	0.980	0.979	0.997	0.983	0.977
−0.096	−0.186	−0.184	−0.250	−0.221	−0.192	−0.186	−0.120
0.954	0.947	0.947	0.954	0.951	0.960	0.948	0.990
0.944	0.969	0.980	0.970	0.971	0.941	0.967	0.983
−0.063	−0.094	−0.036	−0.171	−0.139	−0.138	−0.106	−0.036
0.949	0.934	0.928	0.943	0.940	0.952	0.937	0.978
0.964	0.975	0.972	0.979	0.979	0.956	0.976	0.991
0.145	0.116	0.203	0.053	0.088	−0.083	0.096	0.245
0.956	0.941	0.931	0.948	0.945	0.977	0.945	0.976
0.966	0.976	0.967	0.977	0.977	0.995	0.980	0.976
	0.134	0.210	0.048	0.075	0.029	0.100	0.294
	0.965	0.957	0.975	0.973	0.990	0.971	0.998
	0.971	0.965	0.977	0.979	0.967	0.978	0.964
0.108		0.085	−0.048	−0.006	−0.047	0.001	0.184
1.007		0.991	1.005	1.001	1.018	1.001	1.032
0.971		0.992	0.997	0.995	0.981	0.998	0.988
0.086	−0.015		−0.083	−0.052	−0.053	−0.017	0.170
1.008	1.001		1.009	1.006	1.018	1.003	1.033
0.965	0.992		0.993	0.994	0.971	0.991	0.980
0.144	0.077	0.142		0.037	0.013	0.069	0.257
1.003	0.991	0.984		0.996	1.012	0.994	1.023
0.977	0.997	0.993		0.999	0.982	0.997	0.985
0.103	0.050	0.104	−0.032		−0.018	0.038	0.227
1.007	0.994	0.988	1.003		1.014	0.996	1.026
0.979	0.995	0.994	0.999		0.981	0.996	0.984
0.249	0.205	0.295	0.141	0.178		0.186	0.389
0.977	0.963	0.953	0.971	0.967		0.967	0.993
0.967	0.981	0.971	0.982	0.981		0.984	0.967
0.084	0.013	0.095	−0.045	−0.007	−0.055		0.185
1.008	0.997	0.988	1.004	1.000	1.018		1.030
0.978	0.998	0.991	0.997	0.996	0.984		0.989
0.007	−0.078	0.004	−0.126	−0.089	−0.115	−0.088	
0.966	0.958	0.949	0.963	0.959	0.974	0.960	
0.964	0.988	0.980	0.985	0.984	0.967	0.989	

TABLE 6

Mean seasonal PET values for all methods described in Table 1, for the 12 locations studied. Means followed by the same letter in a column are not significantly different by the Waller–Duncan test at $\alpha = 0.05$. The values following each column are the extreme values normalized to M13. For this range, M2 was included for Charleston, Apalachicola, and Lake Charles only

Apalachicola		Bismarck		Charleston		Columbia, MO		Dodge City		Fresno	
(mm day^{-1})	Mth	(mm day^{-1})	Mth	(mm day^{-1})	Mth	(mm day^{-1})	Mth	(mm day^{-1})	Mth	(mm day^{-1})	Mth
5.15 a	10	6.00 a	11	5.20 a	11	5.72 a	11	8.41 a	10	7.55 a	11
5.11 b	11	5.99 a	10	5.18 a	12	5.72 a	10	8.39 a	11	7.54 a	12
5.09 b	9	5.98 a	12	5.18 a	10	5.69 ab	12	8.36 ab	12	7.53 a	10
5.09 b	12	5.83 b	8	5.05 b	9	5.65 b	9	8.28 bc	9	7.51 ab	9
5.04 c	8	5.79 b	9	5.05 b	8	5.64 b	8	8.20 c	14	7.48 b	14
5.04 c	14	5.76 b	14	5.00 b	14	5.58 c	14	8.09 d	8	7.37 c	8
4.97 d	3	5.49 c	13	4.80 c	3	5.34 d	13	7.68 e	13	7.06 d	13
4.95 d	5	5.28 d	4	4.79 c	1	5.28 e	3	7.60 ef	3	6.91 e	3
4.92 f	15	5.26 de	1	4.77 cd	2	5.27 e	1	7.52 f	15	6.88 e	15
4.92 ef	1	5.23 ed	3	4.75 cde	15	5.21 f	4	7.41 g	1	6.81 f	4
4.89 fg	13	5.20 ef	15	4.74 de	5	5.21 f	15	7.40 g	4	6.77 f	1
4.88 g	6	5.14 fg	5	4.73 de	13	5.15 g	5	7.25 h	5	6.63 g	7
4.86 g	4	5.10 g	7	4.72 e	6	5.09 h	7	7.14 i	7	6.56 h	5
4.81 h	7	5.07 g	6	4.64 f	4	5.09 h	6	7.14 i	6	6.55 h	6
4.64 i	2	4.94 h	2	4.53 g	7	4.94 i	2	6.53 j	2	5.82 i	2
+5.3%	−5.1%	+9.2%	−7.6%	+9.9%	−4.2%	+7.1%	−4.7%	+9.5%	−7.0%	+6.9%	−7.2%

