Adjusting Temperature Parameters to Reflect Well-Watered Conditions

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Abstract: Adjustment coefficients for air temperature and dew point temperature measurements at dry weather sites are determined for predicting reference evapotranspirations (ET_0) for irrigated conditions. Seasonal and regional variation in changes in temperature parameters versus the ratio of effective precipitation to ET_0 are analyzed. The determined adjustment coefficients are tested for validity using weather data from reference weather stations, and paired reference and dry stations. The effects of adjusting air temperature and dew point temperature for site aridity are analyzed using the FAO Penman-Monteith and the Hargreaves equations. Maximum reductions in ET_0 caused by adjustments of temperature data for aridity effects was as high as 25%.

INTRODUCTION

Accurate estimates of evapotranspiration (ET) are essential for responsible planning, design, and operation of irrigation systems. Theoretical and empirical equations have been developed over the years to estimate ET. These equations use one or more of the climatological factors: solar radiation, air temperature, relative humidity, and wind speed. The accuracy with which ET is estimated hinges upon the accuracy with which these weather parameters are measured or estimated.

Evapotranspiration also depends upon crop factors, which may include the type of the crop, height of the crop, and density of the crop. It is virtually impossible to develop theoretical or empirical equations for all sets of crop conditions. Therefore, the idea of reference crop ET (ET_0) was introduced by Doorenbos and Pruitt (1975) and adopted by the United Nations Food and Agriculture Organization (FAO). ET_0 has been defined as the rate of ET from an extended surface of green grass of uniform height—8 to 15 cm tall—actively growing, completely shading the ground, and not short of water (Doorenbos and Pruitt 1975; Allen et al. 1989; Smith et al. 1991). ET from a particular crop under specific sets of conditions is normally calculated by using crop coefficients (Doorenbos and Pruitt 1975; Wright 1982).

Weather stations that comply with the above definition of ET_0 are referred to as ''reference'' stations and those that do not comply with the definition are referred to as ''nonreference'' stations. Most ET equations were developed using weather data from research locations generally falling into the reference station category. However, the majority of the weather data around the globe is reported from nonreference settings such as airports, where sensors may even be on tops of buildings, or at stations having dry, bare soil surfaces and/or concrete surfaces. Using such weather data to estimate ET_0 for planning and design of an irrigation system may cause serious errors due to elevated maximum and minimum air temperatures (TMAX and TMIN) and depressed dew point temperature (TD).

Irrigation modifies the microclimate of an area by influencing the partitioning of radiant energy at the surface (De Vries and Birch 1961). Irrigation water causes more energy to be consumed in ET and less energy to be consumed in heating the air and the soil. This reduces the air temperature and increases the humidity of the air. In other words, irrigation humidifies and cools the equilibrium boundary layer. Therefore, for planning and design of a future irrigation project, data from nonreference, nonagricultural settings should be adjusted so that the adjusted data resemble the data to be expected for the future agricultural and reference condition.

In this study, adjustments to nonreference weather data are made by decreasing maximum and minimum air temperatures and increasing dew point temperature measurements. Adjustment factors for TMAX, TMIN, and TD have been determined using global climatological and weather data.

The objectives of the reported study were:

1. To determine the factor(s) for adjusting maximum and minimum air temperatures and dew point temperature from dry, arid stations in order to obtain equivalent temperatures over well-watered settings.
2. To determine whether maximum, minimum, and dew point temperatures from dry, arid stations should be adjusted in the same proportions.
3. To determine whether temperature adjustment factor(s) change with season or remain constant.
4. To analyze whether the adjustment factors vary with climatic region.
5. To test the effect of adjusting the temperature data on ET_0 values computed using the FAO Penman-Monteith (FAO-PM) (Smith et al. 1991; Allen et al. 1994) and the Hargreaves (ETH) (Hargreaves et al. 1985) equations.

EFFECTS OF SITE ARIDITY

The partitioning of net incoming radiation depends on the moisture content of the evaporating surface. For stations in humid climates having high soil moisture, most of the net incoming radiation is used to evaporate water, and a relatively smaller amount is used to heat the air and soil.

Normally, air temperature decreases during nighttime because of the net loss of longwave radiation into the atmosphere. For stations in humid climates, the net loss of radiative cooling continues until the lower boundary layer becomes saturated with water vapor and reaches dew point temperature. As air temperature falls below TD, water vapor begins to condense because of supersaturation of the air, thereby releasing latent heat. The released latent heat keeps the air temperature from falling further below TD. However, because water vapor is removed from the atmosphere by condensation, both TMIN and TD may decrease together a few degrees during the night. Therefore, it is true and logical to state that at stations in humid locations having adequate soil moisture, minimum daily air temperature is nearly equal to and can be substituted for dew point temperature.

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J. Irrig. Drain Eng. 1999.125:26-33.

On the other hand, for stations in arid, nonirrigated regions, a majority of net incoming radiation under dry soil conditions is used to heat the air and the soil, since there is less water available to evaporate. Increased heating of the air and the soil and decreased ET lead to an increase in TMAX and TMIN and a decrease in TD relative to a well-watered condition or humid climate. Under arid conditions or low soil moisture, air temperature may not cool to TD during the night. This leads to a positive value for the difference between daily TMIN and TD (TMIN-TD), termed here as mean dew point departure (MDD).

