THE ASCE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

Appendices A - F

Environmental and Water Resources Institute
of
the American Society of Civil Engineers

Standardization of Reference Evapotranspiration Task Committee

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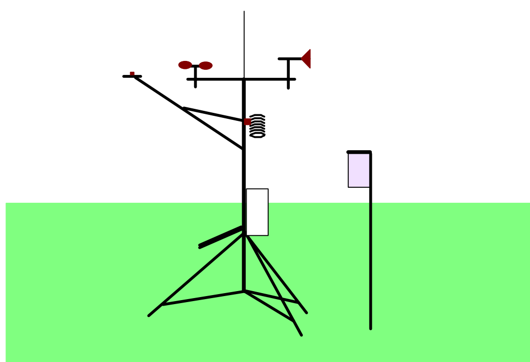

APPENDICES

APPENDIX A

DESCRIPTION OF TASK COMMITTEE'S METHDOLOGY AND PROCEDURES USED TO DERIVE THE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

ASCE-ET RESPONSE TOTHE IRRIGATION ASSOCIATION

Cover Letter

January 26, 2000

Mr. Thomas H. Kimmell
Irrigation Association
8260 Willow Oaks Corporate Drive, Suite 120
Fairfax, VA 22031-4513

Re: Irrigation Association Request for a Benchmark Evapotranspiration Equation

Dear Mr. Kimmell:

In May 1999, the Irrigation Association (IA) requested that the American Society of Civil Engineers Evapotranspiration in Irrigation and Hydrology Committee (ASCE-ET) help establish and define a benchmark reference evapotranspiration (ET) equation.

ASCE-ET is pleased to inform you that a task committee (ASCE Task Committee on Standardization of Reference Evapotranspiration) of ASCE-ET members has developed standardized reference evapotranspiration equations for calculating hourly and daily evapotranspiration (ET) for both a short reference crop and a tall reference crop. Members of the Task Committee (TC) include renowned scientists and engineers, and both researchers and practitioners. A list of the TC members is attached. Using IA's original request as a catalyst, these experts recognized several needs for a standardized method of calculating reference ET. These needs included a standardized calculated evaporative demand that can be used for transferring crop coefficients, reducing confusion among users as to which equation(s) to use, increasing use of the crop coefficient x reference ET procedure to calculate crop ET, and developing more accurate estimates of ET.

One of the first steps in the definition of the equations was the establishment of criteria to be used for the determination of the equation(s). The criteria included:

The equation(s) should be *understandable*, i.e., represent a defined crop or hypothetical surface.

The equation(s) should be *defensible* and should be *traceable* to quality field measurements.

The approach should use *accepted methods*.

The approach should maximize *simplification* without significant loss of accuracy.

The approach should use *existing, readily available data*.

In reviewing IA's request and in their initial evaluation, the TC was concerned that the terms *standard* and *benchmark* carry connotations that may be misconstrued. These terms could lead users to assume that the calculated values determined using "the equation" were for comparison purposes or were a level to be measured against. That is not the purpose of the TC recommendation. **The objective of the TC's recommendations is to establish a methodology for calculating uniform ET estimates and thereby enhance the transferability of crop coefficients and the comparison of ET demands in various climates.**

The TC recommends that two Standardized Reference Evapotranspiration Equations along with *standardized* computational procedures be adopted. The equations are defined as:

Standardized Reference Evapotranspiration Equation, Short (ETo): Reference ET for a short crop with an approximate height of 0.12 m (similar to grass).

Standardized Reference Evapotranspiration Equation, Tall (ETr): Reference ET for a tall crop with an approximate height of 0.50 m (similar to alfalfa).

Two reference surfaces that are similar to known crops were recommended by the TC due to the widespread use of grass and alfalfa across the United States and due to their individual advantages for specific applications and times of the year. Furthermore, the TC concluded that hourly and daily forms of the equations were needed.

The basis of the equations is the ASCE Penman-Montieth as described in ASCE Manual 70 (Jensen et al., 1990) and the net radiation procedure described in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998). Future publications and summaries from the task committee will contain calculation procedures for all parameters required for applying the standardized reference ET equations. These parameters are currently defined and calculation procedures are described in the following publications: Allen et al., 1994, ASCE Hydrology Handbook (Allen et al., 1996), and FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998).

In the attached document, which describes the form of the equations, the TC has reduced the equations down to a single equation with an accompanying table of constants. The constants are a function of time step (hourly or daily) and reference surface (ET_o or ET_r).

Sincerely,

American Society of Civil Engineers
Evapotranspiration in Irrigation and Hydrology Committee
Standardization of Reference Evapotranspiration Equations Task Committee

Dr. Ronald Elliott, Chairman ASCE-ET

Ivan A. Walter, Chairman TC

Encl.
Cc: Bert Clemmens, ASCE Executive Committee

Equation As Sent to the Irrigation Association

Standardized Reference Crop Evapotranspiration Equations

ASCE Committee on Evapotranspiration
in Irrigation and Hydrology

January 2000

The Evapotranspiration in Irrigation and Hydrology Committee recommends that two Standardized Reference Evapotranspiration Equations be adopted for general practice along with *standardized* computational procedures. The standardized equations are derived from the ASCE Penman-Monteith (ASCE-PM) equation as described in ASCE Manual 70 (Jensen et al., 1990), in the ICID Bulletin (Allen et al., 1994), and in the ASCE Hydrology Handbook (Allen et al., 1996). The computation of parameters for the reference equations incorporates procedures for calculating net radiation, soil heat flux, vapor pressure deficit, and air density as described in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998). A constant latent heat of vaporization, λ, equal to 2.45 MJ kg^{-1} is used for simplicity. Albedo for the reference surfaces is fixed at a constant 0.23. The equations assume that measurement heights for air temperature and water vapor content are made at a height in the range of 1.5 to 2.5 m above the ground. The standardized equations require that wind speed, u_2, is measured at or is adjusted to a 2 m measurement height. The coefficients in the ASCE standardized reference evapotranspiration equations presume that the weather data are measured over a grassed surface having a vegetation height of about 0.1 to 0.2 m.

The two standardized reference evapotranspiration (ET) equations are defined as:

Standardized Reference Evapotranspiration Equation, Short (ET_o): Reference ET for a *short* crop having an approximate height of *0.12* m (similar to grass).

Standardized Reference Evapotranspiration Equation, Tall (ET_r): Reference ET for a *tall* crop having an approximate height of *0.50* m (similar to alfalfa).

ASCE Standardized Reference Evapotranspiration Equation(s)

Both standardized reference equations were derived from the ASCE-PM by fixing h = 0.12 m for short crop (ET_o) and h = 0.50 m for tall crop (ET_r). The short crop and tall crop reference equations are traceable to the commonly used terms grass reference and alfalfa reference.

As a part of the standardization, the "full" form of the Penman-Monteith equation and associated equations for calculating aerodynamic and bulk surface resistance have been combined and reduced to a single equation having two constants. The constants vary as a function of the reference surface (ET_o or ET_r) and time step (hourly or daily). This was done to simplify the presentation and application of the methods. The constant in the right-hand side of the numerator (C_n) is a function of the time step and aerodynamic resistance (i.e., reference type). The constant in the denominator (C_d) is a function of the time step, bulk surface resistance, and aerodynamic resistance (the latter two terms vary with reference type, time step and daytime/nighttime).

Equation 1 presents the form of the Standardized Reference Evapotranspiration Equation for all hourly and daily calculation time steps. Table 1 provides values for the constants C_n and C_d.

$$ET_{ref} = \frac{0.408\,\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + C_d u_2)} \tag{1}$$

where ET_{ref} Short (ET_o) or tall (ET_r) reference crop evapotranspiration [mm day^{-1} for daily time steps or mm $hour^{-1}$ for hourly time steps],

R_n net radiation at the crop surface [MJ m^{-2} day^{-1} for daily time steps or MJ m^{-2} $hour^{-1}$ for hourly time steps],

G soil heat flux density at the soil surface [MJ m^{-2} day^{-1} for daily time steps or MJ m^{-2} $hour^{-1}$ for hourly time steps], T mean daily or hourly air temperature at 1.5 to 2.5-m height [°C],

u_2 mean daily or hourly wind speed at 2-m height [m s^{-1}],

e_s mean saturation vapor pressure at 1.5 to 2.5-m height [kPa]; for daily computation, value is the average of e_s at maximum and minimum air temperature,

e_a mean actual vapor pressure at 1.5 to 2.5-m height [kPa],

Δ slope of the vapor pressure-temperature curve [kPa $°C^{-1}$],

γ psychrometric constant [kPa $°C^{-1}$],

C_n numerator constant for reference type and calculation time step, and

C_d denominator constant for reference type and calculation time step.

Table 1. Values for C_n and C_d in Equation 1

Calculation Time Step	Short Reference, ET_o		Tall Reference, Et_r		Units for ET_o, ET_r	Units for R_n, G
	C_n	C_d	C_n	C_d		
Daily or monthly	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly during nighttime	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

Equations associated with calculation of required parameters in Equation 1 and Table 1 have been standardized and will be described in a detailed report by this committee.

Definition of Crop Coefficients

Calculation of crop evapotranspiration (ET_c) requires the selection of the correct crop coefficient (K_c) for use with the standardized reference evapotranspiration (ET_o or ET_r). It is recommended that the abbreviation for crop coefficients developed for use with ET_o be denoted as K_{co} and the abbreviation for crop coefficients developed for use with ET_r be denoted as K_{cr}. ET_c is to be calculated as shown in equation 2.

$$ET_c = K_{co} * ET_o \text{ or } ET_c = K_{cr} * ET_r \quad (2)$$

References

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman, 1989. Operational Estimates of Reference Evapotranspiration. *Agronomy Journal*, 81:650-662.

Allen, R.G., M. Smith, L.S. Pereira, and A. Perrier, 1994. An Update for the Calculation of Reference Evapotranspiration. *ICID Bulletin,* 43(2):35-92.

Allen, R.G., W.O. Pruitt, J.A. Businger, L.J. Fritschen, M.E. Jensen, and F.H. Quinn, 1996. Chapter 4 "Evaporation and Transpiration" in ***ASCE Handbook of Hydrology,*** New York, NY, p. 125-252.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998. ***Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements***. United Nations Food and Agriculture Organization, Irrigation and Drainage Paper 56, Rome, Italy, 300 pages.

Jensen, M.E., R.D. Burman, and R.G. Allen, 1990. ***Evapotranspiration and Irrigation Water Requirements***, ASCE Manuals and Reports on Engineering Practice No. 70:ISBN 0-872627632, 332 p.

The ASCE-ET Task Committee on Standardization of Reference Evapotranspiration developed the recommendations. This Task Committee is sanctioned by the Irrigation and Drainage Council of the Environmental and Water Resources Institute, ASCE. Members of this task committee included I. A. Walter, R. G. Allen, M. E. Jensen, R. L. Elliott, R. H. Cuenca, S. Eching, M. J. Hattendorf, T. A. Howell, D. Itenfisu, D. L. Martin, B. Mecham, R. L. Snyder, T. L. Spofford, P.W. Brown, and J. L. Wright.

TASK COMMITTEE METHODOLOGY AND PROCEDURES

ASCE-ET Meetings

In response to IA, ASCE-ET committee members met on five occasions[1] to discuss the issues and needs for standardizing the definition and calculation of reference evapotranspiration, to review results of analyses, and to organize the TC report. They first met with members of IA's Water Management Committee (IA-WM) in Denver, Colorado on May 25 and 26, 1999 to review the IA request in detail and to select the basis for a Standardized Reference Evapotranspiration Equation. In August 1999, ASCE-ET held its annual meeting in Seattle, Washington and established the ASCE Task Committee on Standardization of Reference Evapotranspiration (TC). Additionally, ASCE-ET selected equations to be evaluated as candidate standardized reference ET equations.

The third meeting, held November 18 and 19, 1999 in Phoenix, Arizona involved TC members (some TC members are joint members of the ASCE-ET committee and the IA-WM committee). The purpose of that meeting was two-fold: (1) to evaluate the results of evapotranspiration estimates calculated using thirteen previously selected equations or variants on equations, data from 12 states, 36 sites, and 61 site-years; and (2) to develop a recommended Standardized Reference Evapotranspiration Equation. Prior to the Denver meeting and continuing after the Phoenix meeting, an extensive amount of e-mail exchanges between ASCE-ET and TC members shared opinions and data on several of the technical issues that needed to be associated with the standardized reference equation. These included the calculation of net radiation, latent heat of vaporization, and measurement units for meteorological data.

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[1] The fourth and fifth meetings were held in Phoenix, November 13, 2000 and Loveland, Colorado, April 5, 6, 2001 for review and editing of the TC report and standardization statement.

Motivations For Implementation

The motivations for establishing and implementing a standardized equation were many. They included:

1. Standardized equation(s) provide a uniform calculation of evaporative demand, which improves transferability of crop coefficients from one region or state to another.

2. Practitioners have been confused by the numerous reference evapotranspiration equations that have been developed and published. The TC evaluated seven of these reference evapotranspiration equations for calculating reference evapotranspiration for grass, alfalfa, or both. A grass reference surface equation has been accepted internationally, but in the U.S.A., both grass and alfalfa reference equations are used.

3. Crop evapotranspiration (ET_c) rates are calculated as the product of reference evapotranspiration (ET_{ref}) and a crop coefficient (K_c). With standardization of a reference ET equation, the procedure will be more readily adopted by the private sector and government agencies.

4. Both the public and private sectors now operate automated weather stations that calculate ET_{ref} directly, and guidance, as to which equation to use, is needed.

5. A better hourly ET_{ref} equation is needed to improve ET_c estimation in coastal areas.

6. When summed over a 24-hour period, calculated hourly ET_{ref} should approximate calculated daily ET_{ref}.

Criteria

The TC established several criteria for the selection of the equation. The criteria used in the selection of the standardized reference evapotranspiration equation were:

1. The equation must be understandable.

2. Whether monthly, daily, or hourly data are used, the equation must be defensible, in that it will provide a precise, reliable measure of evaporative demand.

3. The equation should be a derivation of methods that have been accepted by the science and engineering communities such as those methods described in Jensen et al. (1990), Allen et al. (1989), Allen et al. (1994a, 1994b), and Allen et al. (1998).

4. Simplification of an accepted method to enhance its implementation and ease of calculations by users without significant loss of accuracy is desirable.

5. The equation should have the capability to use data from the numerous weather networks, which currently measure daily and hourly radiation, humidity, temperature, and wind speed.

6. The equation must be based on (or traceable to) measured or experimental data. Specifically, the user of the equation should be able to relate the equation to a known reference crop, evaporative index, or hypothetical surface.

7. Sums of hourly calculated ET should closely approximate daily computed ET values.

BACKGROUND FOR THE EQUATIONS EVALUATED BY THE TASK COMMITTEE

ASCE-ET members have a combined experience with numerous reference evapotranspiration equations totaling hundreds of years. The number of equations presently preferred by the members was relatively limited. They included:

1. ASCE Penman Monteith (grass w/ h=0.12 m and alfalfa w/ h=0.50 m), Jensen et al. (1990)[2]

2. FAO-56 Penman-Monteith (grass), Allen et al.(1998)

3. Kimberly Penman (alfalfa), Wright (1982)

4. Penman (grass), Penman (1948, 1963)

5. CIMIS Penman (grass), Snyder and Pruitt (1985), Snyder and Pruitt (1992)

[2]The ASCE-Penman-Monteith method for grass reference was adopted by the USDA-SCS (now NRCS) into Chapter 2 of the NRCS Irrigation Guide, Martin and Gilley (1993)

6. Hargreaves (grass), Hargreaves et al (1985), Hargreaves and Samani (1985)

In their many years of research and practical experience, TC members have found that no method is perfect. The following is a list of observations and concerns expressed by TC members.

1. In northern Colorado, locating a climate station over alfalfa or grass did not result in significant difference in ET_{ref} values calculated using the 1982 Kimberly Penman (alfalfa reference) or the ASCE-PM (applied to grass reference only). This is a consideration in selecting an agricultural weather station site.

2. The 1982 Kimberly Penman net radiation procedure was developed for the growing season (April-October). Its use outside that period is questionable.

3. Comparison of the ASCE Penman Monteith for alfalfa to a simplified FAO-24 (Doorenbos and Pruitt, 1977) grass reference on a monthly time step found that the monthly ratios of ET_r/ET_o did not vary significantly during summer months.

4. Hourly computation of reference ET_o in coastal regions or windy areas where cold air advection occurs can result in significant differences among equations. Under these conditions, hourly estimates by the CIMIS Penman exceeded those by the FAO-56-PM.

5. Because of stomatal closure at night, the surface resistance (r_s) changes between day and night.

6. At Bushland, Texas and Kimberly, Idaho, comparison of daily-calculated ASCE-PM (0.50-m vegetation height) versus 1982 Kimberly Penman showed total ET estimated for the April-September period to be similar. The 1982 Kimberly Penman values were about 10% lower in the early spring and late fall months.

7. In Idaho, the 1982 Kimberly Penman more closely duplicated lysimeter ET than the ASCE-PM (height = 0.5 m), but differences were not significant. The 1982 Kimberly Penman equation had less scatter in the data, possibly because it reacts better to high wind. Additionally, the Kimberly equation places more weight on the Rn-G term than does the ASCE-PM equation.