TABLE 6 (*continued*)

Ft. Worth		Lake Charles		Madison		Omaha		Phoenix		Washington, DC	
(mm day^{-1})	Mth	(mm day^{-1})	Mth	(mm day^{-1})	Mth	(mm day^{-1})	Mth	(mm day^{-1})	Mth	(mm day^{-1})	Mth
6.12 a	11	5.42 a	11	4.69 a	11	6.11 a	11	8.52 a	9	5.05 a	10
6.11 ba	12	5.41 a	12	4.67 ab	10	6.09 a	8	8.52 a	12	5.02 a	11
6.11 a	10	5.41 a	10	4.65 ab	12	6.09 a	10	8.52 a	11	5.00 a	12
6.06 bc	9	5.28 b	9	4.62 bc	8	6.08 a	12	8.51 a	14	4.90 b	9
6.03 c	14	5.25 b	14	4.59 cd	9	6.01 b	9	8.51 a	10	4.87 b	8
5.94 d	8	5.19 c	8	4.55 d	14	5.96 b	14	8.41 b	13	4.85 b	14
5.85 e	13	5.07 d	3	4.39 e	13	5.73 c	13	8.36 b	8	4.66 c	13
5.78 f	3	5.05 de	5	4.30 f	1	5.70 c	1	8.24 c	4	4.58 d	5
5.75 f	4	5.04 de	15	4.29 fg	4	5.62 d	3	8.13 d	7	4.57 de	3
5.75 f	15	5.01 ef	6	4.27 fg	3	5.59 d	4	8.09 d	3	4.55 de	4
5.66 g	1	5.01 ef	13	4.24 gh	5	5.58 d	15	8.08 d	15	4.54 de	1
5.65 g	5	4.98 f	1	4.24 gh	15	5.50 e	5	7.93 e	1	4.51 ef	15
5.64 g	7	4.94 g	4	4.20 hi	7	5.46 e	7	7.88 ef	5	4.46 fg	6
5.62 g	6	4.84 h	7	4.18 i	6	5.44 e	6	7.87 f	6	4.44 g	7
5.15 h	2	4.83 h	2	4.07 j	2	5.07 f	2	5.77 g	2	4.35 h	2
+4.6%	−3.9%	+8.2%	−3.6%	+6.8%	−4.8%	+6.6%	−5.1%	+1.3%	−6.4%	+8.4%	−4.7%

TABLE 7

Monthly and seasonal (April–September) potential evapotranspiration, as calculated with the 15 methods described in Table 1, for Charleston, SC. Means with the same letter in a column are not significantly different at the 5% level as determined by the Waller–Duncan separation test. Extremes are relative to M13