Allen et al. (1983) used four weather-sensing stations located in the Bruneau Plateau area in Southern Idaho and one station located at and operated by the USDA-ARS research center at Kimberly, Idaho, to illustrate the effect of weather station siting on consumptive use estimates. Two of the four stations were in dry land, desert conditions, and the other two were under irrigated conditions. When air and dew point temperatures from the arid sites were used to calculate ET_0, an overestimation of 17% for the season and 21% for the peak month of July occurred.

Davenport and Hudson (1967) measured maximum and minimum air temperatures, wind velocity, and vapor pressure at windward and leeward edges of a 17-km transect cotton field interspersed among uncropped dry fallow in Gezira, Sudan. They recorded lower mean temperature, wind run, and vapor pressure deficits at the leeward edge as compared to the windward edge.

Burman et al. (1975) gathered ground-level climatic measurements along a 50-km transect going from dry sagebrush land into the center of a large irrigated area in southern Idaho. They observed minimal climatic changes during the month of May, when soil moisture conditions for evaporation were similar in both areas. However, they found average air temperatures in the desert to be about 3°C warmer than near the center of the irrigated site in July. They also measured an increase with distance in vapor pressure (most changes being within the first 2 km) and a 20% decline in estimated ET along the transect in July.

Holmes (1970) used an instrumented aircraft to measure air temperature and radiation temperature of the surface of the earth and a mobile ground station equipped to measure air temperature to identify thermal discontinuities in the atmospheric boundary layer produced by agriculture and a large prairie lake near Brooks, in southern Alberta. He measured a decrease of 3.0 and 2.0°C, respectively, over the lake and over an irrigated region at 20 m elevation. He also recorded a temperature increase of 2.0°C as air moved back to virgin prairie at the same 20 m elevation in the atmosphere.

Ley and Allen (1994) used eight weather stations from the Washington Public Agriculture Weather System (PAWS) to analyze the effects of station sitings on maximum air temperature, minimum air temperature, and vapor pressure. The stations were paired with a single nearest neighbor irrigated reference station, which was situated over irrigated turfgrass with several kilometers of irrigated upwind fetch. The results indicated that, on average, maximum air temperatures at the dry sites were 1.8°C greater in July and 0.9°C greater over the season, minimum air temperatures were 1.1°C greater in July and 0.7°C greater over the season, vapor pressures were 6% less in July and 7% less over the season, and the computed reference ET was 20% greater in July and 19% greater over the season as compared with the irrigated reference station. Wind speeds were found to be greater over the dry locations than over the reference location.

From these analyses it can be concluded that a change of certain magnitude in the measured values of TMAX, TMIN, and TD (due to the aridity of the weather station) can significantly affect the estimation of ET_0. Hence, it may be important to adjust these data values for site aridity before making computation of ET_0.

DATA SETS

CLIMWAT Data Set

The data set used for the development of the weather data adjustment factors was obtained from the United Nations Food and Agriculture Organization (UN-FAO) database known as CLIMWAT (Smith 1993). The CLIMWAT database consists of climatic data from 3,262 meteorological station in 144 countries. The data consist of long-term monthly average values for TMAX, TMIN, solar radiation (RS), mean relative humidity (RH), wind speed (U_2), total precipitation (PTOT), effective precipitation (Peff), and ET_0 computed with the FAO-PM equation.

Eight countries that were found to have relatively high quality records of climatic data were selected from three geographical regions (Africa, Asia, and Europe). The list of countries selected and the number of stations in each country are given in Table 1. The site descriptions of CLIMWAT did not indicate the relative dryness or wetness of the stations.

U.S. Data Sets

Detailed weather data sets from two U.S. locations were evaluated for aridity effects. These were an hourly data set from the Washington Public Agriculture Weather System (WPAWS) in central Washington, for the specific year 1993, and a daily data set from Davis, California, for the years 1965–71. The two U.S. data sets were used to test the validity of the adjustment factors developed from CLIMWAT.

The Washington data (T. Ley, personal communication, 1994) included dry and reference stations that were contrasted with one another to assess the effect of site aridity on temperature parameters and to test the effect of using the adjustment coefficients on computed ET_0. Three weather stations in the data set used for these purposes were Roza (irrigated), Horrigan (dry), and McWhorter (dry).

The Davis weather station is in basically a reference condition. In addition to the climatic data, this data set included

TABLE 1. List of Countries and Number of Stations in Each for CLIMWAT Data Set

Country (1)	Number of stations (2)
Ethiopia	142
Sudan	63
Egypt	28
India	161
Pakistan	24
France	44
Italy	60
Spain	58

TABLE 2. List of Stations, Latitudes, Longitudes, and Elevations for Washington and Davis Data Sets [Included Are Distances from Reference Station (Roza) for Two Dry Stations (Horrigan and McWhorter)

Station (1)	Latitude (deg) (2)	Longitude (deg) (3)	Elevation (m) (4)	Distance from Roza (km) (5)
Roza, Wash.	46.30	119.74	380	—
Horrigan, Wash.	46.13	119.80	400	19.8
McWhorter, Wash.	46.33	119.62	424	9.4
Davis, Calif.	39.00	121.80	16	—

J. Irrig. Drain Eng. 1999.125:26-33.

grass reference evapotranspiration data measured by a precision weighing lysimeter (W. O. Pruitt, personal communication, 1986, to Allen and G. H. Hargreaves). The main purpose of using the Davis data set was to evaluate whether using the adjustment factors at a weather station already in a reference condition can cause unnecessary changes in the computed ET_0. Altitudes, latitudes, longitudes, and relative locations of the U.S. stations are given in Table 2.