8. At Bushland, Texas, comparisons of lysimeter-measured alfalfa and grass ET to the ASCE PM equations, showed that on days of high wind and VPD the equations slightly under predicted ET. On other days, the ASCE-PM equations tracked the daily lysimeter

well. Comparisons with hourly measured ET showed that the ASCE–PM with Manual 70 surface resistance values was slightly low during peak hourly periods.

Measure For Evaluating Equations

TC members have considerable experience comparing the ASCE Penman Monteith (ASCE-PM) equation to ET measured using lysimeters for grass and alfalfa reference crops. TC members agreed that the ASCE-PM equation, when applied using aerodynamic and surface resistance algorithms presented in Jensen et al. (1990), provides accurate estimates of measured ET_{ref}. Wright et al. (2000) reported that the ratio of ET_r to lysimeter ET was 1.00 and the standard error of estimate was 0.65 mm d^{-1} at Kimberly, Idaho. Evett et al. (2000) reported ASCE-PM ET_r calculated using half-hour data compared well with measured reference lysimeter ET (regression r^2 of 0.91, SEE of 0.6 mm h^{-1}, slope of 0.94 and intercept of 0.2 mm). Use of daily data increased the SEE to 0.8 mm d^{-1} (r^2 = 0.91, slope = 0.98) and introduced a positive offset of 0.7 mm. Howell (1998) reported that the ASCE-PM ET_r performed well when compared to measured lysimeter evapotranspiration at Bushland, Texas. Howell et al. (2000) compared FAO-56 PM to measured reference lysimeter ET and reported the equation tended to overestimate grass ET for low rates and underestimate ET for high ET rates. The results were a regression r^2 of 0.701, SEE of 1.16 mm d^{-1}, slope of 0.79 and intercept of 1.39 mm. Ventura et al. (1999) compared Penman-Monteith hourly ET_o with a surface resistance of 42 and 70 s/m to lysimeter-measured ET for 0.12-m tall grass. It was reported that the root mean square errors were 0.26 and 0.44 W/m^2. The symbol ET_o is used for ET_{ref} to approximate 0.12-m tall grass, and ET_r is used for ET_{ref} to approximate 0.5 m tall alfalfa.

Since lysimeter-measured 0.12 m grass and 0.5 m alfalfa data are limited within the United States and worldwide, the TC selected the ASCE-PM reference ET values as the measure to evaluate proposed equations and variations on equations against. A detailed description of the ASCE-PM is presented in Appendix B.

Initially, TC members evaluated the performance of 12 ET_o equations and 8 ET_r equations. A listing of the equations and a brief description is provided in Table A-1. More detail is provided in Appendix B.

Table A-1. Reference Evapotranspiration Equations and Procedures Evaluated

Abbreviation	Method or Procedure	Description
ASCE-PM	ET_o & ET_r	ASCE-Penman Monteith, Jensen et al. (1990) w/Rn 56, G56, r_a & r_s = f(h)
FAO-56-PM	ET_o	ASCE-PM w/ h = 0.12 m, r_s = 70 s/m and albedo = 0.23, R_n 56, G = 0, λ = 2.45 MJ kg^{-1} , Allen et al. (1998)
ASCE-PMD	ET_o & ET_r	ASCE-PM, r_a = f(h), albedo=0.23, daily ET_o, r_s = 70 s/m, hourly ET_o r_s = 50 & 200 s m^{-1}; daily ET_r, r_s = 45 s m^{-1}, hourly ET_r, r_s = 30 s/m & 200 s m^{-1}
ASCE-PMDL	ET_o & ET_r	ASCE-PMD, lambda = 2.45 MJ kg^{-1}
ASCE-PMv	ET_o & ET_r	ASCE-PMD & r_s specified by user
ASCE-PMDR	ET_o & ET_r	ASCE-PM with R_n = R_n Wright (1982)
1982-Kpen	ET_r	1982 Kimberly Penman, Wright (1982 & 1987)
FAO24-Pen	ET_o	FAO-24 Penman, Doorenbos and Pruitt (1977)
1963-Pen	ET_o	1963 Penman, Penman (1963) (same wind function as Penman (1948))
1985-Harg	ET_o	1985 Hargreaves, Hargreaves et al. (1985)
ASCE-PMrf	ET_o & ET_r	ASCE-PM, reduced form: R_n 56, G 56, ET_o, r_s = 70 s m^{-1}; ET_r, r_s = 45 s m^{-1}; ET_o z_w & z_h = 2 m; ET_r z_w & z_h = 1.5 m, d = 0.8 m. The reduced from represented a test of the standardized equation
ASCE-PMrfh	ET_o & ET_r	ASCE-PM reduced form hourly only: ET_o, r_s = 50 s m^{-1}; ET_r, r_s = 30 s m^{-1}.
CIMIS-Pen	ET_o	CIMIS Penman (hourly) with Rn56 and G = 0, Snyder and Pruitt (1985)

R_n 56 = net radiation calculated using FAO-56 procedures, Allen et al. (1998)

$R_{n\ Wright=}$ Wright = net radiation calculated using Wright (1982) procedure

G 56 = Soil heat flux calculated using FAO-56 procedures, Allen et al. (1998)

Issues Addressed

Examination of Table A-1 and equations presented in the Appendices reveals that the TC evaluated several components of reference evapotranspiration. The methods for calculating net radiation and soil heat flux described in Jensen et al. (1990), Wright (1982), Doorenbos and Pruitt (1977), and Allen et al. (1998), were examined in detail. The latent heat of vaporization (λ) was evaluated over a wide range in air temperature and the impact on ET_{ref} of using a constant value (λ = 2.45 MJ kg^{-1}) was evaluated. The adoption of standardized values for surface and aerodynamic resistance occurred after intense review and discussion by e-mail between TC members and following evaluation across the U.S.A. (described later). Other components discussed in detail included the calculation of vapor pressure deficit and measurement units for meteorological data. The TC worked diligently to ensure that its recommendation for each component was within the established criteria.

Description of Evaluation

The evaluation of various ET equations and variations on equation application was accomplished in part by using REF-ET, a software program capable of calculating reference ET using up to 15 of the more common methods (Allen, 1999, 2000). For the TC comparisons, Allen modified the software to incorporate the equations and application variations listed in Table 1 that were established by the TC selected for the initial evaluation. REF-ET was distributed to TC members who had volunteered to calculate ET_o and ET_r using meteorological data within their region. A significant benefit resulting from using REF-ET was that outputs were standardized, which improved the efficiency of the TC analyses. At the 1999 meeting in Phoenix, the TC was able to evaluate results of reference evapotranspiration estimates at 36 sites within Arizona, California, Colorado, Idaho, Montana, Nebraska, Oklahoma, Oregon, South Carolina, Texas, Utah, and Washington. The elevations of sites varied from 2 to 2,895 meters. Mean annual precipitation amounts ranged from 152 to 2,032 mm. Following the 1999 meeting in Phoenix, data from Florida, Georgia, Illinois, and New York were added to the analysis.

The results obtained using REF-ET at all sites were submitted to Drs. Itenfisuo and Elliott of Oklahoma State University (Itenfisu et al., 2000), where the information was compiled and several equation-to-equation comparisons were conducted. The key comparisons were:

- ♦ ET_{ref} versus ASCE-PM using daily data.
- ♦ The sum of 24 hourly ET_{ref} values versus ASCE PM using daily data
- ♦ The sum of 24 hourly ET_{ref} values versus ET_{ref} using the same equation but with daily data.

The comparisons were made for both ET_o and ET_r. Itenfisu et al. (2000) determined the mean ratios of each equation estimate to that from the ASCE-PM, the Root Mean Square Difference (RMSD), and the RMSD as a percentage of ASCE-PM. The RMSD is calculated as the square root of the sum of the squared differences between the two estimates divided by the number of estimates

$$RMSD = \left(\frac{\sum_{i=1}^{n} (x_i - y_i)^2}{n} \right)^{0.5} \tag{A.1}$$

where x_i = the i^{th} observation on estimate x

y_i = the i^{th} observation on estimate y

n = the number of observations.

For each of the site–year combinations, statistics were summarized for the growing season and, if available, for the full calendar year.

At the 1999 meeting in Phoenix, the TC spent two days reviewing and discussing the results for the 61 site-years. A detailed listing of the sites is presented in Appendix B. Conclusions from the analyses follow:

Review of the results of daily ET_o versus ASCE-PM ET_o for the growing season found:

1. The use of net radiation R_n computed using procedures from FAO-56 predicted ET_o and ET_r that was about 2 to 3 percent higher than that predicted using R_n computed using procedures by Wright (1982). These differences were judged to be relatively minor. It was noted that the time-based equations for predicting albedo and emissivity coefficients in the Wright (1982) procedure were developed for use only during the growing season (April-October) and for latitude of approximately 40 degrees north. Some caution should be exercised in applying the Wright (1982) procedures for R_n during the non-growing season and at sites outside an approximately 35 to 45 degree latitude band. For consistency, it is recommended that FAO-56 procedures be used to calculate R_n.

2. The 1985 Hargreaves equation revealed considerable site-to-site scatter in ratios of the Hargreaves ET_{ref} estimates to ASCE-PM estimates than for the other methods evaluated. (See Fig. A-1 and A-3) The 1985 Hargreaves equation did not perform well, and therefore should be calibrated, in high wind and coastal areas. For example, at Bushland Texas (mean monthly wind = 4.25 m/s, range: 3.23 to 5.39 m/s (Howell, et.al. 2000)) the ratio of 1985-Harg ET_o to ASCE-PM ET_o was 0.80. This equation may therefore need to be calibrated at other sites.

3. The 1963 Penman equation ET_o estimates ranged from 0.5 % less to 13% higher than ASCE-PM estimate and averaged about 7% high.

4. FAO-24 Penman, which is an ET_o equation, overestimated ET_o by about 17 % on an annual basis and by about 20 % during the growing season. Ironically, the FAO-24 Penman equation appears to provide a reasonably good estimate of ET_r unless the FAO-24 correction factors for wind and relative humidity are applied.

5. The use of a reduced form of ASCE-PM using constants for lambda (heat of vaporization) and r_s (surface resistance) resulted in a limited loss of accuracy (ranging from –0.06% to 0.04% error).

6. The reduced form of ASCE-PM was always within 1% of estimates by the original ("full-form") ASCE-PM.

The consensus of the TC was that the simplification of surface resistance, aerodynamic resistance, latent heat of vaporization and air density did not result in significant or unacceptable differences in ET_{ref} estimates. All differences were much less than the probable errors in actual ET_o measurements.

Review of the results of Daily ET_r versus ASCE-PM ET_r for the growing season found:

1. ASCE PMDL (the ASCE-PM equation with heat of vaporization fixed at 2.45 MJ kg^{-1}) provides an excellent match to the ASCE–PM.

2. The use of the Wright (1982) Kimberly R_n procedure instead of the FAO-56 R_n procedure causes a reduction in the growing season ET_r estimate of approximately 2 to 3 percent. Largest decreases in ET_r occurred at Montana (4 to 5%), New York (4 to 5%), Georgia (3 to 4%) and Oregon (5 to 6%) stations.

3. Comparison of the 1982 Kimberly Penman to ASCE-PM for yearly data revealed that there was considerable variation, with ratios ranging from 0.86 to 1.04. (See Fig. A-2). The average ratio was about 0.94. Results indicated some correlation between the ratio and the latitude of the location. Additionally, the ratio of ET_r from the 1982 Kimberly Penman to the ASCE PM-ET_r tended to decrease with increase in ET during the peak month.

4. Comparison of the 1982 Kimberly Penman to ASCE PM for growing seasons only, showed the ratio to range from 0.89 to 1.12. The average ratio was about 0.99.

5. Comparison of ASCE PMDR (i.e., the ASCE PM using R_n from Wright (1982)) to ASCE PM (using R_n from FAO-56) revealed that the ratio of the two methods was always 0 % to 3 % less than 1.0.

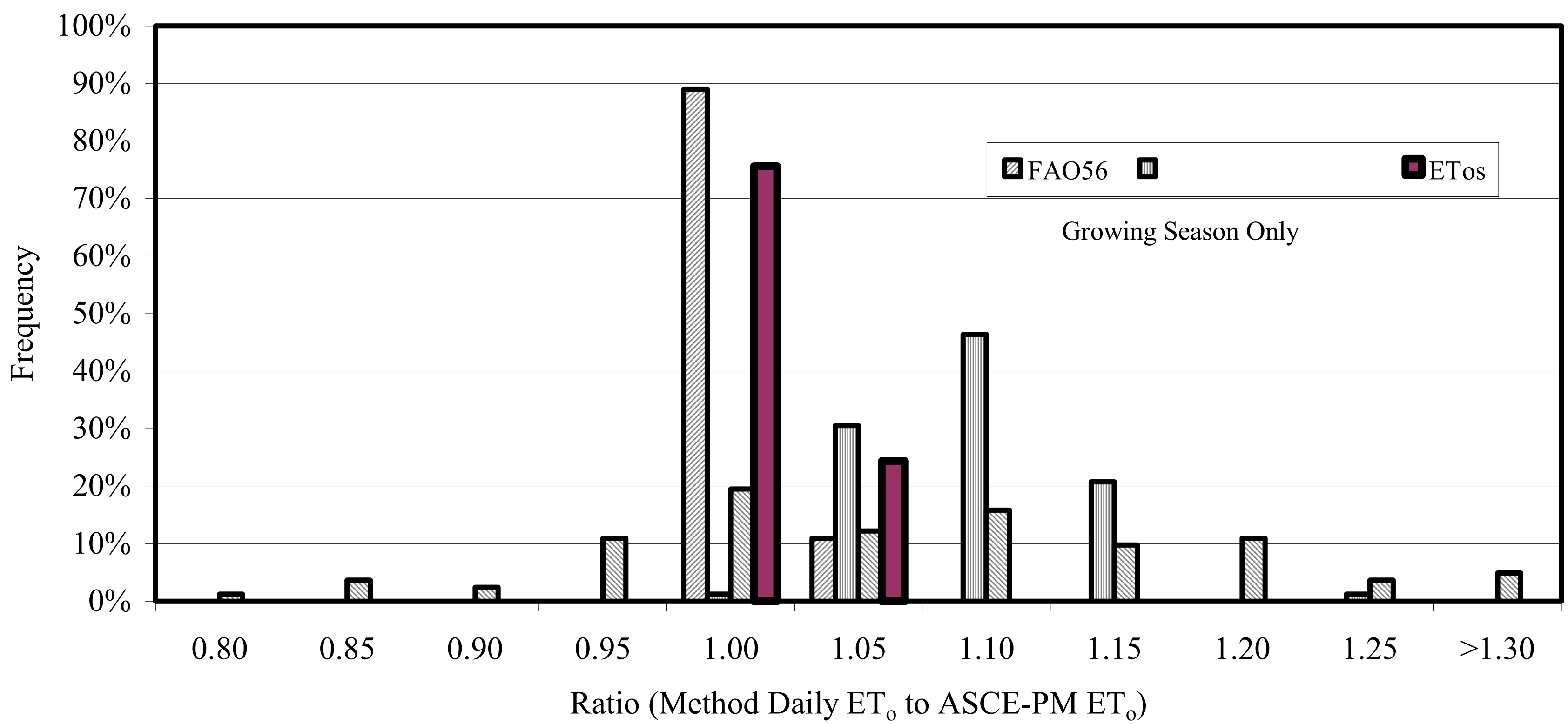

Figure A-1. Frequency of ratio of daily ET_o or ET_{os} to daily ET_o by ASCE-PM equation.

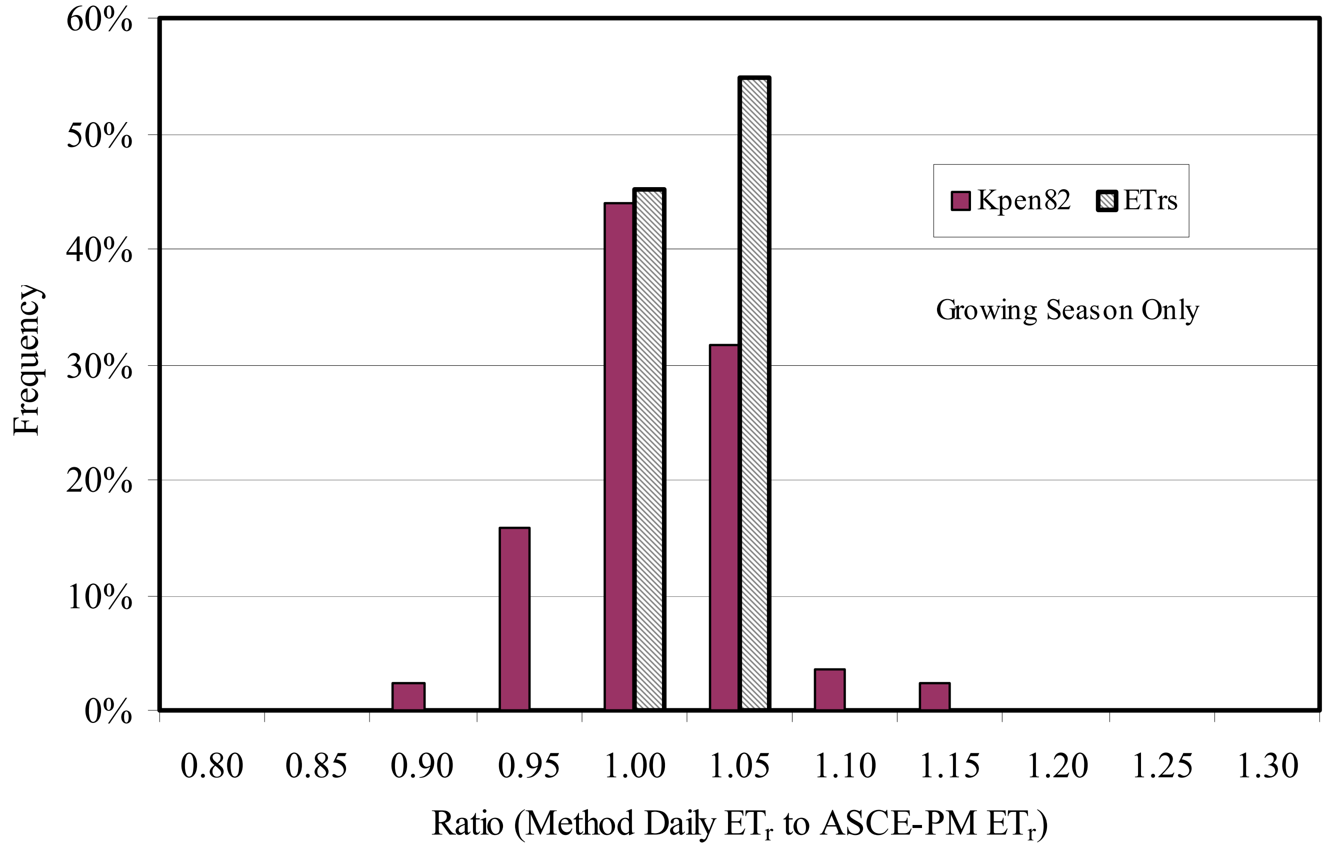

Figure A-2. Frequency of ratio of daily ET_r or ET_{rs} to daily ET_r by ASCE-PM equation.