April			May			June			July			August			September			Seasonal		
	Mean	Mth		Mean	Mth		Mean	Mth		Mean	Mth		Mean	Mth		Mean	Mth		Mean	Mth
a	5.31	11	a	5.66	10	a	5.47	11	a	5.20	10	a	4.85	11	a	4.82	8	a	5.20	11
a	5.28	12	a	5.59	11	a	5.43	12	a	5.19	8	a	4.83	12	a	4.80	11	a	5.18	10
a	5.23	10	cba	5.58	12	ba	5.39	10	a	5.18	11	a	4.83	10	a	4.78	12	a	5.18	12
b	4.98	9	cb	5.52	8	cba	5.36	9	a	5.18	12	ba	4.80	9	a	4.77	10	b	5.05	9
cb	4.88	14	c	5.47	14	cb	5.30	14	b	5.07	9	cb	4.75	14	b	4.62	9	b	5.05	8
cb	4.84	2	c	5.47	9	c	5.25	8	b	5.06	14	dc	4.71	8	b	4.56	14	b	5.00	14
c	4.79	8	d	5.26	1	d	5.11	3	b	5.01	1	ed	4.66	3	b	4.55	2	c	4.80	3
dc	4.71	13	ed	5.22	13	ed	5.09	2	c	4.88	3	fe	4.60	15	b	4.55	1	c	4.79	1
ed	4.58	4	ed	5.21	15	fed	5.05	15	c	4.87	2	f	4.56	1	c	4.35	3	dc	4.77	2
fed	4.57	3	ed	5.21	3	fed	5.01	6	c	4.87	15	gf	4.55	5	dc	4.32	5	edc	4.75	15
gfed	4.55	6	ed	5.19	5	fed	5.00	1	c	4.87	5	gf	4.54	6	dc	4.30	6	ed	4.74	5
gfed	4.54	5	fe	5.12	4	gfe	4.97	5	dc	4.82	6	hg	4.48	13	dc	4.29	15	ed	4.73	13
gfe	4.47	15	gf	5.08	6	gf	4.96	13	ed	4.79	13	h	4.43	2	ed	4.22	13	e	4.72	6
gf	4.40	7	g	5.00	7	hg	4.87	4	e	4.72	4	h	4.42	4	fe	4.12	4	f	4.64	4
g	4.37	1	h	4.86	2	h	4.77	7	f	4.64	7	i	4.35	7	f	4.02	7	g	4.53	7
Max.	+12.7%			+8.4%			+10.3%			+8.6%			+8.2%			+14.2%			+9.9%	
Min.	−7.2%			−6.9%			−3.8%			−3.1%			−2.9%			−4.7%			−4.2%	

TABLE 8

Monthly and seasonal (April–September) potential evapotranspiration, as calculated with the 15 methods described in Table 1, for Omaha, NE. Means with the same letter in a column are not significantly different at the 5% level as determined by the Waller–Duncan separation test. Method 2 was not used in calculations of the extremes, shown at the bottom of each column

April		May		June		July		August		September		Seasonal	
Mean	Mth	Mean	Mth	Mean	Mth	Mean	Mth	Mean	Mth	Mean	Mth	Mean	Mth
a 5.89	11	a 6.23	10	a 6.76	8	a 7.03	11	a 6.54	8	a 4.35	11	a 6.11	11
a 5.88	8	a 6.20	11	a 6.75	10	ba 7.01	10	b 6.41	10	a 4.35	10	a 6.09	10
a 5.83	9	a 6.17	12	ba 6.73	11	ba 7.00	12	b 6.41	11	a 4.35	12	a 6.09	8
a 5.82	12	a 6.13	9	ba 6.72	12	ba 6.96	9	b 6.39	12	a 4.33	8	a 6.08	12
a 5.78	10	ba 6.10	8	ba 6.64	9	ba 6.90	14	c 6.24	14	b 4.23	9	b 6.01	9
a 5.75	14	ba 6.04	14	b 6.62	14	b 6.87	8	c 6.21	9	b 4.19	14	b 5.96	14
b 5.44	13	cb 5.91	13	c 6.39	13	c 6.59	13	c 6.17	1	c 4.04	1	c 5.73	13
b 5.41	1	dc 5.80	4	dc 6.36	1	c 6.59	3	d 5.96	13	dc 4.04	13	c 5.70	1
cb 5.36	3	dc 5.73	3	ed 6.24	3	c 6.53	15	ed 5.86	15	edc 3.93	5	d 5.62	3
dcb 5.28	4	d 5.70	1	e 6.23	4	c 6.50	1	ed 5.84	3	ed 3.93	3	d 5.59	4
dcb 5.28	15	ed 5.65	5	e 6.22	15	dc 6.45	4	fe 5.81	4	e 3.92	4	d 5.58	15
dc 5.13	7	ed 5.65	7	fe 6.13	5	ed 6.34	5	fe 5.81	5	e 3.91	6	e 5.50	5
d 5.07	5	ed 5.64	15	fe 6.11	7	ed 6.32	6	fe 5.80	2	e 3.89	15	e 5.46	7
d 5.06	6	e 5.47	6	f 6.07	6	e 6.29	7	fe 5.77	6	e 3.88	2	e 5.44	6
e 4.19	2	f 4.96	2	g 5.71	2	f 5.85	2	f 5.70	7	e 3.84	7	f 5.07	2
+8.3%		+5.4%		+5.8%		+6.7%		+9.7%		+7.7%		+6.6%	
−7.0%		−7.4%		−5.0%		−4.6%		−4.4%		−5.0%		−5.1%	