PROCEDURES

Data Analyses

The ratio of mean monthly effective precipitation to mean monthly ET_0 (PRATIO) was used to characterize the relative dryness of each CLIMWAT station. The relative value for PRATIO indicates whether natural precipitation was sufficient to satisfy the general evaporative demand of the atmosphere represented by ET_0. A ratio of one and greater implies that natural precipitation was generally sufficient to satisfy the evaporative needs of the atmosphere, assuming that the precipitation was relatively evenly distributed within the month. Therefore, an assumption was made that when PRATIO > 1, grass or other vegetation was actively growing and transpiring, so that reference conditions probably existed.

For the CLIMWAT data set, lapse-rate-adjusted maximum and minimum air temperatures, actual TD, and MDD were plotted against PRATIO to analyze the effect of site aridity on these parameters (Figs. 1–4). Lapse rate adjustments were necessary to eliminate natural, orographic changes in air temperatures with elevation. A dry adiabatic lapse rate of 1°C per 100 m was used.

It was found that TMAX, TMIN, and TD change more or less linearly with PRATIO, particularly over the nonreference

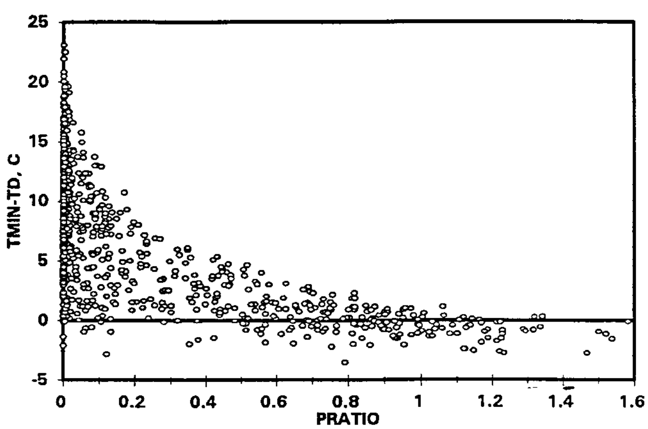

FIG. 1. TMIN-TD vs. PRATIO, January–December, Sudan

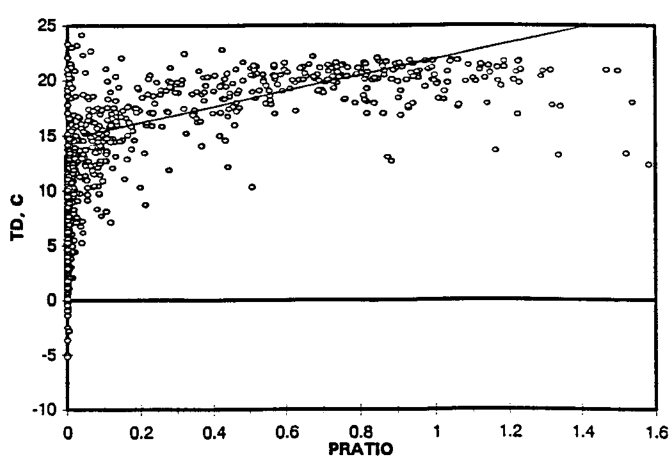

FIG. 2. TD vs. PRATIO, January–December, Sudan

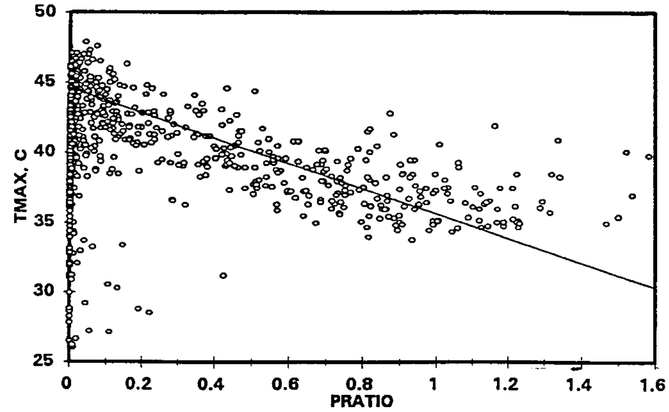

FIG. 3. TMAX (Adjusted to Sea Level) vs. PRATIO, January–December, Sudan

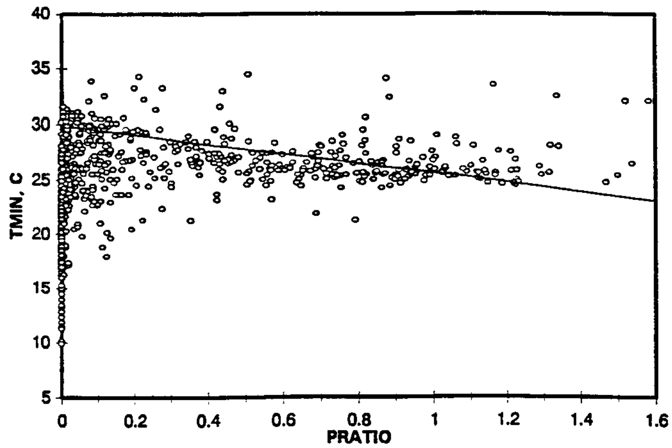

FIG. 4. TMIN (Adjusted to Sea Level) vs. PRATIO, January–December, Sudan

(dry) range ($0 \leq$ PRATIO ≤ 1) (Figs. 3–4). Therefore, slope lines were visually fitted over this range. Visual fitting was used because of the wide scatter of points observed in most graphs. Generally, trend lines for TD were drawn to follow the central ''mass'' of observations lying between 0 < PRATIO < 1 (e.g., Fig. 2) and the trend lines for TMAX and TMIN were drawn to follow the upper mass of observations lying between 0 < PRATIO < 1 (e.g., Figs. 3 and 4). This was done so that adjustments made to data would be conservative. The actual slope of lines did not substantially impact the final procedure for adjusting the dew point and temperature data. Rather, the slopes were used to determine whether general trends in TD, TMAX, and TMIN with PRATIO were similar between climates and regions.

The scatter within figures was greater for stations in humid regions and were mainly created by the wide variety of the site environments used in the analyses. Therefore, the slope lines were drawn to exclude certain points that were considered to be outliers and to follow general patterns as much as possible. The fitted slope lines were used to indicate the approximate rate of change of temperature parameters per unit change in PRATIO. After the lines were visually fitted and their slopes estimated, comparisons of these slopes were made using the SAS statistical software package (SAS 1989).

Adjustment Procedures

The objective was to bring TMIN and TD, under nonreference conditions, closer together in order to reflect conditions where the surface is well-watered and at a reference weather condition reflective of irrigated agriculture. The amount by which air temperature has to be decreased and dew point tem-

J. Irrig. Drain Eng. 1999.125:26-33.