When analyzing the results of summed hourly ET_o to daily ASCE PM ET_o, the TC significant findings or discussions were as follows:

1. Soil Heat Flux (G). Concern was expressed that calculation of G in FAO-56 and ASCE Hydrology Handbook (G=0.1 R_n [for daytime] and G = 0.5 R_n [for nighttime]) might overpredict G. After viewing data provided by Cuenca from Oregon and Brown from Arizona, the TC concluded that the FAO-56 procedure provided good estimates.

2. Surface Resistance (r_s). The hourly r_s values of 50 and 200 s m^{-1} (day and night) were concluded to be reasonably accurate in matching ET_o calculated by the ASCE-PM using a daily time step. The yearly ratio averaged 0.944 and ranged from 0.876 to 1.019 and the growing season ratio averaged 0.952 and ranged from 0.896 to 1.041.

3. The ASCE PMDL equation (same as the ASCE PMD, but with fixed latent heat of vaporization) agreed well with and generally had a good fit relative to the ASCE PM computed daily. The yearly ratio averaged 0.993 and ranged from 0.937 to 1.047 and the growing season ratio averaged 1.001 and ranged from 0.937 to 1.074. This indicates that the use of constant lambda does not introduce significant error.

4. The CIMIS equation (computed hourly and using R_n from FAO-56[3] and G=0) showed the most variability from site to site relative to the ASCE PM equation computed daily, with ratios for the growing seasons ranging from 0.969 to 1.220 and averaging about 1.08. Much of the higher estimation by the CIMIS equation stemmed from using G = 0 for the hourly computations. The hourly applications of the ASCE-PM equation used G = 0.1 R_n during daytime and G = 0.5 R_n during nighttime.

When analyzing the results of summed hourly ET_r to daily ASCE-PM ET_r, the TC found the results were similar to and follow the discussion for ET_o above.

1. The results showed that the ASCE-PM applied hourly and summed daily matched the daily ASCE PM fairly well when applied with r_s values of 30 and 200 s m^{-1} for day and night respectively (i.e., the ASCE PMD method). The yearly ratio averaged 0.976 and ranged from 0.902 to 1.069 and the growing season ratio averaged 0.995 and ranged from 0.899 to 1.079.

---

[3] The standard CIMIS Penman application by CIMIS utilizes a R_n calculation procedure that is different from that by FAO-56.

2. The ASCE PMDL (same as the ASCE PMD, but with $\lambda = 2.45$ MJ kg^{-1}) was within acceptable accuracy. The yearly ratio averaged 0.974 and ranged from 0.902 to 1.064 and the growing season ratio averaged 0.992 and ranged from 0.897 to 1.075.

PERFORMANCE OF THE STANDARDIZED REFERENCE EVAPOTRANSPIRATION EQUATION

Following the 1999 meeting in Phoenix additional sites were added to improve the overall coverage for the U.S.A. Drs. Intenfisu and Elliott recompiled the results for preparation of the final report (Itenfisu et al., 2000). To avoid confusion, the standardized ET_{ref} symbols are referred to as ET_{os} for the 0.12 m tall vegetative surface and as ET_{rs} for the 0.5 m tall vegetative surface. A comprehensive summary of the final comparison of ET_{os} and ET_{rs} to the ASCE-PM at the 49 sites was presented in Itenfisu et al. (2000). A partial listing of the Itenfisu et al. (2000) results is provided in Table A-2 and Appendix F.

The statistical summary is listed in Table A-2 and Appendix F. Table -3 shows that the summed hourly ET compared as well or better versus daily ET for the standardized equation as compared to the same analyses for the ASCE-PM equation. The comparisons of daily ET_{os} to daily ASCE-PM ET_o and daily ET_{rs} to daily ASCE-PM ET_r reveal very small differences; therefore, the simplifications are judged to have minimal impact on reference ET estimates. The third comparison of hourly sums of ET_{os} and ET_{rs} to daily ASCE-PM shows that ET_{os} and ET_{rs} agree closely with the ASCE-PM daily values.

Table A-2. Statistical summary of the comparisons between the Standardized Reference Evapotranspiration Equations and ASCE Penman-Monteith for the growing season

METHOD	RATIO				RMSD (mm d^{-1})				RMSD as % of Mean Daily ET
	Max	Min	Mean	Std Dev	Max	Min	Mean	Std Dev	Mean
Hourly Sum ET_o vs. Daily ET_o (within method)									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
ASCE Stand'zed	1.081	0.941	1.012	0.028	0.663	0.228	0.334	0.084	7.7
Hourly Sum ET_r vs. Daily ET_r (within method)									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.931	1.022	0.037	1.048	0.315	0.540	0.152	9.6
Daily ET_o vs. Daily ASCE-PM ET_o									
ASCE Stand'zed	1.007	0.982	0.995	0.006	0.146	0.008	0.041	0.032	0.9
Daily ET_r vs. Daily ASCE-PM ET_r									
ASCE Stand'zed	1.025	0.974	0.998	0.010	0.300	0.014	0.069	0.058	1.28
Hourly Sum ET_o vs. Daily ASCE-PM ET_o									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
ASCE Stand'zed	1.080	0.937	1.007	0.029	0.678	0.235	0.335	0.086	8.0
Hourly Sum ET_r vs. Daily ASCE-PM ET_r									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.933	1.020	0.037	1.067	0.331	0.532	0.144	9.41

The daily-to-daily comparisons are illustrated graphically in Figs. A-3 and A-4 for growing season periods. In the figures, the 82 site-year combinations are plotted along the horizontal axis in order of longitude (refer to Table F-1 to match a site to the corresponding site-year index). Figure A-3 shows mean ratios of daily calculations by the various ET_o equations to daily calculations by the ASCE-PM ET_o method. These ratios are the basis for the mean ratios presented in Table A-2. The similarity of the ASCE Standardized ET_{os}, FAO56-PM ET_{os}, and ASCE-PM ET_{os} results is obvious and is due to the commonality in the equations.

Mean daily ET_o and ET_r calculations for growing season periods for all locations are plotted against the full ASCE-PM equation estimates in Fig. A-5 and A-6. The data in Fig. A-5 show ET_o estimates by the original Penman method (1963 Penman) to have an approximately 0.3 mm d^{-1} bias relative to the daily ASCE ET_o estimates across all locations and magnitudes of mean ET_o. Fig. A-6 shows mean growing season daily estimates of ET_r by the 1982 Kimberly Penman method to predict progressively lower than the daily ASCE ET_r as mean ET_r for the growing season increased. Calculations by the standardized PM equation (ET_{os} and ET_{rs}) predicted closely to daily ET_o and ET_r by the full ASCE-PM equation over all sites and ranges of climate.

Comparisons of the method hourly sums to ASCE-PM daily are shown in Figs. A-7 and A-8 for growing season periods. The hourly ET_o by the 1963 Penman and CIMIS Penman equations have similar trends and both have ratios to ASCE-PM ET_o that average about 1.1 at many sites. The higher ratio by the 1963 Penman can be attributed to its linear wind function which becomes relatively strong during day time hours when wind speed and vapor pressure deficit have larger values. The higher ratios for the CIMIS equation, which has a wind function that is calibrated for hourly time steps, may be due to the absence of the soil heat flux term in the equation as applied by CIMIS (see Appendix B). The wind functions of the CIMIS equation were developed without the inclusion of a soil heat flux term.

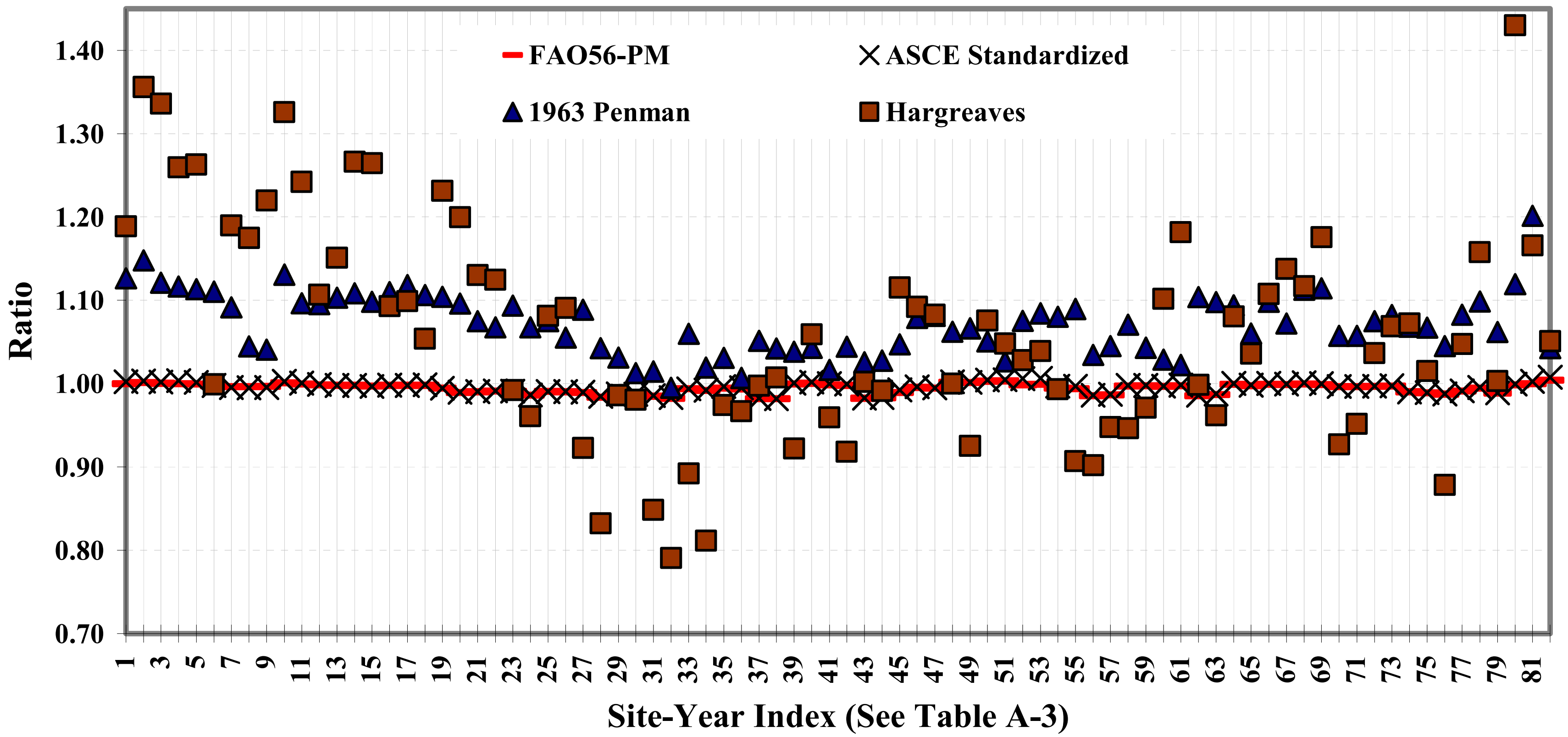

Figure A-3. Average ratio of daily ET_o or ET_{os} to daily ET_o by ASCE-PM ET_o equation.

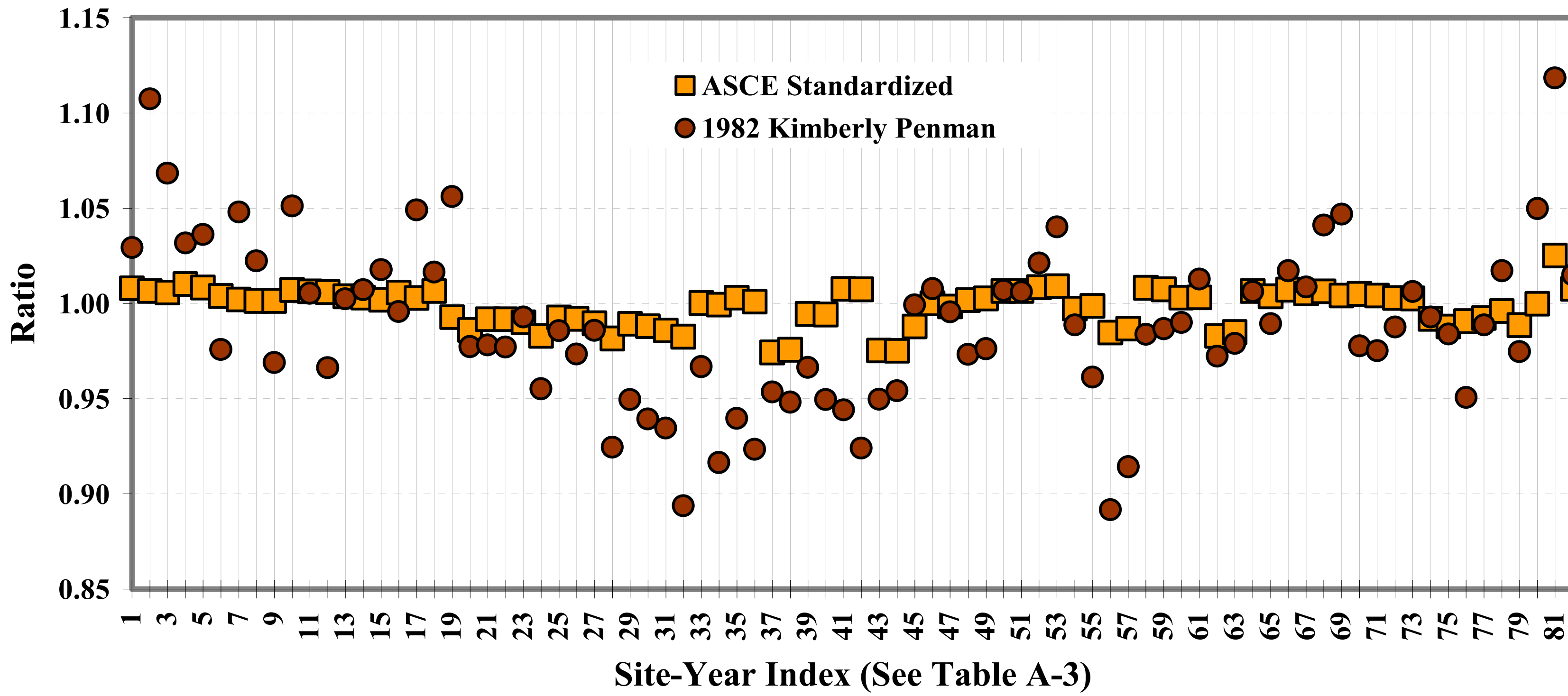

Figure A-4. Average ratio of daily ET_r or ET_{rs} to daily ET_r by ASCE-PM equation.