TABLE 9

Monthly and seasonal (April–September) potential evapotranspiration, as calculated with the 15 methods described in Table 1, for Phoenix, AZ. Means with the same letter in a column are not significantly different at the 5% level as determined by the Waller–Duncan separation test. Method 2 was not used in calculation of the extremes, shown at the bottom of each column

April		May		June		July		August		September		Seasonal	
Mean	Mth	Mean	Mth	Mean	Mth	Mean	Mth	Mean	Mth	Mean	Mth	Mean	Mth
a 6.30	11	a 8.85	11	a 8.34	12	a 10.05	9	a 9.16	9	a 8.48	10	a 8.52	11
a 6.29	12	a 8.84	12	a 8.33	11	a 10.04	14	ba 9.15	11	a 8.43	12	a 8.52	9
ba 6.27	9	a 8.82	10	a 8.33	14	a 10.01	11	ba 9.14	12	a 8.42	11	a 8.52	12
ba 6.26	10	a 8.82	9	a 8.33	9	ba 10.00	10	ba 9.13	14	a 8.42	9	a 8.51	10
ba 6.26	14	a 8.82	14	a 8.33	13	cba 10.00	12	ba 9.13	10	ba 8.39	14	a 8.51	14
ba 6.25	13	ba 8.78	13	ba 8.32	10	dcb 9.84	13	b 9.04	13	cb 8.26	8	b 8.41	13
cb 6.16	8	b 8.69	8	cb 8.22	8	dc 9.84	8	c 8.91	8	c 8.16	13	b 8.36	8
dc 6.11	4	c 8.51	4	dc 8.14	4	ed 9.70	4	c 8.90	4	d 8.01	3	c 8.24	4
ed 6.02	7	d 8.41	7	d 8.05	7	e 9.67	3	dc 8.80	3	ed 8.00	4	d 8.13	7
fe 5.92	3	e 8.20	3	e 7.88	3	e 9.66	15	dc 8.79	7	fed 7.99	15	d 8.09	3
fe 5.91	15	e 8.19	15	e 7.88	15	fe 9.57	7	d 8.78	15	gfed 7.88	7	d 8.08	15
gf 5.81	1	f 8.06	1	f 7.77	1	gf 9.46	1	e 8.56	6	gfe 7.87	5	e 7.93	1
g 5.76	6	f 7.98	6	f 7.69	5	g 9.38	5	e 8.56	5	gf 7.85	1	fe 7.88	5
g 5.74	5	f 7.98	5	f 7.69	6	g 9.36	6	e 8.55	1	g 7.79	6	f 7.87	6
h 4.70	2	g 5.94	2	g 5.75	2	h 6.42	2	f 6.13	2	h 5.61	2	g 5.77	2
+0.8%		+0.8%		+0.1%		+2.1%		+1.3%		+3.9%		+1.3%	
−8.2%		−9.1%		−7.7%		−4.9%		−5.4%		−4.5%		−6.4%	

M1 with M13, for which the seasonal mean values were insignificantly different at the 5% level. The slope was 0.966, and the intercept was 0.172. These values indicate no significant systematic difference was detected between the two methods. A moderate degree of scatter in the relationship is reflected in the r^2 of 0.915. Figure 2 has a relationship between M1 and M3 with slope, intercept, and r^2 all improved over that in Fig. 1, yet the means were significantly different by the Waller–Duncan test at the 5% level. Figure 3 shows a systematic linear relationship between M6 and M10 with $r^2 = 0.967$, but with both slope (0.85) and intercept (0.26) different from that of the 1:1 line. This comparison also had significantly different means at the 5% level.

The regression coefficients for all possible comparisons among methods are given for Charleston, SC, Omaha, NE, and Phoenix, AZ, in Tables 3, 4, and 5, respectively. Coefficients of determination were nearly always greater than 0.90 except for those involving M2, for which high PET values were consistently underestimated.

Seasonal mean daily PET values are presented for all locations and methods in Table 6. The extreme seasonal errors were within the band of $\pm 10\%$ of M13 values. The highest values for each site were 1.3–9.9% higher than M13, and the lows were 3.6–7.6% lower than M13. The seasonal extremes obtained at each site were 8–17% of M13 at that site. Method 2 was not included for determination of these ranges except at Charleston, Apalachicola, and Lake Charles.