perature increased depends on the extent of aridity (dryness) of the weather station. In this regard, MDD was used as an indicator of the extent of aridity of the weather station. MDD was used, rather than PRATIO, due to the unknown and complicating effects of irrigation, soil moisture storage and vegetation, or relations between aridity and PRATIO. The slopes of TMIN and TD versus PRATIO were used to determine the fraction of MDD to be subtracted from the measured TMIN (and also TMAX) and the fraction to be added to the measured TD. Higher proportions of MDD are applied to the parameter having greater slope. These fractions, termed here as adjustment coefficients, were determined as

$$K_n = \frac{S_n}{S} \tag{1}$$

$$K_d = \frac{S_d}{S} \tag{2}$$

$$K_x = \left(\frac{S_x}{S_n}\right) K_n \tag{3}$$

where K_n, K_d, and K_x = adjustment coefficients for TMIN, TD, and TMAX, respectively [see (4)–(6)]; S_n, S_d, and S_x = absolute values of average slopes for TMIN, TD, and TMAX, respectively, for each climatic group; and S = sum of absolute values of average slopes of minimum air temperature and dew point temperature for each climatic group.

Minimum air temperature does not always cool to the dew point, even under reference conditions. Reasons may include the continual mixing of warm, dry air from overhead into the equilibrium boundary layer at night, especially when wind speeds are greater than a few miles per second. Other reasons may include variations of the dew point temperature during the day relative to early morning recordings, and the means by which average daily TD is calculated from RH in addition to sensor recording errors. When PRATIO is greater than unity, it is common for MDD to take on values of about 0 ± 2°C. Therefore, a TMIN-TD (MDD) ''window'' of 2°C was used to represent the reference condition during the adjustment of air temperatures and dew point temperature. Expressed in an equation form, the adjustments are

$$TMAX_0 = TMAX - K_x(MDD - 2) \tag{4}$$

$$TMIN_0 = TMIN - K_n(MDD - 2) \tag{5}$$

$$TD_0 = TD + K_d(MDD - 2) \tag{6}$$

for MDD > 2°C, where $TMAX_0$, $TMIN_0$, and TD_0 = maximum air temperature, minimum air temperature, and dew point temperature adjusted to approximate measurements under ET conditions, respectively; TMAX, TMIN, and TD = measured maximum air temperature, minimum air temperature, and dew point temperature, respectively; K_x, K_n, and K_d = adjustment factors for maximum, minimum, and dew point temperatures, respectively, taken from (1)–(3).

The validity of adjustment factors determined from the CLIMWAT database was tested using the Washington and Davis data sets. Linear regressions of ET_0 for the reference station versus ET_0 for the dry stations were made for the Washington data set. The regressions were made for both adjusted and unadjusted air and dew point temperatures. Similarly, linear regressions of ET_0 before adjustment and ET_0 after adjustment versus the lysimeter ET (LYS) were made for the Davis data set. In all of the regressions, the Y-intercepts were forced through the origin because ET_0 for both the dependent and independent variables should theoretically approach the origin when there is no ET. Standard errors of Y estimates (SEE), the square of the correlation coefficient (r^2), and the X coefficient (b) were used to assess the validity of the adjustment coefficients.