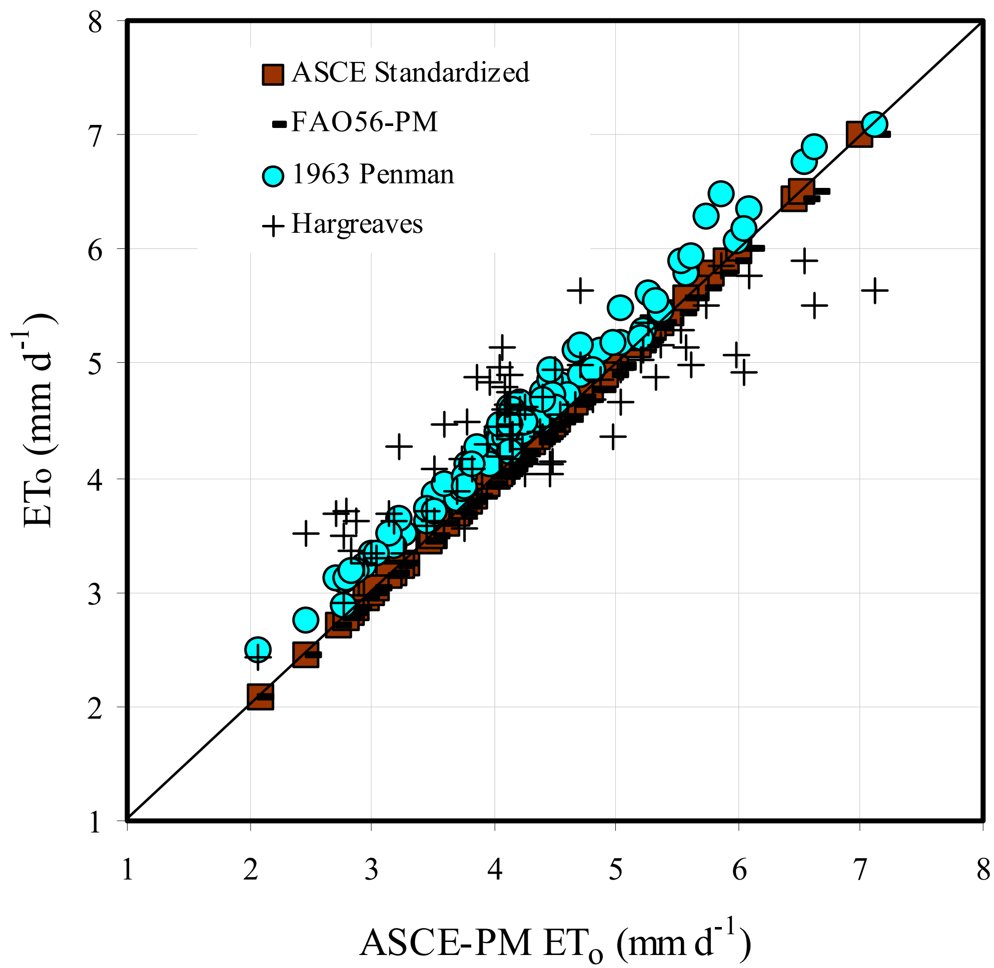

Figure A-5. Mean daily ET_o for the growing season computed using various ET_o methods and ET_{os} vs. mean daily ET_o for the growing season using the full ASCE-PM equation, for daily time steps. Each data point represents one-site year of data (see App. F)

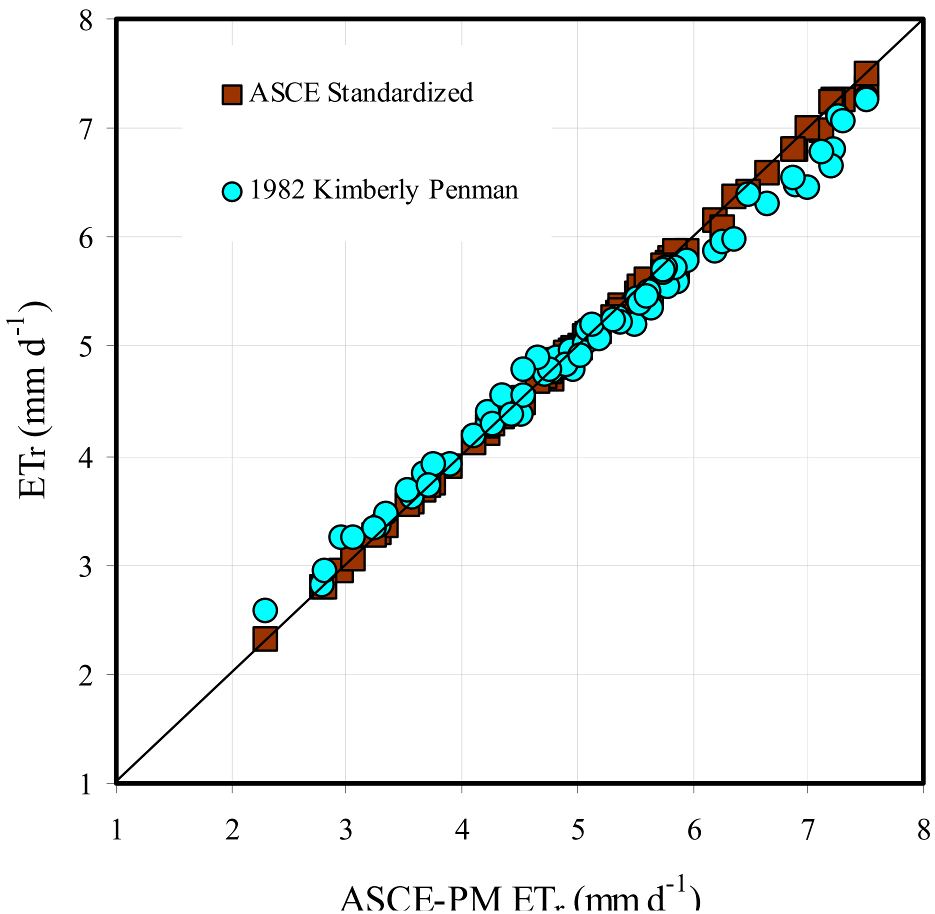

Figure A-6. Mean daily ET_r for the growing season computed using the 1982 Kimberly Penman method and ET_{rs} vs. mean daily ET_r for the growing season using the full ASCE-PM equation, for daily time steps. Each data point represents one-site year of data (see App. F)

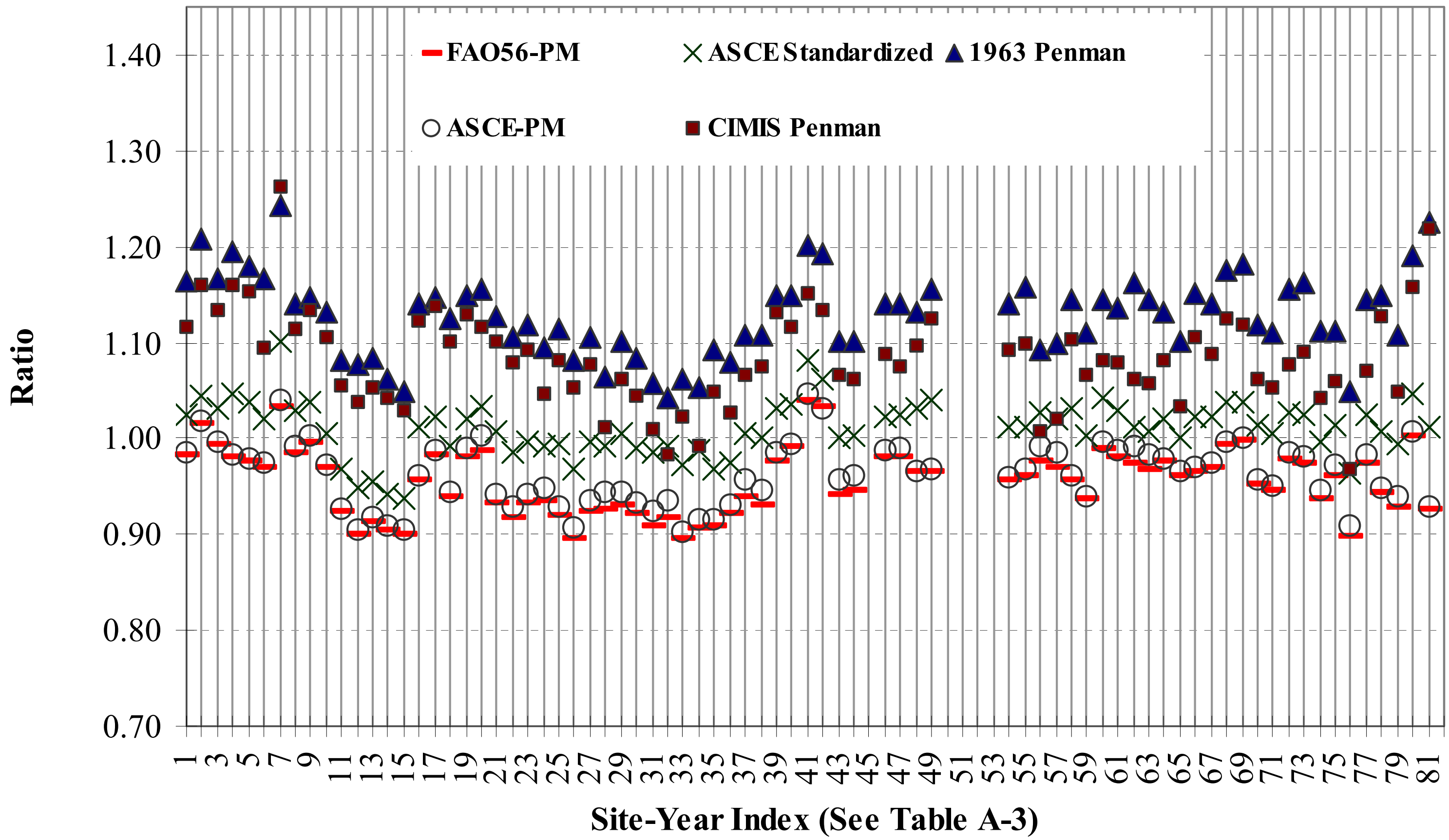

Figure A-7. Average ratio of summed hourly ET_o or ET_{os} to daily ET_o by ASCE-PM ET_o equation.

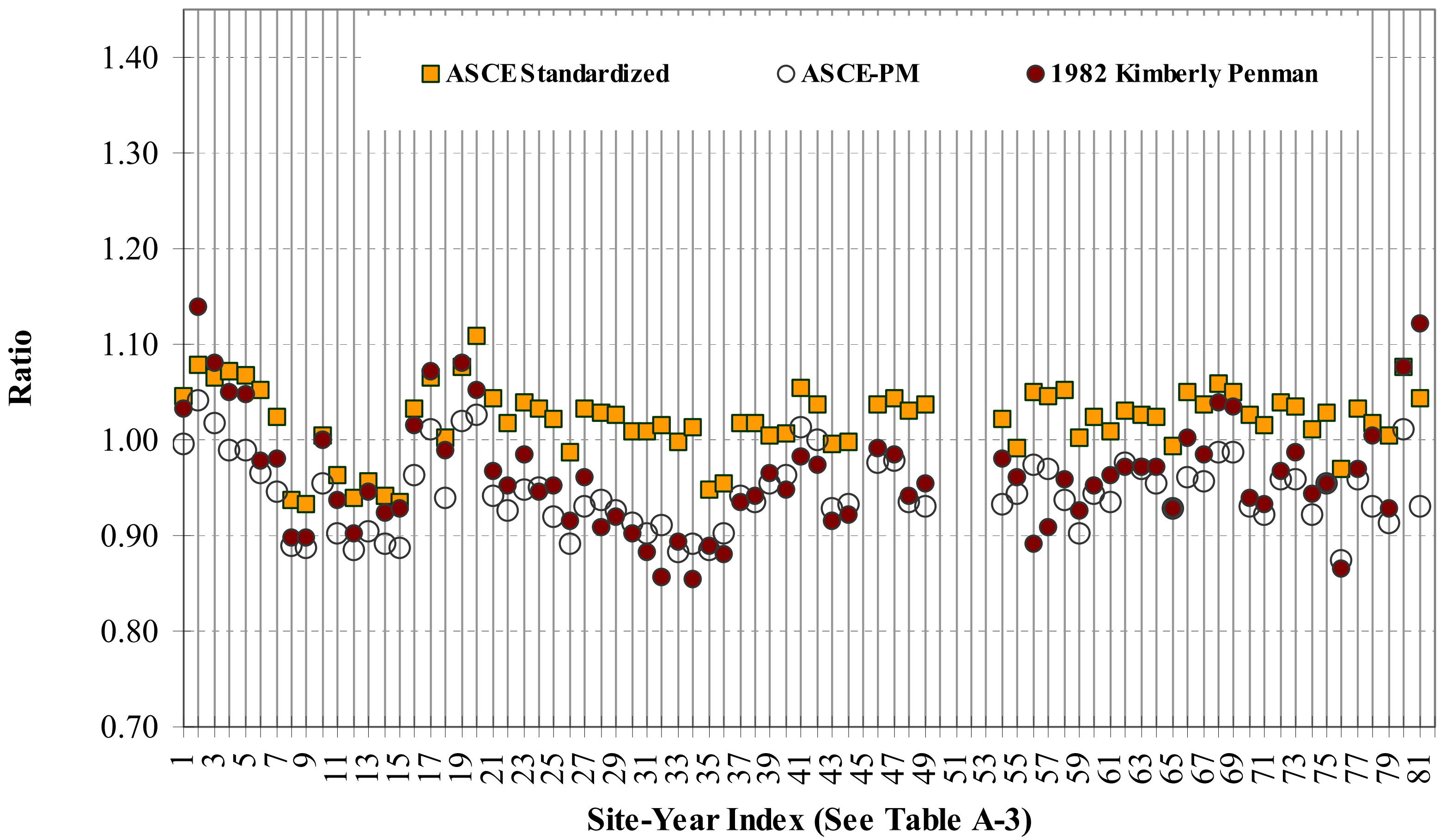

Figure A-8. Average ratio of summed hourly ET_r or ET_{rs} to daily ET_r by ASCE-PM ET_r equation.

TASK COMMITTEE CREDENTIALS

Credentials of members of the Task Committee are as follows:

Ivan A. Walter is a consulting engineer at W. W. Wheeler and Associates, Inc. He has 25 years of experience in water resources and agriculture irrigation engineering. His engineering has involved projects related to surface and groundwater hydrology, water supply planning and development, irrigation engineering and water rights analysis. This involvement has included the investigation and analysis of evapotranspiration by agricultural crops and native vegetation, hydrologic studies and modeling of river basins, and computer modeling of surface water and groundwater hydrologic systems.

Richard Allen is a professor of water resources engineering at the University of Idaho. He has 25 years of national and international experience in measuring weather and evapotranspiration and in development of methodology for computing evapotranspiration parameters. Allen was a joint author of FAO-56 and coeditor of ASCE Manuals and Reports on Engineering Practice No. 70.

Ronald Elliot is head of the Department of Biological and Agricultural Engineering, Oklahoma State University and is a co-principal investigator for the Oklahoma Mesonet.

Marvin E. Jensen is retired from the Agricultural Research Service, USDA, in 1987 and from Colorado State University in1993. Since 1993, he has been consulting on water consumption issues. He has 25 years experience in measuring evapotranspiration in field experiments and over 40 years experience in estimating evapotranspiration. Jensen was the editor of the 1974 ASCE Report Consumptive Use of Water and Irrigation Water Requirments and was senior editor of the 1990 ASCE Manuals and Reports on Engineering Practices No. 70.

Daniel Itenfisu is an irrigation engineer and a postdoctoral fellow at Oklahoma State University. He has ten years of experience in irrigation water management, evapotranspiration and soil moisture modeling and measurements.

Brent Mecham is a Water Conservation Officer with the Northern Colorado Water Conservency District. He has more than 20 years experience in developing landscape management techniques and practices and crop coefficients.

Terry Howell is an Agricultural Engineer and Research Leader with the USDA-ARS Water Management Laboratory in Bushland, Texas. He has over 30 years experience in crop water requirements and ET measurement including lysimeter systems.

Richard Snyder is a biometeorology specialist for the University of California-Cooperative Extension. He was the principle investigator on the California Irrigation Management Information System (CIMIS), which provides reference evapotranspiration to California growers, water purveyors and public agencies. He is also involved in research to measure evapotranspiration and to refine crop coefficients.

Paul Brown is a biometeorology specialist for Arizona Cooperative Extension. He developed and presently oversees the operation of the Arizona Meteorological Network (AZMET) which provides weather-based information, including reference ET information, to Arizona growers and municipalities. His research interests include improving crop coefficients for use in arid irrigation management, and investigating the impact of weather station siting on computed values of Et_{ref}.

Simon Eching is a water use and evapotranspiration specialist with the California Department of Water Resources with applications in the CIMIS network. He has over 15 years experience in irrigation water management, crop water use, and soil moisture measurement. He has also been involved in several international projects to develop weather station networks that provide reference evapotranspiration to irrigators.

Tom Spofford is Irrigation Engineer with the USDA-Natural Conservation Resources Service Technical Center in Portland, Oregon.

Mary Hattendorf is an engineer with the Northern Colorado Water Conservancy District and was formerly manager of the Washington PAWS weather network for Washington State University.

James Wright is a Soil Scientist with the USDA-ARS Irrigation and Soils Research Laboratory at Kimberly, Idaho. He has 35 years experience in development of evapotranspiration equations and crop coefficients and measurement of evapotranspiration.

Derrel Martin is professor of Bioresources Engineering at the University of Nebraska and has over 25 years experience in irrigation water management, irrigated systems, and irrigation water requirements.

DATA CONTRIBUTORS

The following individuals provided weather data sets and/or REF-ET results: Paul Brown* (Arizona); Richard Snyder* and Simon Eching* (California); Ivan Walter*, Marvin Jensen*, and Brent Mecham* (Colorado); Brian Boman (Florida); Wanda Cavender and Gerrit Hoogenboom (Georgia); Richard Allen* and Peter Palmer (Idaho and Montana); Bob Scott and Steve Hollinger (Illinois); Lineu Rodriquez and Derrel Martin* (Nebraska); Art DeGaetano (New York); Daniel Itenfisu* and Ronald Elliott* (Oklahoma); Indi Sriprisan and Richard Cuenca* (Oregon); Dean Evans and Carl Camp (South Carolina); Don Dusek and Terry Howell* (Texas); Richard Allen* and Robert Hill (Utah); and Mary Hattendorf* (Washington). (*member of the ASCE TC or standardization study team).