At these three sites, a total of six methods group with M13, and two (M6 and M15) are not significantly different at any of these three sites. Over all other, less humid locations, only three methods were shown to be statistically indistinguishable from M13. This result indicated that the selection of method was less critical in humid areas. However, even in humid sites, use of improper methods imparted seasonal biases to PET estimates. This was consistent with inferences from differences noted in sample $\bar{V}$ calculations (Jensen, 1974) and with the PET differences between Methods M13, M14 and M15 reported for several locations in the Great Plains (Heermann, 1985).

For Charleston, Lake Charles, and Apalachicola, the three most humid sites, M6 and M15 were not significantly different from M13, which was chosen for the reference. Method 6 is of particular interest because it is the widely used method recommended by Doorenbos and Pruitt (1977). On a seasonal basis, there was no difference between M6 and M13 for these sites. On a monthly basis, one month for Charleston and three for Lake Charles had M6 significantly different from M13. From these results, one cannot conclude that the use of M6 rather than M13 causes long-term errors in PET calculations in humid areas.

The Charleston, Omaha, and Phoenix data are presented by month and season in Tables 7, 8, and 9, respectively, as representative of the humid southeast, the more moderate Great Plains, and the more arid west. These data are provided to show monthly mean values and ranges.

The single time of day (0700 h LST) dew point measurement (M1) was suggested as a standard by Burman et al. (1983) and included by both Jensen (1974) and Cuenca and Nicholson (1982). In only three cases – Apalachicola, Lake Charles, and Omaha – was PET as calculated by M1 the same as by M13. Based on these results, it is recommended that single time of day dew point measurements be used carefully and also that local correlations be done to determine adequacy of the estimate.

A related method (M2), proposed for humid areas by Merva and Fernandez (1985), used the minimum air temperature as the estimate of dew point. This method presumes that air temperature approaches the dew point each morning or, equivalently, that the relative humidity approaches saturation. If this does not normally occur, the method would not be recommended. Of the three humid sites, only in Charleston was PET by M2 the same as by M13. As expected, M2 was clearly an underestimator of PET at other sites and was not included in calculations of the range of PET values for these sites.

If a long-term bias between methods existed for a site, one could argue that the bias could be removed using an equation such as given in Tables 3–5. However, because of deviations from typical diurnal patterns of temperature and humidity, the effect of each method was not constant from day to day, as seen by the scatter in Figs. 1–3. To further evaluate daily variation of PET as calculated by the 15 methods, the daily PET value was divided by PET as calculated by M13, which previously had been selected as the best estimate of PET. Over all sites, this daily ratio varied from 0.2 to over 2.0.

At Charleston, this range was 0.19–1.78, at Omaha 0.34–2.08, and at Phoenix 0.82–1.25. (Method 2 was excluded from this range at all sites but Charleston, Apalachicola, and Lake Charles.) Deviation of this ratio from unity suggests two conclusions. First, a simple correction may not be adequate. Second, a different distribution of PET values is probable if methods are changed, which has possible implications for statistical climatologies of PET.

CONCLUSIONS

Potential evapotranspiration as calculated with the combination equation showed considerable dependence on the method of calculation of $\bar{V}$, the daily average vapor pressure deficit. Because the range of values obtained (within $\pm 10\%$) was comparable to the accuracy claimed for the combination equation, it could be argued that errors attributable to selection of method were negligible. However, this study has shown that these errors can be systematic, resulting in a long-term bias in the PET estimate. To be sure, it remains for the individual researcher to determine whether these differences affect experimental conclusions.

The recommendation is to select a form of the combination equation, including the wind function, and use the ∇ method that was used to derive the wind function. Because of observed variability between the methods, we endorse Heermann's (1985) recommendation that testing proceed as rapidly as possible to develop wind functions for values averaged on an hourly basis. Estimates based on these values should provide better stability than extreme values and use the capabilities of modern data-collection equipment to improve the resulting information.