Finally, the effect of adjusting temperatures parameters upon the changes in computed ET_0 was analyzed using the FAO-PM and the ETH equations for the CLIMWAT data set. Simple arithmetic ratios of ET_0 after adjustment to ET_0 before adjustment of the temperature parameters (ETRATIO) were evaluated.

RESULTS AND DISCUSSIONS

The CLIMWAT stations used in this study were grouped into two climatic categories, arid and humid (see Table 3). The grouping was based on numerical values of maximum departures of MDD values from values expected for reference surfaces, and on average PRATIOs for individual countries.

The ''maximum'' departure of MDD was defined and expressed as the difference between the peak MDD value at PRATIO ≈ 0 (dry condition) and the average MDD for PRATIO ≥ 1 (moist condition). This term indicates the maximum deviation of MDD, due to the aridity of the station, from what would have occurred if the surface had been in a reference condition.

An average PRATIO was calculated as an arithmetic average of PRATIOs of all stations and all months within a given country. The higher the maximum range in MDD and the lower the average PRATIO, the greater is the aridity of the region. Specific procedures are discussed in Temesgen (1996).

The first climatic category included data from Ethiopia, Sudan, Egypt, India, and Pakistan. This group essentially represented dry, arid (and semiarid) tropical climates. The second climatic category included data from France, Italy, and Spain. This group was categorized as representing humid or semihumid temperate climates.

Seasonal and Regional Variations

Tables 3 and 4 show the results of the visually fitted slopes of TMAX, TMIN, and TD relative to PRATIO for the whole season, and for summer (May, June, July) and winter (November, December, January) seasons for the eight CLIMWAT countries, respectively. Included in the tables are the maximum departure of MDD as well as average PRATIO (only in Table 3). The results indicate that there was more scatter of points during the winter than during the summer, particularly for the humid climates. In addition, PRATIOs during the winter sea-

TABLE 3. Slopes of Maximum and Minimum Air Temperatures and Dew Point Temperature vs. PRATIO, Averaged over Twelve Months of the Year for CLIMWAT Data Set (Included are Maximum Range in MDD and Average PRATIO)

Country (1)	Slopes of Temperatures vs. PRATIO: TMAX (°C) (2)	TMIN (°C) (3)	TD (°C) (4)	Range in TMIN-TD (0 < PRATIO < 1), °C (5)	Average PRATIO (6)
Arid					
Ethiopia	−7	−4	9	15	0.59
Sudan	−9	−4	8	23	0.27
Egypt	−8	−6	6	20	0.05
India	−9	−4	9	20	0.53
Pakistan	−10	−5	6	16	0.22
Humid					
France	−9	−8	−7	5	1.45
Italy	−9	−8	−8	7	1.27
Spain	−11	−10	−11	10	0.78
Average arid (n = 5)	−8.6	−4.6	7.6	18.8	0.33
Average humid (n = 3)	−9.7	−8.7	−8.7	7.3	1.17

J. Irrig. Drain Eng. 1999.125:26-33.

TABLE 4. Slopes of Maximum and Minimum Air Temperatures and Dew Point Temperature vs. PRATIO and Maximum Range in MDD for Summer and Winter Seasons for CLIMWAT Data Set

	Summer Season (May, June, July)				Winter Season (November, December, January)			
Country (1)	TMAX (°C) (2)	TMIN (°C) (3)	TD, (°C) (4)	Max MDD, (°C) (5)	TMAX (°C) (6)	TMIN (°C) (7)	TD (°C) (8)	Max MDD, (°C) (9)
Arid								
Ethiopia	−7	−4	7	10	−7	−5	10	6
Sudan	−8	−4	10	18	−7	−5	9	8
Egypt	—[a]	—[a]	—[a]	16	−8	−6	8	4
India	−9	−4	9	15	−7	—[a]	10	6
Pakistan	−9	−8	10	15	−8	−5	8	6
Humid								
France	−9	−8	−9	2	−2	−2	−2	1
Italy	−9	−9	−9	4	−4	−4	−4	2
Spain	−11	−10	−10	6	−3	−2	−2	3

[a]See text for explanations.

sons were mostly greater than 1.0 for the humid categories. Figures showing plots of MDD, TD, TMAX, and TMIN versus PRATIO for stations used in this study are presented in Temesgen (1996).

Asterisks (*) in Table 4 indicate conditions for which it was not possible to fit sloped lines to the data. For Egypt, the maximum PRATIO during the summer season was only 0.03 (essentially no precipitation occurred during this season), so that there was insufficient length of abscissa from which the slope could be determined. For India, on the other hand, the plot of minimum air temperature versus PRATIO during the winter season did not have any consistent trend. The primary reason for this was the fact that India is a large country having a wide variety of climatic conditions (North to South) within the same season.