APPENDIX B

SUMMARY OF REFERENCE EVAPOTRANSPIRATION EQUATIONS USED IN EVALUATION

INTRODUCTION

This appendix contains descriptions of the reference ET methods that were evaluated by the Task Committee at the 81 site-locations. The ET methods included known methods, (e.g. ASCE-Penman Monteith, 1982 Kimberly Penman) and hybrids of the ASCE-PM. The calculation procedures are summarized in Table B-1. Additional information for the hybrids of the ASCE-PM is provided in the discussion following Table B-1. Listed in Table B-1 for each parameter of each equation is the equation number, constant value or procedure used to calculate that parameter. The labels for variations on the ASCE-PM equation are the same as those referred to in Table A-1, Appendix A.

Table B-1. Parameter equation numbers, etc. used in the Reference Equations Evaluated

Parameter	ASCE Penman-Monteith					ASCE Standardized Penman-Monteith	FAO-56 Penman-Monteith	1982 Kimberly Penman	1963 Penman	FAO-24 Penman	CIMIS Penman	1985 Hargreaves
	"ASCE-PM"	"ASCE-PMD"	"ASCE-PMDL"	"ASCE-PMv"	"ASCE-PMDR"							
Reference Types	ET_o, ET_r	ET_o, ET_r	ET_o, ET_r	ET_o, Et_r	ET_o, ET_r	ET_{os}, ET_{rs}	ET_o	ET_r	ET_o	ET_o	ET_o	ET_o
timestep	m, d, h	m, d, h	m, d, h	m, d, h	m, d, h	m, d, h	m, d, h	m, d, (h)[a]	m, d, h	m, d	h	m, d
Δ	5, 36	5, 36	5, 36	5, 36	5, 36	5, 36	5, 36	5	5	5	5	--
γ	B.12	B.12	B.12	B.12	B.12	4	4	B.12	B.12	B.12	B.12	--
λ	B.7	B.7	$\lambda = 2.45$ MJ/kg	B.7	B.7	$\lambda = 2.45$ MJ/kg	$\lambda = 2.45$ MJ/kg	B.7	B.7	B.7	B.7	--
P	B.8	B.8	B.8	B.8	B.8	3	3	B.8	B.8	B.8	B.8	--
α	α=0.23	α=0.23	α=0.23	α=0.23	α=B.25	α=0.23	α=0.23	α=B.25	α=0.23	α=0.23	α=0.23	--
R_n	15-18, 42-45	15-18, 42-45	15-18, 42-45	15-18, 42-45	B.22-B.25	15-18, 42-45	15-18, 42-45	B.22-B.25	15-18, 42-45	15-18	42-45	--
G	30,32, 61-62	30,32, 61-62	30,32, 61-62	30,32, 61-62	30,32, 61-62	30,32, 61-62	30,32, 61-62	B.26 (24-hr), 61-62 (hrly)	30,32, 61-62	30,32	G = 0.	--
R_{so}	19(24-hr), 46 (hrly)	19 (24-hr), 46 (hrly)	19 (24-hr), 46 (hrly)	19 (24-hr), 46(hrly)	19 (24-hr), 46-(hrly)	19 (24-hr), 46 (hrly)	19 (24-hr), 46 (hrly)	19 (24-hr), 46 (hrly)	19 (24-hr), 46 (hrly)	19 (24-hr)	466 (hrly)	--
u_2	Uses u_z	Uses u_z	Uses u_z	Uses u_z	Uses u_z	33/63	33/63	33, 63	33, 63	33	63	--
r_s	B.3-B.6	70 and 45 s m^{-1} (24-hr), 50 and 30 s m^{-1} day, 200 s m^{-1}, night	70 and 45 s m^{-1} (24-hr), 50 and 30 s m^{-1} day, 200 s m^{-1}, night	User defined	70 and 45 s m^{-1} (24-hr), 50 and 30 s m^{-1} day, 200 s m^{-1}, night	70 and 45 s m^{-1} (24-hr), 50 and 30 s m^{-1} day, 200 s m^{-1}, night (hrly)	70 s m^{-1} (all time steps)	--	--	--	--	--

Table B-1. Parameter equation numbers, etc. used in the Reference Equations Evaluated

Parameter	ASCE Penman-Monteith					ASCE Standardized Penman-Monteith	FAO-56 Penman-Monteith	1982 Kimberly Penman	1963 Penman	FAO-24 Penman	CIMIS Penman	1985 Hargreaves
	"ASCE-PM"	"ASCE-PMD"	"ASCE-PMDL"	"ASCE-PMv"	"ASCE-PMDR"							
		(hrly)	(hrly)		(hrly)							
r_a	B.2	B.2 for h=0.12m, H=0.5 m	B.2 for h=0.12m, h=0.5 m	B.2	B.2 for h=0.12m, H=0.5 m	B.2 is embedded in Eq. 1 for h=0.12m, h=0.5 m	B.2 is embedded in Eq. B.15 for h=0.12m	B.18	1.0	1.0	0.29 day 1.14 night	--
ρ	B.10	B.10	B.10	B.10	B.10	--	--	B.19	0.537	0.862	0.53 day 0.40 night	--
e_s	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6, 37	6	37	--
e_a	order of preference is given in Tables 3 and 4 of the main text											

Numbers in cells refer to equations listed in the main text and appendices.

[a] The Kimberly Penman equations are not intended to be applied hourly, but they were evaluated for hourly timesteps in this study.

The variations on the ASCE Penman-Monteith equation are described as follows:

1. ***"ASCE-PM" is the "full-form" ASCE Penman-****Monteith* using resistance equations by Allen et al., (1989*)* and in ASCE Manual 70 (Jensen et al., 1990). In ASCE-PM, r_s is computed from the leaf area index (LAI), which is a function of the height specified for the reference type (grass or alfalfa). Algorithms for LAI depend on reference type. The value of r_s (and r_a) will change with height specified for the reference. The values for r_s for 24-hour timesteps, based on the ASCE LAI algorithms, are r_s = 70 s m^{-1} for 0.12 m tall grass and r_s = 45 s m^{-1} for 0.5 m tall alfalfa. This equation was the measure against which the other equation were compared.

2. ***"ASCE-PMD" is the "full-form" ASCE Penman-Monteith*** and is the same as (1) except that the values for r_s for <u>hourly or shorter</u> timesteps were fixed at r_s = 50 s m^{-1} for 0.12 m tall grass and r_s = 30 s m^{-1} for 0.5 m tall alfalfa during daytime hours and r_s = 200 s m^{-1} for both 0.12 m tall grass and 0.5 m tall alfalfa during nighttime hours. The purpose of the variation was to evaluate whether use of different values of r_s for nighttime and daytime could improve the accuracy of hourly timestep calculations.

3. ***"ASCE-PMDL" is the "full-form" ASCE Penman-Monteith*** and is identical to (2) except that the value for the heat of vaporization was fixed at λ = 2.45 MJ kg^{-1}.The purpose of the variation was to evaluate whether use of a constant value for λ versus a calculated value impacts the accuracy significantly.

4. ***"ASCE-PMv" is the "full-form" ASCE Penman-Monteith with user supplied resistance****.* This method is the same as number 1, except that members of the TC had the option of specifying unique values for 24-hour, daytime and nighttime surface resistance, r_s, for each site. The purpose of the variation was to allow the TC members to test data from their region to determine what value of r_s resulted in the most accurate estimate of ET_{ref} in their region.

5. ***"ASCE-PMDR" is the "full-form" ASCE Penman-Monteith*** and is identical to (2) except that net radiation was calculated following Wright (1982) rather than Eq. 15 – 18 and 42 – 45. The purpose of this variation was to evaluate the degree to which using the Wright (1982) net radiation procedure in place of the standardized procedure impacted the ET_{ref} calculation.

6. ***ASCE Standardized Penman-Monteith equation*** is the standardized form of the ASCE PM equation (ET_{sz}) specified by equations provided in the main text body.

7. ***FAO 56 Penman-Monteith equation.*** The FAO-56 PM method uses essentially identical calculation procedures as the standardized ET_{sz} equation, except for a constant surface resistance (70 s m^{-1}) that is applied to all timesteps and its application to ET_o, only.

Basic equations and supporting parameter equations for equations other than the standardized equation are listed in the following sections.

ASCE PENMAN-MONTEITH METHOD

The Penman-Monteith form of the combination equation (Monteith 1965, 1981) is:

$$ET_{ref} = \left(\frac{\Delta (R_n - G) + K_{time}\, \rho_a\, c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \dfrac{r_s}{r_a} \right)} \right) / \lambda \tag{B.1}$$

where

ET_{ref}	= reference evapotranspiration [mm d^{-1} or mm h^{-1}],
R_n	= net radiation [MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}],
G	= soil heat flux [MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}],
$(e_s - e_a)$	= vapor pressure deficit of the air [kPa],
e_s	= saturation vapor pressure of the air [kPa],
e_a	= actual vapor pressure of the air [kPa],
ρ_a	= mean air density at constant pressure [kg m^{-3}],
c_p	= specific heat of the air [MJ kg^{-1} $^oC^{-1}$],
Δ	= slope of the saturation vapor pressure temperature relationship [kPa $^oC^{-1}$],
γ	= psychrometric constant [kPa $^oC^{-1}$],
r_s	= (bulk) surface resistance [s m^{-1}],
r_a	= aerodynamic resistance [s m^{-1}],
λ	= latent heat of vaporization, [MJ kg^{-1}],
K_{time}	= units conversion, equal to 86,400 s d^{-1} for ET in mm d^{-1} and equal to 3600 s h^{-1} for ET in mm h^{-1}.

The aerodynamic resistance, applied for neutral stability conditions, is:

$$r_a = \frac{\ln\left[\dfrac{z_w - d}{z_{om}}\right] \ln\left[\dfrac{z_h - d}{z_{oh}}\right]}{k^2\, u_z} \tag{B.2}$$

where

r_a	= aerodynamic resistance [s m^{-1}],
z_w	= height of wind measurements [m],
z_h	= height of humidity and or air temperature measurements [m],
d	= zero plane displacement height [m], = 0.67 h
z_{om}	= roughness length governing momentum transfer [m], = 0.123 h
z_{oh}	= roughness length for transfer of heat and vapor [m], = 0.0123 h

k = von Karman's constant, 0.41 [-],
u_z = wind speed at height z [m s^{-1}]
h = mean height of the vegetation [m].

Bulk surface resistance is:

$$r_s = \frac{r_l}{LAI_{active}} \tag{B.3}$$

where

r_s = (bulk) surface resistance [s m^{-1}],
r_l = bulk stomatal resistance of a well-illuminated leaf [s m^{-1}],
LAI_{active} = active (sunlit) leaf area index [m^2 (leaf area) m^{-2} (soil surface)]

For ASCE calculations for dense vegetation, LAI_{active} is calculated as:

$$LAI_{active} = 0.5\,LAI \tag{B.4}$$

where

LAI = leaf area index [m^2 of leaf per m^2 of soil surface = dimensionless]

For clipped grass:

$$LAI = 24\ h \tag{B.5}$$

For alfalfa:

$$LAI = 5.5 + 1.5\ln(h) \tag{B.6}$$

where

h = vegetation height [m]

In the "full-form" ASCE Penman-Monteith method, the following "full-form" ancillary equations are used. Many of these have been simplified for use with the ET_{sz} form of the Penman-Monteith equation and are listed in the main text.

Latent Heat of Vaporization (λ)[1]

$$\lambda = 2.501 - (2.361 \times 10^{-3})\, T_{mean} \qquad (B.7)$$

where:

λ = latent heat of vaporization [MJ kg^{-1}]
T_{mean} = mean air temperature for the time interval [°C]

The value of the latent heat varies only slightly over normal temperature ranges. ET_{sz}, a single value is taken: $\lambda = 2.45$ MJ kg^{-1}. The inverse of λ is presented as 0.408.

Atmospheric Pressure (P)[2]

Mean atmospheric pressure for a location is predicted from site elevation using a formulation of the universal gas law:

$$P = P_o \left(\frac{T_{Ko} - \alpha_1 (z - z_o)}{T_{Ko}} \right)^{\frac{g}{\alpha_1 R}} \qquad (B.8)$$

where:

P = atmospheric pressure at elevation z [kPa]
P_o = atmospheric pressure at sea level = 101.3 [kPa]
z = weather site elevation [m]
z_o = elevation at reference level (i.e., sea level) [m]
g = gravitational acceleration = 9.807 [m s^{-2}]
R = specific gas constant = 287 [J kg^{-1} K^{-1}]
α_1 = constant lapse rate moist air = 0.0065 [K m^{-1}]
T_{Ko} = reference temperature [K] at elevation z_o given by

$$T_{Ko} = 273.16 + T_{mean} \qquad (B.9)$$

where:

[1] Reference: Harrison (1963)

[2] Reference: Burman *et al.* (1987)

T_{mean} = mean air temperature for the time period of calculation [°C]

When assuming P_o = 101.3 kPa at z_o = 0 m, and T_{Ko} = 293 K for a standard reference temperature of T_{mean} = 20 °C, equation (B.8) becomes equation 3 of the main text.

Atmospheric Density (ρ_a)[3]

$$\rho_a = \frac{1000\,P}{T_{Kv}\,R} = 3.486\,\frac{P}{T_{Kv}} \tag{B.10}$$

where:

ρ = atmospheric density [kg m^{-3}]
R = specific gas constant = 287 [J kg^{-1} K^{-1}]
T_{Kv} = mean virtual temperature for period [K]

$$T_{Kv} = T_K \left(1 - 0.378\,\frac{e_a}{P}\right)^{-1} \tag{B.11}$$

where:
T_K = mean absolute temperature [K] : T_K = 273.16 + T_{mean} [°C]
e_a = actual vapor pressure [kPa]

In derivation of the ET_{sz} equation, equation (B.11) was reduced to $T_{Kv} \approx 1.01\,(T_{mean} + 273)$ that holds for most conditions. T_{mean} is set equal to mean daily temperature for 24-hour calculation time steps.

Psychrometric Constant (γ)[4]

The pyschrometric constant, γ, is used in the numerator and denominator of the standardized Penman-Monteith equation:

$$\gamma = \frac{c_p\,P}{\varepsilon\,\lambda} \tag{B.12}$$

where:

[3] Reference: Smith *et al.* (1991)

[4] Reference: Brunt (1952)

γ = psychrometric constant [kPa °C^{-1}]
c_p = specific heat of moist air = 1.013 x 10^{-3} [MJ kg^{-1} °C^{-1}]
P = atmospheric pressure [kPa]
ε = ratio of the molecular weight of water vapor/dry air ("epsilon") (ε = 0.622 for standard, dry air)
λ = latent heat of vaporization [MJ kg^{-1}] (λ = 2.45 MJ kg^{-1} for standardized calculations)

The simplification of λ = 2.45 MJ kg^{-1} in equation B.12 and reduction results in Eq. 4 for the ET_{sz} equation. This simplification causes less than 2% error in γ over the range of $0 < T_{mean} <$ 40 °C and less than 1% error over the range of $11 < T_{mean} < 31$ °C. This translates into errors in ET_{os} and ET_{rs} that are generally less than 0.2%.

Soil Heat Flux Density (G) for hourly periods[5]

The full equation for hourly G, on which equations 61 and 62 for ET_{sz} are based, is:

$$G_{hr} = K_G \exp(-0.5\,LAI)\ R_n \tag{B.13}$$

where

K_G = 0.4 during daytime (defined as when $R_n > 0$)
K_G = 2.0 during nighttime (defined as when $R_n < 0$)
LAI = leaf area index [dimensionless]

Units for G_{hr} and R_n are the same.

Wind Speed Adjustment for Measurement Height

To adjust wind speed data obtained from instruments placed at elevations other than the standard height of 2 m for use in all combination equations, a logarithmic wind speed profile is used. The exception is Eq. B.1 for the full-form Penman-Monteith equation above, which uses the actual wind speed and actual measurement height in calculating r_a as in Eq. B.2:

[5] Reference: Choudhury et al., (1987), Choudhury (1989)

$$u_2 = u_z \frac{\ln\left(\frac{2-d}{z_{om}}\right)}{\ln\left(\frac{z_w - d}{z_{om}}\right)} \qquad \text{(B.14)}$$

where

u_2	=	wind speed at 2 m above ground surface [m s^{-1}],
u_z	=	measured wind speed at z_w m above ground surface [m s^{-1}],
z_w	=	height of measurement above ground surface [m],
d	=	zero plane displacement height for the weather site vegetation, m, (d = 0.67 h)
z_{om}	=	aerodynamic roughness length for the weather site vegetation, m, (z_{om} = 0.123 h)

This equation serves as the basis for Equations 33 and 63 of the text, where for 0.12 m tall grass, (B.14) reduces to:

$$u_2 = u_z \frac{4.87}{\ln(67.8\, z_w - 5.42)} \qquad \text{(B.14b)}$$

Allen and Wright (1997) described procedures for adjusting wind speed measured over non-grassed surfaces to account for differences between the vegetation at the measurement surface and the vegetation type for the reference. These procedures are recommended where the vegetation of the measurement site is aerodynamically different from clipped grass or full-cover alfalfa or where the "full" Penman-Monteith equation (B.1) is applied to vegetation other than the two reference types. The following (B.14c) is a special application of (B.14) for the case where wind speed is measured over approximately 0.5 m tall alfalfa and is to be adjusted to an equivalent speed at 2 m height over grass for use in the standardized equation for ET_{os} or ET_{rs}. In this situation, the d and z_{om} in the numerator of (B.14) are set to 0.08 m and 0.062 m, representing d for clipped grass and z_{om} for alfalfa. However, the d and z_{om} in the denominator of (B.14) are set to 0.335 m and 0.062 m, representing values for alfalfa. This "hybrid" combination of using d for both grass and alfalfa in (B.14c) is required because coefficients used in the standardized ET_{rs} equation (1) presume that wind is measured over grass, even for the tall reference (see Table 2 of the main text). Using these substitutions, (B.14) reduces to:

$$u_2 = u_z \frac{\ln\left(\frac{2-0.08}{0.062}\right)}{\ln\left(\frac{z_w - 0.335}{0.062}\right)} = u_z \frac{3.44}{\ln(16.3\, z_w - 5.42)} \qquad \text{(B.14c)}$$

Equation (B.14c) is used to adjust wind measured over alfalfa for use in calculating ET_{os} and ET_{rs}.