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LIST OF SYMBOLS

α	albedo of surface to shortwave radiation
A, B	empirical constants
A_1, B_1	empirical constants
C_p	heat capacity at constant pressure: 0.242 J $(\mathrm{kg}\ ^\circ\mathrm{C})^{-1}$
δ	vapor pressure deficit (kPa)
Δ	the slope of the saturation vapor pressure curve (kPa $^\circ\mathrm{C}^{-1}$)
∇	daily average vapor pressure deficit (kPa)
ϵ	vapor pressure (kPa)
$F(U)$	wind function (J m^{-2} day^{-1} kPa^{-1})
γ	psychrometric constant (kPa $^\circ\mathrm{C}^{-1}$)
G	soil heat flux (J m^{-2} day^{-1})
κ	von Karmann's constant (0.41)
λ	latent heat of vaporization (J kg^{-1})
M_a	molecular weight of air (kg mol^{-1})
M_v	molecular weight of water (kg mol^{-1})
P	barometric pressure (kPa)
PET	potential evapotranspiration (kg m^{-2} day^{-1}) (or mm day^{-1})
ρ	density of air (kg m^{-3})
R_b	net outgoing longwave radiation (J m^{-2} day^{-1})
R_{bo}	net outgoing longwave radiation on a clear day (J m^{2} day^{-1})
R_n	net radiation (J m^{-2} day^{-1})
R_s	solar radiation (J m^{-2} day^{-1})
R_{so}	clear sky solar radiation (J m^{-2} day^{-1})
σ	Stephan–Boltzmann constant (J m^{-2} day^{-1} $^0\mathrm{K}^{-4}$)
T	temperature ($^\circ$C)
T_k	temperature (K)

T_w wet bulb temperature (°C)
U wind speed (m day^{-1})
Z height of measurements (m)
Z_o roughness length (0.01 m)

APPENDIX

The combination equation as given by Van Bavel (1966) was used. This analysis, however, could have been made on any of several forms of the equation

$$PET=\left[\frac{\Delta}{(\Delta+\gamma)}\frac{(R_n+G)}{\lambda}\right]+\left[\frac{\gamma}{(\Delta+\gamma)}\frac{F(U)}{\lambda}V\right] \quad (1)$$

All symbols and units are listed in the list of symbols. Since soil heat flux, G, was not available, and these calculations were made on a daily basis, G was assumed to be zero. Wind speed measurements at the stations were taken at varying heights as recorded in the station histories, and wind speed in the TMY data set was not adjusted to a single height. Therefore, wind speed was adjusted according to the log-law wind profile model to match the height of the collateral measurements. Each of the other variables in this equation were calculated from published relationships with data on the TMY tape.

The slope of the vapor pressure function, Δ, was calculated from the derivative of the equation of Murray (1967)

$$\epsilon=0.61078e^{\left[\frac{17.269T}{237.3+T}\right]} \quad (2)$$

and

$$\Delta=0.61078\left[\left(\frac{17.269}{237.3+T}\right)-\left(\frac{17.269T}{(237.3+T)^2}\right)\right]e^{\left(\frac{17.269T}{237.3+T}\right)} \quad (3)$$

The psychrometric constant, γ, was calculated from the equation of Jensen (1974)

$$\gamma=\frac{C_pP}{\lambda\frac{M_v}{M_a}} \quad (4)$$

The latent heat of vaporization, λ, was calculated from the equation given by Fritschen and Gay (1979)

$$\lambda=(2500-2.365T_w)1000 \quad (5)$$

Since the daily average T_w was not known, we substituted the average air temperature in this calculation. This assumption does not influence the result, because of the weak dependency upon air temperature. Net radiation was also not available, so the procedure outlined in Jensen (1974) was followed

$$R_n = (1-\alpha)R_s - R_b \quad (6)$$

$$R_b = R_{bo}\left(A\frac{R_s}{R_{so}} + B\right) \quad (7)$$

and

$$R_{bo} = (A_1 + B_1(10\epsilon)^{0.5})\sigma T_k^4 \quad (8)$$

In eqs. 7 and 8, the empirical constants were taken from Jensen (1974). The locations were classified according to Thornthwaite (1948) for the selection of the humidity-dependent parameters A and B (see Table 2 for values). Clear sky solar radiation was calculated using routines based on Robertson and Russelo (1968).

The dependence of the second term upon wind speed was calculated as in Van Bavel (1966), which in turn was based on the form of Businger (1956)

$$F(U) = \frac{M_v}{M_a}\frac{\lambda\rho\kappa^2}{P}\frac{U}{\left(\ln\frac{Z}{Z_0}\right)^2} \quad (9)$$

The density of the air was calculated from air temperature and humidity using routines in Jensen (1974) and Fritschen and Gay (1979).

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