Results of the statistical analyses on seasonal and regional variations can be summarized as follows:

1. For the arid climates, there were no significant differences in the slopes of the corresponding temperature parameters with PRATIO between summer and winter seasons. For the humid climates, on the other hand, there was significant statistical evidence to indicate that the slopes of all temperature parameters relative to PRATIO are significantly different between summer and winter seasons. This implies that for the humid temperate regions the slopes of all three temperature parameters with PRATIO are different for summer and winter seasons, and therefore different adjustment coefficients may be needed to adjust them for site aridity. However, examination of MDD versus PRATIO for the humid climates reveals that during the winter season MDD barely exceeds about two degrees, and PRATIO is usually greater than unity. Therefore, there is no need to adjust measured air temperatures and dew point temperature for site aridity during the winter season at these locations. Hence, it was decided to use the same adjustment coefficients for all seasons for both arid and humid climates.
2. There is no significant difference in the slopes of TMAX versus PRATIO between the arid and humid climates. Also, the absolute values of the slopes of TD are not significantly different between arid and humid climates. However, the slopes of TMIN with PRATIO are significantly different between the arid and humid climates. The slopes of TD with PRATIO were positive for arid regions and negative for humid regions. Negative slopes in humid areas are caused by effects of clouds or cooling of the air mass and consequent reduction in the vapor holding capacity with greater PRATIO (Temesgen 1996).

Variations between Temperature Parameters

The statistical analyses on the variation of the temperature parameters indicated that for the arid tropical climates TMAX is affected by the dryness of the site more than is TMIN, and slopes are different. On the other hand, for humid temperate climates, the rate of decrease in TMAX and TMIN per unit increase in PRATIO is about the same.

The main reason for this is that in an arid climate, with low TD and soil moisture, more RS is available to heat the air (fewer clouds) during the daytime. Fewer clouds in arid areas also promotes more rapid cooling of soil and air at night so that TMIN does not stay elevated at low PRATIO. Therefore, for the arid climates, the slope of TMIN versus PRATIO is lower than the slope of TMAX. In humid regions, a greater number of clouds reduces the heating during daytime (less RS) and the cooling during nighttime so that the nighttime and daytime temperatures are closer.

The same statistical analyses show that for both arid and humid regions the effects of site aridity on TMAX and TD are nearly equal when the absolute values of the slopes are compared. The results also indicate that there is a statistically significant difference between the absolute values of the slopes for TMIN and for TD in the arid regions, with the slope being greater for TD. For the humid regions, these slopes are nearly the same.

Adjustment Coefficients

Adjustment coefficients K_x, K_n, and K_d were determined using (1)–(3) and are listed in Table 5 for each climatic category. Values for K_n and K_d add to unity in each case since they have the same denominator.

Testing Adjustment Coefficients

The validity of the determined adjustment coefficients and the ability to extend these relationships to other regions were tested using weather data from the United States.

Central Washington

The three Washington weather stations were situated close enough to have similar climates. However, the fact that Roza is irrigated while the other two are dry creates a difference in the partitioning of the incoming radiant energy between the dry and reference stations, resulting in differences in the measured weather parameters.

An integrity analysis of weather data (Allen 1996) indicated that, on some days, maximum and minimum relative humidities at Roza were low for a reference station condition (for example, maximum and minimum relative humidities dropped as low as 45 and 15%, respectively). Some of these low values were probably caused by localized aridity at Roza, which might have been caused by fallow research plots at the station (Ley and Allen 1994). Other causes might have been advection of dry air from outside the irrigated area. Therefore, weather

TABLE 5. Adjustment Coefficients for Maximum and Minimum Air Temperatures and Dew Point Temperature for Arid and Humid Categories for Use with (6)–(8)

Category (1)	K_x (2)	K_n (3)	K_d (4)
Arid	0.7	0.4	0.6
Humid	0.5	0.5	0.5

J. Irrig. Drain Eng. 1999.125:26-33.

parameters at Roza were also adjusted for site aridity similar to the dry stations.

Fig. 5 shows daily average ET_0 computed with the FAO-PM equation for Horrigan versus ET_0 for Roza, using the unadjusted, measured weather data for both stations. Predicted ET_0 rates were greater at the dry station mainly because of increased TMAX and TMIN and decreased TD resulting from station aridity.

Fig. 6 shows ET_0 estimates for the same locations and time period as Fig. 5 after TMAX, TMIN, and TD for the dry station were adjusted for site aridity using $K_x = K_n = K_d = 0.5$. Adjusting air temperature and dew point temperature data at the dry location improved the agreement in ET_0 between the reference and the dry stations.

Table 6 summarizes the results of the linear regressions of the reference station (ET_{ref}) versus the reference ET of the dry stations (ET_{dry}). Adjustments were made at both the dry and the reference stations using the coefficients in Table 5 in addition to $K_x = K_n = 0.4$, $K_d = 0.6$. The latter case ($K_x = K_n = 0.4$, $K_d = 0.6$) assumes that maximum and minimum air temperatures are affected by the same proportions.

Differences between outcomes of using different combinations for K_x, K_n, and K_d were not very significant. Based on the SEE values, two categories (i.e., $K_x = K_n = 0.4$, $K_d = 0.6$ and $K_x = K_n = K_d = 0.5$) resulted in best agreement between the paired stations when both reference and dry stations were adjusted. Using these two categories, some overestimation of ET_0 at the two arid sites was still present (regression slope b $\sim$ 0.92–0.96). However, most of this was likely caused by higher winds at the dry sites, caused by effects of surface heating and lower roughness of the arid sites (Ley and Allen 1994). Wind speeds averaged 43% greater at McWhorter and 42% greater at Horrigan, as compared with Roza. Overall, adjustment of air and dew point temperatures using any three of the combinations of K_x, K_n, and K_d reduced differences between the nonreference and reference sites from the initial 15% down to about 4–8%.