FAO-56 PENMAN-MONTEITH METHOD

The FAO-56 Penman-Monteith equation is a grass reference equation that was derived from the ASCE equations (B.1 – B.6) by fixing h = 0.12 m for clipped grass and by assuming measurement heights of z_w = 2 m and z_h = 2 m and using λ = 2.45 MJ kg^{-1}. The result is an equation that defines the reference evapotranspiration from a hypothetical grass surface having a fixed height of 0.12 m, bulk surface resistance of 70 s m^{-1}, and albedo of 0.23. For 24-hour time steps:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \dfrac{900}{T+273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34 u_2)} \tag{B.15}$$

where

ET_o = grass reference evapotranspiration [mm day^{-1}],
R_n = net radiation at the crop surface [MJ m^{-2} day^{-1}],
G = soil heat flux density [MJ m^{-2} day^{-1}],
T = mean daily air temperature at 2 m height [°C],
u_2 = wind speed at 2 m height [m s^{-1}],
e_s = saturation vapor pressure [kPa],
e_a = actual vapor pressure [kPa],
e_s-e_a = vapor pressure deficit [kPa],
Δ = slope of saturation vapor pressure temperature relationship [kPa $°C^{-1}$],
γ = psychrometric constant [kPa $°C^{-1}$].

The FAO-56 Penman-Monteith equation for hourly time steps assumes that r_s = 70 s m^{-1} so that:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{37}{T_{hr} + 273} u_2\,(e_s(T_{hr}) - e_a)}{\Delta + \gamma\,(1 + 0.34 u_2)} \tag{B.16}$$

where

ET_o = grass reference evapotranspiration [mm h^{-1}],
R_n = net radiation at the crop surface [MJ m^{-2} h^{-1}],
G = soil heat flux density [MJ m^{-2} h^{-1}],

T_{hr} = mean hourly air temperature at 2 m height [°C],
u_2 = wind speed at 2 m height [m s^{-1}],
e_s = saturation vapor pressure [kPa],
e_a = actual vapor pressure [kPa],
e_s-e_a = saturation vapor pressure deficit [kPa],
Δ = slope vapor pressure curve [kPa $°C^{-1}$],
γ = psychrometric constant [kPa $°C^{-1}$].

OTHER PENMAN EQUATIONS

The classical form of the Penman equation (Penman, 1948, 1956, 1963) is:

$$ET = \left(\frac{\Delta}{\Delta + \gamma} (R_n - G) + K_w \frac{\gamma}{\Delta + \gamma} (a_w + b_w u_2)(e_s - e_a) \right) / \lambda \qquad (B.17)$$

where:

K_w = is a units constant
a_w and b_w = are wind function coefficients
u_2 = wind speed at 2 m, [m s^{-1}]
λ = latent heat of vaporization, MJ kg^{-1}

All other terms and definitions are the same as those used for the Penman-Monteith equation. Parameter K_w = 6.43 for ET in mm d^{-1} and K_w = 0.268 for ET in mm $hour^{-1}$. The a_w and b_w terms are empirical wind coefficients that have often received local or regional calibration and apply to a specific reference type of crop or surface.

THE 1963 PENMAN METHOD

The values for a_w and b_w for the original Penman equation, first applied by Penman (1948) to open water and implicitly to grass, and later by Penman (1963) to clipped grass were a_w = 1.0 and b_w = 0.537, respectively, for wind speed in m s^{-1}, e_s - e_a in kPa and grass ET_o in mm d^{-1}. The equations were intended for with daily computations. R_n for the 1963 Penman equation was calculated similar to Eq. 15-18, and saturation vapor pressure was based on only mean daily air temperature rather than on T_{max} and T_{min}. For hourly applications, G was predicted using Eq. 61 and 62 and for daily applications, G was predicted using Eq. 30.

THE KIMBERLY PENMAN METHOD.

The 1982 Kimberly Penman methods (Wright, 1982,) use B.17 with wind coefficients that vary with time of year. In addition, the coefficients used for computation of net radiation and the method to predict 24-hour soil heat flux are unique to the Kimberly method.

The 1982 Kimberly-Penman equation was developed from intensive studies of evapotranspiration using measurements of full-cover alfalfa ET from precision weighing lysimeters at Kimberly, Idaho (Wright and Jensen 1972; Wright 1981; Wright 1982; Wright 1988). The 1996 Kimberly wind function for grass ET_o (Wright, 1996) was developed from five years of weighing lysimeter data from extremely well-managed clipped fescue grass having high leaf area and maintained at 0.8 to 0.15 m height and well-fertilized.

The Kimberly Penman and associated wind functions are intended for application with 24-hour time steps (K_w =6.43). The form and all units and definitions are the same as those in Eq. B.17. The Kimberly a_w and b_w wind function coefficients for alfalfa vary with time of year and are computed for ET_r as (Wright 1987, pers. comm. and Jensen et al. 1990):

$$a_w = 0.4 + 1.4 \ \exp\left(\left[-\left(\frac{J - 173}{58}\right)^2\right]\right) \qquad \text{(B.18)}$$

$$b_w = 0.605 + 0.345 \ \exp\left(-\left[\left(\frac{J - 243}{80}\right)^2\right]\right) \qquad \text{(B.19)}$$

where J is the day of the year. For latitudes south of the equator, one should use J' in place of J, where J' = (J - 182) for J ≥ 182 and J' = (J + 182) for J < 182. The (e_s - e_a) term in the 1982 and 1996 Kimberly Penmans is computed the same as for the Penman-Monteith equation (as the average of e_s computed at maximum and minimum temperatures).

In the original (Wright, 1982) definition for the 1982 Kimberly Penman equation, net long wave radiation was computed for Kimberly as:

$$R_{nl} = \sigma \left[\frac{T_{max,K}{}^4 + T_{min,K}{}^4}{2} \right] \left(a_1 + b_1 \sqrt{e_a} \right) \left(a_c \frac{R_s}{R_{so}} + b_c \right) \qquad \text{(B.20)}$$

where

R_{nl}	=	net outgoing longwave radiation [MJ m^{-2} d^{-1}],
σ	=	Stefan-Boltzmann constant [4.901 10^{-9} MJ K^{-4} m^{-2} d^{-1}],
$T_{,K\ max}$	=	maximum absolute temperature during the 24-hour period [K = °C + 273.16],
$T_{K\ min}$	=	minimum absolute temperature during the 24-hour period [K = °C + 273.16],
e_a	=	actual vapor pressure [kPa],
R_s/R_{so}	=	relative shortwave solar radiation (limited to ≤ 1.0),
R_s	=	measured or calculated solar radiation [MJ m^{-2} d^{-1}],
R_{so}	=	calculated clear-sky radiation [MJ m^{-2} d^{-1}].

Eq. B.20 has the same form as used for Eq. 18 of the ET_{sz} procedure. However, coefficients a_1, b_1, a_c and b_c have different values.

Parameter a_1 for alfalfa at Kimberly (42 º N) is:

$$a_1 = 0.26 + 0.1 \exp\left(- [0.0154\,(J - 180)\,]^2 \right) \qquad \text{(B.21)}$$

where J is the day of the year, and where J for the southern hemisphere is replaced with J' as described for Eq. B.18-B.19. Parameter b_1 = -0.139 in Wright (1982).

Wright (1982) predicted a_c and b_c as:

$$\begin{aligned} a_c &= 1.126 \quad \text{and} \quad b_c = -0.07 \quad \text{for} \quad R_s / R_{so} > 0.7 \\ a_c &= 1.017 \quad \text{and} \quad b_c = -0.06 \quad \text{for} \quad R_s / R_{so} \le 0.7 \end{aligned} \qquad \text{(B.22)}$$

Wright (1982) predicted albedo as:

$$\alpha = 0.29 + 0.06 \sin\left[(J + 96) / 57.3 \right] \qquad \text{(B.23)}$$

where J is the day of the year, and where J for the southern hemisphere is replaced with J' as described for Eq. B.18-B.19.

Soil heat flux for 24-hour periods is predicted for the alfalfa reference by Wright (1982) using the difference between mean air temperature of the current day and the mean air temperature of the previous three days:

$$G_{24} = 0.38 \left(T_{mean} - \sum_{i=1}^{3} T_{mean\ i} / 3 \right) \qquad \text{(B.24)}$$

where G_{24} is 24-hour soil heat flux in MJ m^2 d^{-1}, T_{mean} is mean air temperature on the current day and $T_{mean\ I}$ is the mean air temperatures for the previous three days. Equation B.24 may not predict well under various conditions. In a study on 24-hour heat flux at Kimberly and Logan, Allen and Wright (unpublished paper, 1996) found that using G=0 for 24-hour periods under alfalfa and grass produced less error relative to measured G than using Eq. B.24. For hourly applications, G was predicted using Eq. 61 and 62.

THE CIMIS PENMAN METHOD.

Pruitt (Pruitt and Doorenbos 1977a) developed a_w and b_w for predicting grass ET_o for hourly periods for a clipped grass reference. These coefficients have been adopted for standard ET_o estimation in the California Irrigation Management Information Service (CIMIS) (Snyder and Pruitt, 1985, Snyder and Pruitt, 1992). The result is the "CIMIS" Penman ET_o equation where $a_w = 0.29$ and $b_w = 0.53$ for $R_n > 0$ and $a_w = 1.14$ and $b_w = 0.40$ for $R_n \leq 0$. These coefficients are applied hourly using Eq. B.17 where ET_o = mm $hour^{-1}$, R_n = MJ m^{-2} $hour^{-1}$, and $K_w = 0.268$.

The net radiation calculation for the CIMIS method as applied by CIMIS is different than that applied during the Task Committee study. In the Task Committee application and evaluation, R_n for the CIMIS Penman equation was computed using Eq. 42-45 of the text. This decision was based on sensitivity in the prediction of R_{nl} based on R_s/R_{so} in the CIMIS routines when R_s/R_{so} is close to 1.0.

Standard CIMIS calculations assume G = 0, although G in hourly applications should normally be considered. In the Task Committee analyses, G was set equal to G = 0 to be consistent with standard CIMIS usage.

FAO-24 PENMAN METHOD.

The FAO-24 Penman was applied for only daily timesteps using net radiation as computed in the FAO-24 publication (Doorenbos and Pruitt, 1977). In the FAO-24 Penman, $a_w = 1.0$ and $b_w = 0.862$ for u_2 in m s^{-1} and vapor pressure in kPa and radiation in MJ m^{-2} d^{-1}. R_n for the FAO-24 Penman equation is calculated similar to Eq. 15-18, except that only mean daily air temperature is used in place of T_{max} and T_{min}. Saturation vapor pressure is also based only on mean daily air temperature. The FAO-24 "correction" was applied using the regression equation by Allen and Pruitt (1991).

THE 1985 HARGREAVES METHOD

The 1985 Hargreaves method (Hargreaves and Samani, 1985 and Hargreaves et al., 1985) requires only maximum and minimum daily air temperature and it can be applied on 24-hour, weekly, 10-day, or monthly time steps. It has the form:

$$ET_o = 0.0023(T_{max} - T_{min})^{0.5}\ (T_{mean} + 17.8)\ R_a \qquad \text{(B.25)}$$

where:

- ET_o = grass reference ET, mm d^{-1}
- T_{max} = maximum daily air temperature, ^oC
- T_{min} = minimum daily air temperature, ^oC
- T_{mean} = mean daily air temperature, $T_{mean} = (T_{max} + T_{min}) / 2$
- R_a = extraterrestrial radiation, mm d^{-1} (see Eq. 21 – 29 in main text) (R_a in mm d^{-1} = R_a in MJ m^{-2} d^{-1} / 2.45).

APPENDIX C

EXAMPLE CALCULATIONS FOR DAILY AND HOURLY STANDARDIZED REFERENCE EVAPOTRANSPIRATION

TABLE OF CONTENTS

EXAMPLE CALCULATIONS FOR DAILY AND HOURLY STANDARDIZED REFERENCE EVAPOTRANSPIRATION

INTRODUCTION

The following examples demonstrate application of the standardized ET_{SZ} equation and supporting calculations for daily and hourly time periods. These examples provide a standardized set of calculations for checking computer software. Various software programs are also available for making the calculations for the equations presented in this standardization statement, including the REF-ET software available from the University of Idaho (http://www.kimberly.uidaho.edu/ref-et/) and the ETo spreadsheet by Snyder (2000). The REF-ET software is Windows-based and can read a wide range of file formats and unit types.

The location selected for this example application is an agricultural weather site near Greeley, CO[1] operated by the Northern Colorado Water Conservation District. The weather station utilizes electronic, automated equipment and is situated above irrigated grass having an expanse of approximately 50 x 50 m. Surroundings beyond the grassed weather surface are irrigated residential turf and agriculture. The technical data in Table C-1 describe the weather station.

Additional constants for the Greeley site that are a part of the standardized calculations are listed in Table C-2 along with the equation number used for the calculation.

[1] Data were provided courtesy of Mr. Mark Crookston and Mr. Brent Mecham of the Northern Colorado Conservancy District, Loveland, CO.

Example calculation results are presented in the following sections for daily (i.e., 24-hour) and hourly timesteps. Calculated values can be compared with computations by user software programs to confirm accuracy of the programs.

Table C-1. Characteristics of the Greeley, Colorado weather station

Attribute	Value
Latitude	40.41 degrees N
Longitude	104.78 degrees W
Elevation	1462.4 m
Anemometer height	3 m
Height of air temperature and RH meas.	1.68 m
Longitude of center of time zone	105 degrees W
Type of surface at weather station	irrigated grass
Height of vegetation of weather station	0.12 m

Table C-2. Calculation constants for the Greeley, Colorado weather station

Variable	Equation(s)	Value
Mean atmospheric pressure	3	85.17 kPa
Psychrometric Constant (γ)	**4**	0.0566 kPa $^oC^{-1}$
K_{ab} for predicting R_{so}	19, 20	0.779
Multiplier for adjusting wind speed to 2m height	33	0.921
Latitude in radians	22	0.7053 radians

DAILY CALCULATION TIMESTEP

Calculation results for daily time steps are presented in Table C-3 for 10 days in July, 2000 for the Greeley, CO agricultural weather site operated by the Northern Colorado Water Conservation District. Columns 3 - 7 of Table C-3 are the original weather data reported for the station. Average daily vapor pressure, e_a, was reported for the Greeley station. These values were calculated inside the electronic data logging system at the weather site throughout the course of a day using measured air temperature and relative humidity (via equations 37 and 41), and an average vapor pressure for the day was calculated. An equivalent dew-point temperature for each day was calculated from e_a using Eq. D.7 of Appendix D.

INTEGRITY OF DATA

Daily solar radiation data for the complete year 2000 are plotted in Figure D-2 for Greeley, along with clear sky R_{so} envelopes that were determined using Eq. 19 and using the more detailed procedure of Appendix D. The good agreement between measured R_s for cloud-free days and the computed R_{so} curves supports using the solar radiation data.

The daily mean dew-point temperature, computed from daily mean vapor pressure, was plotted against daily minimum air temperature as shown in Figure D-9a of Appendix D, and computed daily maximum relative humidity and daily minimum relative humidity are plotted in Figure D-9b. The humidity and air temperature data for the Greeley location during 2000 were judged to be of good integrity and representative of a well-watered, agricultural (i.e., “reference ET”) condition.

Daily mean wind speed data were plotted vs. day of year as described in Appendix D. The wind speed appeared to be well distributed and with ranges and averages typical of agricultural areas.

However, no comparisons using an independent anemometer or using wind speed data from a nearby weather station were made.

CALCULATIONS OF VARIABLES AND STANDARDIZED REFERENCE EVAPOTRANSPIRATION

Table C-3 contains calculations required for computation of ET_{sz} for daily time steps for the 10 day period at Greeley, Colorado. ET_{os} and ET_{rs} for the short and tall references are listed in the last two columns.

Table C-3. Measured data, calculations, and ET_{os} and ET_{rs} for daily time steps for July 1-10, 2000 near Greeley, Colorado.

Month	Day	T_{max}	T_{min}	vapor press. e_a	R_s	wind @3m	Day of Year	T_{mean}	Δ	$e^o(T_{max})$	$e^o(T_{min})$	e_s	wind @2m
		^oC	^oC	kPa	MJ m^{-2} d^{-1}	m s^{-1}		^oC	kPa $^oC^{-1}$	kPa	kPa	kPa	m s^{-1}
							Eq. 25	Eq. 3	Eq. 5	Eq. 7	Eq. 7	Eq. 6	Eq. 33
7	1	32.4	10.9	1.27	22.4	1.94	183	21.7[a]	0.1585	4.88	1.31	3.09	1.79
7	2	33.6	12.2	1.19	26.8	2.14	184	22.9	0.1692	5.21	1.42	3.31	1.97
7	3	32.6	14.8	1.40	23.3	2.06	185	23.7	0.1762	4.91	1.69	3.30	1.90
7	4	33.8	11.8	1.18	29.0	1.97	186	22.8	0.1684	5.27	1.39	3.33	1.81
7	5	32.7	15.9	1.59	27.9	2.98	187	24.3	0.1820	4.94	1.81	3.37	2.74
7	6	36.3	15.8	1.58	29.2	2.37	188	26.0	0.1990	6.03	1.79	3.91	2.18
7	7	35.5	16.7	1.13	23.2	2.43	189	26.1	0.1996	5.78	1.9	3.84	2.24
7	8	34.4	18.3	1.38	22.1	1.95	190	26.4	0.2027	5.45	2.11	3.78	1.80
7	9	32.7	15.1	1.38	26.5	1.75	191	23.9	0.1781	4.94	1.72	3.33	1.61
7	10	32.7	15.7	1.59	27.7	2.31	192	24.2	0.1809	4.95	1.78	3.37	2.13

[a] T_{mean} was calculated from T_{max} and T_{min} following standardized procedure. These differ slightly from T_{mean} computed from hourly averages.

Table C-3. Continued.

Month	Day	$T_{k\ max}$	$T_{k\ min}$	d_r	declin.	sunset hr	R_a	R_{so}	R_s/R_{so}	R_{nl}	R_n	ET_{os}	ET_{rs}
		K	K		radians	radians	MJ m^{-2} d^{-1}			MJ m^{-2} d^{-1}	MJ m^{-2} d^{-1}	mm d^{-1}	mm d^{-1}
				Eq. 23	Eq. 24	Eq. 28	Eq. 21	Eq. 20		Eq. 18	Eq. 15	Eq. 1	Eq. 1
7	1	305.6	284.1	0.9670	0.4017	1.941	41.63	32.43	0.691	3.96	13.31	5.71	7.34
7	2	306.8	285.4	0.9670	0.4003	1.939	41.58	32.39	0.827	5.45	15.20	6.71	8.68
7	3	305.8	288.0	0.9670	0.3988	1.938	41.53	32.36	0.720	4.15	13.78	5.98	7.65
7	4	307.0	285.0	0.9671	0.3972	1.936	41.48	32.32	0.897	6.14	16.19	6.86	8.73
7	5	305.9	289.1	0.9671	0.3954	1.934	41.43	32.27	0.864	5.15	16.33	7.03	9.07
7	6	309.5	289.0	0.9671	0.3936	1.932	41.37	32.23	0.906	5.67	16.83	7.50	9.60
7	7	308.7	289.9	0.9672	0.3916	1.930	41.31	32.18	0.721	4.71	13.15	7.03	9.56
7	8	307.6	291.5	0.9673	0.3895	1.928	41.25	32.13	0.688	4.02	13.00	6.16	7.99
7	9	305.9	288.3	0.9674	0.3873	1.925	41.18	32.08	0.826	5.16	15.27	6.20	7.68
7	10	305.9	288.9	0.9674	0.3850	1.923	41.11	32.02	0.865	5.15	16.15	6.61	8.28

HOURLY CALCULATION TIMESTEP

Calculation results for hourly time steps are presented in Table C-4 for a 31-hour period spanning from 1600 hours on July 1 to 2200 hours on July 2, 2000 for the Greeley, CO agricultural weather site operated by the Northern Colorado Water Conservation District. The 31-hour period was selected to contain both nighttime and daytime conditions and to illustrate how the ratio of R_s/R_{so} is selected for nighttime periods.

Columns 4 - 7 of Table C-4 are the original weather data reported for the station. Average hourly vapor pressure, e_a, was reported in the data set. These values were calculated inside the electronic data logging system at the weather site using measured air temperature and relative humidity (via equations 37 and 41) on an hourly or shorter basis.

INTEGRITY OF DATA

Integrity of daily solar radiation, humidity, air temperature and wind data were assessed as discussed in the previous section describing daily timesteps. Solar radiation data were additionally assessed for the hourly time steps by plotting measured R_s vs. computed clear sky R_{so} envelopes as illustrated in Figure D-2 of Appendix D. The good agreement between measured hourly R_s for cloud-free conditions and the computed R_{so} curves supports using the solar radiation data.

CALCULATION OF VARIABLES AND STANDARDIZED REFERENCE EVAPOTRANSPIRATION

Table C-4 contains calculations of variables that are required for computation of the standardized reference evapotranspiration for hourly time steps for the 31-hour period at Greeley, Colorado. Calculations for the standardized reference ET_{os} and ET_{rs} for the short and tall references are listed in the last two columns of the table.

Notes concerning the calculation of the variables in Table C-4 are the following:

- The beginning and ending times for each hourly period, expressed in radians (ω_1 and ω_2) were limited to the sunset hour angle as recommended in Eq. 55.

- The ratio R_s/R_{so} was limited to $0.25 < R_s/R_{so} <= 1.0$ as recommended following Eq. 45.

- The ratio R_s/R_{so} during nighttime periods was set equal to R_s/R_{so} for a period approximately 3 hours before sunset each day, as recommended in the text in the subsection titled "R_s/R_{so} for Hourly Periods." This ratio and the nighttime ratios are bolded in Table C-4.

The soil heat flux was calculated according to reference type and daytime or nighttime period using Eq. 61 and 62.

- "The reference ET calculated for some nighttime hours is negative. In practice, the user may wish to set negative values to zero before summing over the 24-hour period. However, in some situations, negative hourly computed ET_{os} or ET_{rs} may indicate the condensation of vapor during periods of early morning dew and should therefore be registered as negative during the summing of 24-hour ET. In other situations, negative hourly ET_{os} or ET_{rs} during nighttime reflect the uncertainties in some parameter estimates and assumptions implicit to the combination equation. In general, the impact on ET summed over daily periods by negative hourly values is less than a few percent."

Table C-4. Measured data, calculations, and ET_{os} and ET_{rs} for hourly time steps for July 1-2, 2000 near Greeley, Colorado.

Month	Day	Hour	T_{hr}	vapor pressure e_a	R_s	wind speed @3m	Day of Year	Δ	$e_s = e^o(T_{hr})$	wind @2m	$T_{k\ max}$
			^oC	kPa	$MJ\ m^{-2}\ h^{-1}$	$m\ s^{-1}$		$kPa\ ^oC^{-1}$	kPa	$m\ s^{-1}$	K
							Eq. 51	Eq. 36	Eq. 37	Eq. 63	
7	1	1600	30.9	1.09	2.24	4.07	183	0.2548	4.467	3.74	304.1
7	1	1700	31.2	1.15	1.65	3.58	183	0.2586	4.544	3.30	304.3
7	1	1800	29.1	1.21	0.34	1.15	183	0.2329	4.029	1.06	302.3
7	1	1900	28.3	1.21	0.32	3.04	183	0.2237	3.846	2.80	301.5
7	1	2000	26.0	1.13	0.08	2.21	183	0.1989	3.361	2.03	299.2
7	1	2100	22.9	1.20	0.00	1.04	183	0.1692	2.792	0.96	296.1
7	1	2200	20.1	1.35	0.00	0.58	183	0.1457	2.353	0.53	293.2
7	1	2300	19.9	1.35	0.00	0.95	183	0.1441	2.324	0.87	293.0
7	1	2400	18.4	1.32	0.00	0.30	183	0.1328	2.116	0.28	291.5
7	2	100	16.5	1.26	0.00	0.50	184	0.1195	1.877	0.46	289.6
7	2	200	15.4	1.34	0.00	1.00	184	0.1124	1.750	0.92	288.5
7	2	300	15.5	1.31	0.00	0.68	184	0.1130	1.761	0.63	288.6
7	2	400	13.5	1.26	0.00	0.69	184	0.1009	1.547	0.63	286.7
7	2	500	13.2	1.24	0.03	0.29	184	0.0992	1.517	0.27	286.4
7	2	600	16.2	1.31	0.46	1.24	184	0.1175	1.842	1.15	289.4
7	2	700	20.0	1.36	1.09	1.28	184	0.1449	2.338	1.18	293.1
7	2	800	22.9	1.39	1.74	0.88	184	0.1692	2.792	0.81	296.1
7	2	900	26.4	1.25	2.34	0.72	184	0.2030	3.442	0.67	299.6
7	2	1000	28.2	1.17	2.84	1.52	184	0.2226	3.824	1.40	301.3
7	2	1100	29.8	1.03	3.25	1.97	184	0.2412	4.195	1.81	302.9
7	2	1200	30.9	1.02	3.21	2.07	184	0.2548	4.467	1.90	304.0
7	2	1300	31.8	0.98	3.34	2.76	184	0.2664	4.701	2.54	305.0
7	2	1400	32.5	0.87	2.96	2.90	184	0.2757	4.891	2.67	305.6
7	2	1500	32.9	0.86	2.25	3.10	184	0.2811	5.002	2.85	306.1
7	2	1600	32.4	0.93	1.35	2.77	184	0.2743	4.863	2.55	305.6
7	2	1700	30.2	1.14	0.88	3.41	184	0.2461	4.292	3.14	303.3
7	2	1800	30.6	1.27	0.79	2.78	184	0.2510	4.391	2.56	303.7
7	2	1900	28.3	1.27	0.27	2.95	184	0.2237	3.846	2.72	301.5
7	2	2000	25.9	1.17	0.03	3.27	184	0.1979	3.342	3.01	299.1
7	2	2100	23.9	1.20	0.00	2.86	184	0.1783	2.966	2.64	297.1

Table C-4. Continued.

Month	Day	Hour	d_r	declin.	sunset hr angle	solar time angle	ω_1	ω_2	R_a	R_{so}	R_s/R_{so}
				radians	radians	radians	radians	radians	MJ m^{-2} h^{-1}	MJ m^{-2} h^{-1}	
			Eq. 49	Eq. 48	Eq. 59	Eq. 54	Eq. 52	Eq. 53	Eq. 47	Eq. 46	
7	1	1600	0.9670	0.4017	1.941	0.904	0.773	1.035	3.26	2.54	0.881
7	1	1700	0.9670	0.4017	1.941	1.166	1.035	1.297	2.52	1.96	**0.842**
7	1	1800	0.9670	0.4017	1.941	1.428	1.297	1.558	1.68	1.31	0.260
7	1	1900	0.9670	0.4017	1.941	1.689	1.558	1.820	0.81	0.63	0.505
7	1	2000	0.9670	0.4017	1.941	1.951	1.820	1.941	0.09	0.07	1.000
7	1	2100	0.9670	0.4017	1.941	2.213	1.941	1.941	0.00	0.00	**0.842**
7	1	2200	0.9670	0.4017	1.941	2.475	1.941	1.941	0.00	0.00	**0.842**
7	1	2300	0.9670	0.4017	1.941	2.737	1.941	1.941	0.00	0.00	**0.842**
7	1	2400	0.9670	0.4017	1.941	2.998	1.941	1.941	0.00	0.00	**0.842**
7	2	100	0.9670	0.4003	1.939	-3.024	-1.939	-1.939	0.00	0.00	**0.842**
7	2	200	0.9670	0.4003	1.939	-2.762	-1.939	-1.939	0.00	0.00	**0.842**
7	2	300	0.9670	0.4003	1.939	-2.500	-1.939	-1.939	0.00	0.00	**0.842**
7	2	400	0.9670	0.4003	1.939	-2.238	-1.939	-1.939	0.00	0.00	**0.842**
7	2	500	0.9670	0.4003	1.939	-1.977	-1.939	-1.846	0.05	0.04	0.731
7	2	600	0.9670	0.4003	1.939	-1.715	-1.846	-1.584	0.72	0.56	0.815
7	2	700	0.9670	0.4003	1.939	-1.453	-1.584	-1.322	1.59	1.24	0.879
7	2	800	0.9670	0.4003	1.939	-1.191	-1.322	-1.060	2.43	1.90	0.918
7	2	900	0.9670	0.4003	1.939	-0.929	-1.060	-0.799	3.19	2.49	0.941
7	2	1000	0.9670	0.4003	1.939	-0.668	-0.799	-0.537	3.81	2.97	0.956
7	2	1100	0.9670	0.4003	1.939	-0.406	-0.537	-0.275	4.26	3.32	0.980
7	2	1200	0.9670	0.4003	1.939	-0.144	-0.275	-0.013	4.49	3.50	0.917
7	2	1300	0.9670	0.4003	1.939	0.118	-0.013	0.249	4.51	3.51	0.952
7	2	1400	0.9670	0.4003	1.939	0.380	0.249	0.510	4.29	3.34	0.885
7	2	1500	0.9670	0.4003	1.939	0.641	0.510	0.772	3.87	3.01	0.747
7	2	1600	0.9670	0.4003	1.939	0.903	0.772	1.034	3.26	2.54	0.531
7	2	1700	0.9670	0.4003	1.939	1.165	1.034	1.296	2.52	1.96	**0.449**
7	2	1800	0.9670	0.4003	1.939	1.427	1.296	1.558	1.68	1.31	0.604
7	2	1900	0.9670	0.4003	1.939	1.689	1.558	1.819	0.81	0.63	0.427
7	2	2000	0.9670	0.4003	1.939	1.950	1.819	1.939	0.09	0.07	0.444
7	2	2100	0.9670	0.4003	1.939	2.212	1.939	1.939	0.00	0.00	**0.449**

Table C-4. Continued.

Month	Day	Hour	R_{nl}	R_n	G_{os}	G_{rs}	ET_{os}	ET_{rs}
			$MJ\ m^{-2}\ h^{-1}$	$MJ\ m^{-2}\ h^{-1}$	$MJ\ m^{-2}\ h^{-1}$	$MJ\ m^{-2}\ h^{-1}$	$mm\ h^{-1}$	$mm\ h^{-1}$
			Eq. 45	Eq. 42	Eq. 61	Eq. 62	Eq. 1	Eq. 1
7	1	1600	0.284	1.440	0.144	0.058	0.61	0.82
7	1	1700	0.262	1.009	0.101	0.040	0.48	0.66
7	1	1800	0.000	0.262	0.026	0.010	0.14	0.20
7	1	1900	0.104	0.142	0.014	0.006	0.20	0.33
7	1	2000	0.313	-0.251	-0.126	-0.050	0.06	0.09
7	1	2100	0.230	-0.230	-0.115	-0.046	0.01	0.02
7	1	2200	0.211	-0.211	-0.105	-0.042	-0.01	-0.01
7	1	2300	0.210	-0.210	-0.105	-0.042	-0.00	0.00
7	1	2400	0.208	-0.208	-0.104	-0.042	-0.02	-0.03
7	2	100	0.207	-0.207	-0.103	-0.041	-0.01	-0.02
7	2	200	0.198	-0.198	-0.099	-0.040	-0.01	-0.01
7	2	300	0.201	-0.201	-0.100	-0.040	-0.01	-0.02
7	2	400	0.198	-0.198	-0.099	-0.040	-0.01	-0.02
7	2	500	0.161	-0.138	-0.069	-0.028	-0.01	-0.02
7	2	600	0.193	0.161	0.016	0.006	0.06	0.08
7	2	700	0.224	0.616	0.062	0.025	0.19	0.23
7	2	800	0.245	1.095	0.109	0.044	0.32	0.37
7	2	900	0.278	1.524	0.152	0.061	0.46	0.52
7	2	1000	0.299	1.888	0.189	0.076	0.60	0.70
7	2	1100	0.331	2.171	0.217	0.087	0.72	0.85
7	2	1200	0.308	2.164	0.216	0.087	0.73	0.88
7	2	1300	0.333	2.239	0.224	0.090	0.79	0.97
7	2	1400	0.317	1.962	0.196	0.078	0.74	0.93
7	2	1500	0.248	1.485	0.148	0.059	0.62	0.81
7	2	1600	0.134	0.905	0.091	0.036	0.44	0.60
7	2	1700	0.084	0.593	0.059	0.024	0.35	0.52
7	2	1800	0.147	0.461	0.046	0.018	0.29	0.42
7	2	1900	0.070	0.138	0.014	0.006	0.19	0.31
7	2	2000	0.077	-0.054	-0.027	-0.011	0.10	0.14
7	2	2100	0.076	-0.076	-0.038	-0.015	0.08	0.11

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APPENDIX D

WEATHER DATA INTEGRITY ASSESSMENT AND STATION SITING

TABLE OF CONTENTS

INTRODUCTION

Most automated weather stations (AWS) measure the primary variables affecting ET: solar radiation, air temperature, wind speed and humidity, and therefore provide more complete data for predicting ET than do manually-operated weather stations measuring only air temperature that were used in the past. An AWS measures temperature, humidity and wind speed within the dynamic boundary overlying the ground surface. Properties of this boundary layer characterize the energy balance at the surface and are used to predict the ET rate. As studies in southern Idaho by Burman et al. (1975) have shown, the lower level of the atmosphere changes when going from desert to a patchwork of irrigated and non-irrigated fields. Humidity, temperature and wind speed variables also change when entering an irrigated field surrounded by dry or poorly irrigated fields. It is important, when making calculations of ET_{sz}, that weather measurements are accurate and that the weather measurements reflect the environment that is defined by the reference surface.