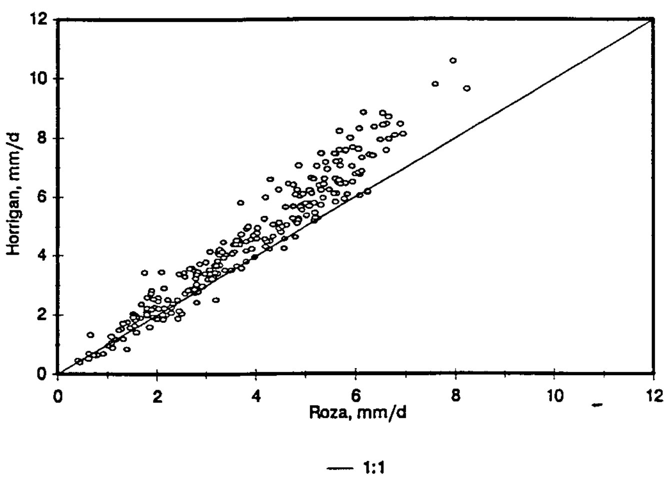

FIG. 5. Plots of Computed Daily Reference ET, Horrigan vs. Roza, Wash., Both Unadjusted for Aridity, April–October, 1993.

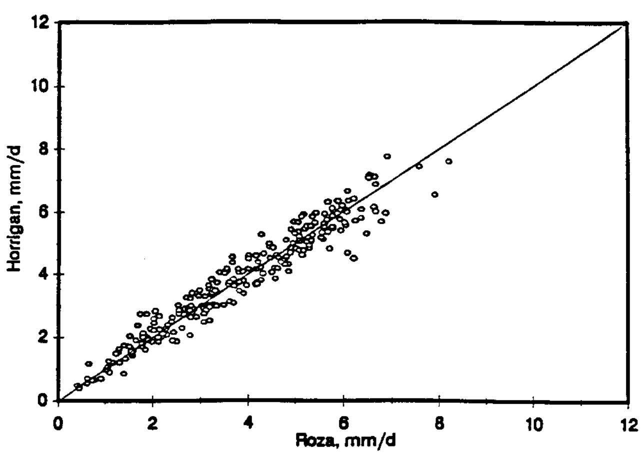

FIG. 6. Plots of Computed Daily Reference ET, Horrigan vs. Roza, Wash., with Only Horrigan Adjusted for Aridity, April–October, 1993

TABLE 6. Regression Results for Estimated Reference ET for Reference (Roza) Weather Station vs. Dry (McWhorter and Horrigan) Weather Stations in Washington

	Roza vs. McWhorter			Roza vs. Horrigan		
Category (1)	SEE[a] (mm/d) (2)	r^2 (3)	b[b] (4)	SEE[a] (mm/d) (5)	r^2 (6)	b[b] (7)
Using unadjusted TMAX, TMIN, TD	0.37	0.95	0.86	0.46	0.93	0.84
Using $K_x = K_n = 0.4$, $K_d = 0.6$ with both stations adjusted	0.23	0.98	0.92	0.35	0.95	0.95
Using $K_x = K_n = K_d = 0.5$ with both stations adjusted	0.22	0.98	0.93	0.36	0.95	0.96
Using $K_x = K_n = K_d = 0.5$ with Roza not adjusted	0.28	0.97	0.97	0.42	0.94	1.00
Using $K_x = 0.7$, $K_n = 0.4$, $K_d = 0.6$ with both stations adjusted	0.23	0.98	0.95	0.40	0.93	1.00

[a]SEE of ET_0 at McWhorter or Horrigan vs. ET_0 of Roza, before regression.
[b]Regression coefficient for regression through origin where ET_0 of Roza is dependent variable.

Davis, California

For the Davis weather station, ET_0 estimates by the reference equation agreed closely with the lysimeter over a wide range in ET_0, indicating that the weather data were reflective of a reference condition. A few days of high wind and low RH occurred, which caused the FAO-PM to underestimate.

Linear regression with lysimeter ET as the dependent variable and ET estimates as the independent variable (Table 7) indicate that the first two sets of adjustment coefficients produced better agreement with lysimeter measurements. However, use of the adjustment coefficients had little or no effect on the computed ET values at this reference site, which was expected.

Adjustment of daily data reduced ET_0 estimates at Davis by only 3% on the average. Reduction occurred on days having TMIN greater than TD, which does not necessarily violate reference requirements. Most of the adjustments occurred on the ''high ET_0'' days, where measured ET_0 was greater than

TABLE 7. Regression Results of Measured vs. Computed Reference Evapotranspiration for Daily and Monthly Averaged Data for Davis Data Set Using Various Sets of Adjustment Coefficients

	Daily			Monthly		
Category (1)	SEE[a] (mm/d) (2)	r^2 (3)	b[b] (4)	SEE[a] (mm/d) (5)	r^2 (6)	b[b] (7)
Unadjusted	0.76	0.89	0.98	0.31	0.99	0.97
$K_x = K_n = 0.4$, $K_d = 0.6$	0.83	0.87	1.01	0.30	0.98	0.97
$K_x = K_n = K_d = 0.5$	0.84	0.87	1.01	0.30	0.98	0.97
$K_x = 0.7$, $K_n = 0.4$, $K_d = 0.6$	0.89	0.86	1.01	0.30	0.98	0.96

[a]SEE before regression.
[b]Regression coefficient for regression through origin.

8 mm/d. These were days when dry air masses moved into the Davis area from outside the region. Relatively no adjustment (less than 1% change in ET_0 estimates) occurred with monthly time steps. This indicates that the aridity correction procedure is relatively robust and automatic in its application of data adjustments, in that it does not make adjustments under conditions where adjustments are not needed. The Davis example also demonstrates that the concept TD $\approx$ (TMIN-2) is valid under most reference conditions having calm to moderate wind speeds.

For both of the Washington and Davis data sets, using either $K_x = K_n = K_d = 0.5$ (humid category) or $K_x = K_n = 0.4$, $K_d = 0.6$ (arid category) had similar effect. The two sets of coefficients produced the lowest SEE against the lysimeter in Davis, California. Therefore, for simplicity, use of $K_x = K_n = K_d = 0.5$ is recommended. In other words, when TMIN > (TD + 2), the two parameters are brought toward each other by half the difference between them.

Effects of Using Adjustments

The effect of using the adjustment on computed ET_0 was tested for the CLIMWAT data set. The two equations selected for this purpose were the FAO-PM and the ETH. Ratios of ET_0 after adjustment to ET_0 before adjustment (ETRATIO) were used for the analyses (Table 8).

The Penman-Monteith equation is more sensitive to solar radiation than to any other weather parameter (Saxton 1975; Baselga 1990). However, as shown in Table 8, adjusting temperature parameters alone for effects of site aridity decreased the computed ET_0 by as much as 27% in Sudan, when $K_x = K_n = 0.4$, $K_d = 0.6$ was used.

The 1985 Hargreaves equation (Hargreaves et al. 1985) is one of the simplest (though more accurate) empirical equations used to estimate grass reference evapotranspiration. The correction to the ET_0 estimates by the ETH equation were less than the correction to ET_0 estimate by the FAO-PM equation for both arid and humid categories (Table 8). This is primarily due to the fact that the Hargreaves equation does not explicitly use dew point temperature and wind speed, both of which are affected by site aridity. The humidity term is only implicitly contained in the temperature range (TR) of the Hargreaves equation.

Another reason for fewer corrections by the Hargreaves equation may be that the Hargreaves method is less sensitive to the effects of site aridity. This is because the aridity of the site increases wind speed, which mixes up the top and bottom layers of the atmosphere. The mixing of different layers in turn reduces the TR by decreasing TMAX during daytime and by increasing TMIN during nighttime, thereby keeping the increase in estimated ET_0 lower as aridity increases.

TABLE 8. Minimum Ratios of Reference Evapotranspiration ($ET_{0after}/ET_{0before}$) Computed by FAO-PM and ETH Equations (Adjustments Were Made Using $K_x = K_n = 0.4$, and $K_d = 0.6$)

Country (1)	Minimum ETRATIO ($ET_{0after}/ET_{0before}$) FAO-PM (2)	Hargreaves (3)
Ethiopia	0.80	0.89
Sudan	0.73	0.85
Egypt	0.78	0.87
India	0.75	0.87
Pakistan	0.77	0.88
France	0.92	0.98
Italy	0.87	0.96
Spain	0.75	0.93

CONCLUSIONS AND RECOMMENDATIONS

Accurate estimates of ET_0 are important in improving the effectiveness of water use in irrigated settings. The methods used in this study and the coefficients developed improve the accuracy of estimation of ET_0 at nonreference stations. This reduces the extra cost that would be incurred by overestimating ET_0, when weather data from nonreference locations are used in design and sizing of irrigation systems.

By using the coefficients developed in this study, it was possible to reduce ET_0 estimates by as much as 27% in the Sudan. On the average, the maximum correction was about 23% for the dry, arid climates and 15% for the humid climates with the FAO-PM equation. These values are well within the range of the overestimation of ET_0 reported by different researchers.

Because of the differences in the amount of radiant energy received and released at different regions, users may wish to determine local adjustment coefficients for different regions. However, test results at Washington and Davis, California, indicate that one set of adjustment coefficients may be satisfactory for a wide range in climates.

Agreement between ET_0 predicted for the dry and reference stations within the Washington Agriculture Weather System was improved by using the aridity correction coefficients developed in this study. At McWhorter, Washington, for example, an estimated average overestimation of 16% was reduced to about 9% and at Horrigan an average overestimation of 19% was reduced to about 5%. Much of the remaining positive biases is felt to be due to higher wind conditions at the dry sites, ones not included in the adjustment.

At Davis, California, the effect of applying adjustments to daily data for a reference station was a reduction of only about 3% of ET_0, since the station was already in a reference state. These results indicate that the proposed adjustment procedure for station aridity is conservative, robust, and automatic.

It is recommended that future studies consider the use of paired reference and nonreference stations with detailed descriptions of the weather environment, such as the size of the green fetch, location of the weather station relative to the irrigated field, amounts of irrigation applied, and the type of the soil. Future studies should also consider adjusting the measured wind speed for site aridity.

It is strongly recommended that the adjustment procedures developed in this study not be used by hydrologists or others who are interested in estimating ET for natural vegetation under natural conditions. The adjustments proposed by this study should be made only for planning, design, and management of irrigation projects.

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