WEATHER DATA INTEGRITY ASSESSMENT

The standardized ASCE reference ET equation (ET_{sz}) requires climatic data that reflect the environment of the area for which ET is estimated. The ET_{sz} estimate is dependent on the quality of the weather data. Weather data must be screened before use in any ET equation, including the standardized equation, to ensure that data are of good quality and are representative of well-watered conditions. This is especially important with electronically collected data, since human oversight and maintenance may be limited. When weather measurements are determined to be faulty, they can be adjusted or corrected using a justifiable and defensible procedure, or the user may elect to replace perceived faulty data with estimates. This Appendix reviews some general procedures that may prove useful when assessing the integrity and representativeness of weather data used for ET_{ref} calculation. Procedures for estimating data in situations where data are shown to be of poor quality or are missing are summarized in Appendix E.

WEATHER STATION SITING

The standardized ET_{ref} equation was developed using meteorological data collected over dense, fully transpiring canopies of grass or alfalfa meeting the definition of the reference surface condition. When possible, meteorological data used for estimation of ET_{ref} should be measured over vegetation that approximates the reference surface. Ideally, weather stations should be centrally located within a large, nearly level expanse of uniform vegetation that is supplied with sufficient water through precipitation and/or irrigation to support ET at or near maximum levels. In an ideal setting, the vegetation extends at least 100 m in all directions from the weather station. However, it is recognized that frequently such a weather station site is not available. The preferred vegetation for the site is clipped grass; alfalfa or a grass-legume pasture maintained at a height of less than 0.5 m may also serve as an effective vegetation for the site. Meteorological measurements made over other short, green, actively transpiring crops will approach reference measurements, provided canopy cover exceeds approximately 70%. A station may be located on the periphery of a field meeting reference conditions provided the station is located downwind of the field during daytime hours.

Weather stations should be isolated from nearby obstacles and obstructions that can impede airflow and/or shade the site. The recommended horizontal separation distance from such obstacles should exceed 10 times the height of the obstacle. Fences used to protect the station from unwanted intrusions by animals should be made of a porous fencing material (e.g., woven wire or chain link); fence height should not extend above the height of the anemometer.

Meteorological data sets obtained from true reference settings are generally difficult to come by. Often, weather stations are located over or adjacent to: 1) annual row crops that proceed through a distinct annual growth (and cover) cycle, or 2) range and/or pasture land that is subjected to seasonal deficits in soil moisture. Many urban weather stations fail both the underlying surface requirement and the recommended separation distance from obstacles. Failure of a weather station site to meet the definition of a reference condition described above does not preclude use of the data for estimation of ET_{ref}. However, data from such a station should be examined carefully before use, and may, in some cases, require adjustment to make the data more representative of reference conditions. New weather stations installed for the express purpose of estimating ET_{ref} should be located in sites that closely approximate the reference conditions outlined above.

DATA QUALITY CONTROL

Meteorological data sets acquired for the purposes of estimating ET_{ref} should be subjected to a number of quality control checks prior to use.

The first and most important quality control check involves contacting the source of the weather data to obtain information on:

1. Siting of the weather station providing the data.
2. Type and exposure of meteorological sensors employed at the station.
3. Procedures used to maintain and calibrate sensors.
4. Quality control procedures performed and/or data adjustments already performed on the data.
5. Availability of shorter interval data sets (e.g., hourly) to aid the overall QC process.
6. The station operator's experience and/or recommendations pertaining to use of the data for ET_{ref} assessment.

Recommendations pertaining to station siting were discussed in the opening section of this appendix. The types of sensors employed and their exposure (e.g., height of installation or type of radiation shelter) provide insight into expected error levels for specific measurements, and may identify measurements requiring some form of adjustment (e.g., height adjustment for wind speed).

Procedures used to maintain and calibrate meteorological sensors are of extreme importance. Maintenance can be divided into non-technical and technical categories. Non-technical maintenance activities include site maintenance (e.g., mowing, irrigation, and fence repair); cleaning sensors; and leveling radiation sensors and rain gauges. Technical maintenance involves repair and replacement of sensors and equipment, and represents an important component of the overall calibration process. Technical maintenance should be based on the concept of preventive maintenance; that is, replacement of sensors and equipment before their performance degrades. On-site calibration can be performed at regular intervals by comparing sensors with calibrated sensors that are taken to the site for inter-comparison purposes. The operator of the station should provide both the technical and non-technical maintenance protocols and schedule logs either on request basis or on a public web site.

It is always advisable to investigate the various quality control (QC) routines that have been employed on the data set by the operator of the station. Data from weather stations operated as part of a weather network are generally subjected to some form of QC assessment (e.g., Snyder et al., 1985; Stanhill,1992; Meek and Hatfield, 1994; Snyder et al., 1996; Shafer et al., 2000). Common QC assessments include comparing incoming parameters against relevant physical extremes (e.g., relative humidity >100%); using statistical techniques to identify extreme or anomalous values; and comparing data with neighboring stations. Some networks flag questionable data while other networks may replace questionable data with estimated values. The user should be aware, however, that QC procedures of some networks contain rather broad or coarse data range assessments, so that application of a QC procedure does not necessarily provide valid data.

Seeking the advice of the station operator regarding the fitness of a given meteorological data set for ET_{ref} assessment is always advisable. The operator should have considerable insight into whether station sites approach reference conditions, and if not, suggestions on how to correct or adjust either the raw meteorological data or the final ET_{ref} values. Subsequent sections of this document provide procedures for assessing the integrity of meteorological data sets used in the computation of ET_{ref}. Possible procedures for adjusting data to better reflect reference conditions are also included in these sections. While these procedures are applicable in many circumstances, they are by no means a universal solution to all potential problems with meteorological data. Users of the standardized ASCE Penman-Monteith reference ET equation are therefore encouraged to seek local input regarding the subject of assessment and correction of meteorological data for use in computation of ET_{ref}.

SOLAR RADIATION

Solar radiation data can be screened by plotting measurements against clear sky R_{so} envelopes for hourly or for daily periods. Generally, the best estimates of R_{so} should be used, which may require applying equations that include the influence of sun angle, turbidity, atmospheric thickness, and precipitable water, for example, Eq. D.1 – D.6 that are presented in the following section. For daily data sets, one can plot measured R_s and computed R_{so} against the day of the year (see Figure 1 in the text and Figure D-1 following). For hourly data, one can plot measured R_s and computed R_{so} against time of day, one day at a time, for perhaps five to ten selected "clear sky" days (Figure D-2).

After creating the R_s and R_{so} plots, the user can observe whether measured R_s "bumps" up against the clear sky envelope some of the time (i.e., on cloud-free days for daily data or during cloud-free hours for hourly data). R_s will fall below the clear sky curve on cloudy or hazy days and during times when the atmosphere is more turbid than under conditions of clean air.

Conditions of relatively clean air occur following cleansing rain or snow showers. If the "upper" values of measured R_s lie routinely above or below the computed R_{so} curve by more than 3 to 5%, then the user should scrutinize the maintenance and calibration of the R_s sensor. Improper calibration, leveling errors, the presence of contaminants on the sensor (e.g., dust, salt, or bird droppings), or electrical problems can cause R_s to deviate from R_{so} on clear days. "Abrupt" changes in the clear-day relationship between R_s and R_{so} generally indicate: 1) appearance or removal of contaminants from the sensor; 2) change in sensor level; 3) change in sensor calibration; 4) sensor replacement; or 5) problem with wiring or data-acquisition system. Pyranometer maintenance records, if available, may help explain changes in the relationship between R_s and R_{so} and aid decisions related to data adjustment. Occasionally, R_s during hourly periods may exceed R_{so} due to reflection of sunlight from nearby clouds.

Values of R_s that are consistently above or below R_{so} on clear days can be adjusted by dividing R_s by the average value of R_s/R_{so} on clear days. This adjustment should be used with appropriate caution as the procedure assumes: 1) computed values of R_{so} are correct; 2) clear days can be effectively identified (for example, during midseason at Greeley in Fig. D-1 following, there is a substantial period of no completely cloud-free days); and 3) the factor causing R_s to deviate from R_{so} is static over time. The R_{so} curves computed by Eq. D.1-D.6 following or by Eq. 19 and 20 in the main body of the report are not "perfect." They assume clean air and common relationships between the diffuse and beam components of short wave radiation along with typical spectral densities within the short wave band. Identification of clear days can be difficult in cloud prone areas, especially if hourly R_s data are not available to aid in the assessment process. Finally, many of the factors causing R_s to deviate from R_{so}, including leveling errors and contaminant accumulation (See Stanhill, 1992), may not be static over time.

DETAILED PROCEDURE FOR CLEAR-SKY SHORT WAVE RADIATION (RSO)

A simplified procedure for estimating R_{so} is shown in Eq. 20 and 46. A more complex and perhaps more accurate procedure involves considering the effects of sun angle and water vapor on absorption of short wave radiation and by separating the components of beam and diffuse radiation, so that:

$$R_{so} = (K_B + K_D) R_a \tag{D.1}$$

where:

- K_B = the clearness index for direct beam radiation [unitless]
- K_D = the transmissivity index for diffuse radiation [unitless]
- R_a = extraterrestrial radiation [MJ m^{-2} d^{-1}] or [MJ m^{-2} h^{-1}]

The following equation for K_B, extended from Majumdar et al., (1972) by Allen (1996) and Allen et al., (1998), is applied here with improved coefficients developed from the Task Committee evaluation of solar radiation data from many of the sites evaluated for ET_{os} and ET_{rs}:

$$K_B = 0.98 \exp\left[\frac{-0.00146\ P}{K_t \sin\phi} - 0.075\left(\frac{W}{\sin\phi}\right)^{0.4}\right] \tag{D.2}$$

where:

- K_t = turbidity coefficient [unitless], $0 < K_t \leq 1.0$ where $K_t = 1.0$ for clean air and $K_t \leq 0.5$ for extremely turbid, dusty or polluted air.
- P = atmospheric pressure at the site elevation, as calculated in Eq. 3 [kPa]
- ϕ = angle of the sun above the horizon [radians]
- W = precipitable water in the atmosphere [mm]

The value for K_t may vary with time of year and with cleansing of the atmosphere by precipitation. General values for K_t for a region can be determined using a pristine pyranometer that has a calibration traceable to the national or international solar standard. In general, for routine prediction of R_n and R_{so} envelopes, $K_t = 1.0$ is recommended. The value for ϕ can be calculated using Eq. D.5 (daily) and Eq. D.6 (hourly).

Precipitable water is predicted as:

$$W = 0.14\, e_a\, P + 2.1 \tag{D.3}$$

where:

W	= precipitable water in the atmosphere [mm]
e_a	= actual vapor pressure of the air (at approximately 2 m) [kPa]
P	= atmospheric pressure at the site elevation, as calculated in Eq. 3 [kPa]

The diffuse radiation index is estimated from K_B:

$$\begin{aligned} K_D &= 0.35 - 0.36\, K_B \quad \text{for } K_B \geq 0.15 \\ K_D &= 0.18 + 0.82\, K_B \quad \text{for } K_B < 0.15 \end{aligned} \tag{D.4}$$

For clear sky conditions, K_B is always > 0.15 for daily data and is nearly always > 0.15 for hourly periods, even those close to sunrise and sunset. Therefore, generally K_D for use in R_{so} can be computed as $K_D = 0.35 - 0.36\ K_B$, ignoring the second conditional of Eq. D.4.

For daily (24-hour) time periods, the average value of ϕ, weighted according to R_a, can be approximated from Allen (1996) as:

$$\sin \phi_{24} = \sin\left[0.85 + 0.3\,\varphi \sin\left(\frac{2\pi}{365} J - 1.39\right) - 0.42\,\varphi^2\right] \tag{D.5}$$

where:

ϕ_{24}	= average ϕ during the daylight period, weighted according to R_a [radians]
φ	= latitude [radians]
J	= day of the year [unitless]

The "sin ϕ_{24}" variable is to be used in place of sin ϕ in Eq. D.2 and represents the weighted average sun angle during daylight hours. The value for ϕ_{24} should be limited to ≥ 0.

For hourly or shorter periods the sun angle ϕ is calculated as:

$$\sin\phi = \sin\varphi\ \sin\delta + \cos\varphi\ \cos\delta\ \cos\omega \tag{D.6}$$

where:

φ = latitude [radians]

δ = solar declination ("delta")[radians]

ω = solar time angle at the midpoint of the hourly or shorter period [radians]

The user is cautioned that the R_{so} estimate is a theoretical approximate, and that there may be reasons why measured R_s on cloud-free days may deviate from the R_{so} curve. These reasons include air turbidity and haziness caused by dust and aerosols, nearly invisible clouds high overhead, and late afternoon clouding.

Daily measured R_s is plotted in Fig. D-1 for a full year at two CIMIS weather stations in the Imperial Valley of California. R_{so} has been calculated using two methods: Eq. 19 of the text and Eq. D.1 – D.5 of this appendix. Eq. 19 is a simplified procedure, where R_{so} is computed as a constant fraction of R_a and with the constant predicted from site elevation. In the case of Imperial Valley, which is at or below sea level, the constant is about 0.75 for both stations. Comparison of the R_{so} curves with measured R_s from Calipatria, California (Figure D-1a) indicates that the pyranometer was measuring about 12% low on clear-sky days through about day 200. At around day 200, the sensor was replaced, and readings for clear-sky days increased to about 5 to 10% higher than the R_{so} curves. R_s data from the nearby Seeley weather station (about 40 km to the SW) during the same year did not exhibit this shift in data. Therefore, for the Calipatria data for year 1999, the data user is encouraged to contact the data collector and provider for information concerning pyranometer calibration and the user may wish to pursue options for applying some sort of correction to the data.

The more theoretical R_{so} curve from Eq. D.1-D.5 exceeds the more simple R_{so} curve from Eq. 19 by a few percent during mid summer at Seeley and Calipatria, and fits the measured R_s on clear-sky days more closely at Seeley during mid-summer (Fig. D-1b). R_s measured at Seeley on some of the clear-sky days during spring and fall routinely lie a few percent above the R_{so} curves. This indicates that the pyranometer calibration may be a few percent high or that the theoretical R_{so} curve is a few percent low for this location. The data user may wish to investigate the pyranometer calibration at this site and perhaps conduct an independent assessment of clear-sky R_s using an accurate pyranometer having calibration traceable to the National Standard housed with the Solar Radiation Research Laboratory (http://srrl.nrel.gov/bms/) located in the National Renewable Energy Laborabory (NREL) at Golden, CO (http://www.NREL.GOV/). However, agreement between measured R_s and R_{so} at Seeley appears to be good enough for application in the standardized equations without any adjustment or correction.

A few unreasonably low values of R_s are shown in Figure D-1a and b, where measured R_s was reported as less than 0.1 R_a. Generally, the lower bound for 24-hour R_s is about 0.2 R_a. These values occurred due to sensor or datalogger malfunction or during site maintenance. Missing or faulty data should be substituted by data from surrounding stations as described in Appendix E.

A third set of daily measured R_s is plotted in Fig. D-2 for a full year at Greeley, Colorado. Both R_{so} curves (Eq. 19 and Eq. D.1-D.5) follow the upper bound of measured R_s quite well for the Greeley data. Agreement is good throughout the year, except for the late spring – early summer period, when there were no days having completely clear conditions. This was confirmed by scanning records of hourly R_s, which indicated that essentially all days at Greeley during the late spring – early summer period were subject to afternoon clouding during 2000. This example is included to caution the data user that sometimes deviation of measured R_s from the R_{so} curve for extended periods may be real and valid. The good agreement between measured R_s for cloud-free days and the computed R_{so} curve for winter, early spring and fall periods supports using the solar radiation data from this weather station for the year shown. The R_{so} curve computed using Eq. D.1 – D.5 drops a small amount below the R_{so} curve from Eq. 19 during summer (day 180 on) due to increased absorption by increased humidity levels of the atmosphere during this period.

Figure D-3 illustrates a comparison of hourly measured solar radiation with R_{so} computed using the simple method of Eq. 46 of the text and using the more complicated method described above, Eq. D.1-D.6. The data are from the agricultural weather station near Greeley, Colorado, and data from only two days in August are shown. August 5 had a brief period of cloudiness at around 0800 and then some cloudiness during the afternoon. August 6 was essentially a cloud-free day. The R_s data from August 6 compare well with both R_{so} methods throughout the day. The measured data plot slightly higher than the simpler R_{so} estimate from Eq. 46 during the morning hours and slightly below the R_{so} estimate during the afternoon. This may hint of a slight error in the level of the instrument or in the time setting for the data-logger clock. In general, the solar radiation data appear to be of excellent quality and calibration.

As mentioned in the previous paragraph, plotting hourly measured R_s against the theoretical R_{so} can be helpful in detecting errors or shifts in the reported times associated with the data set (i.e., errors in datalogger time clocks). Plotting of data can also provide an indication of a lack of level of the instrument. Shifts in time and lack of instrument level can both cause measured R_s to plot out of phase with the theoretical R_{so} curve.

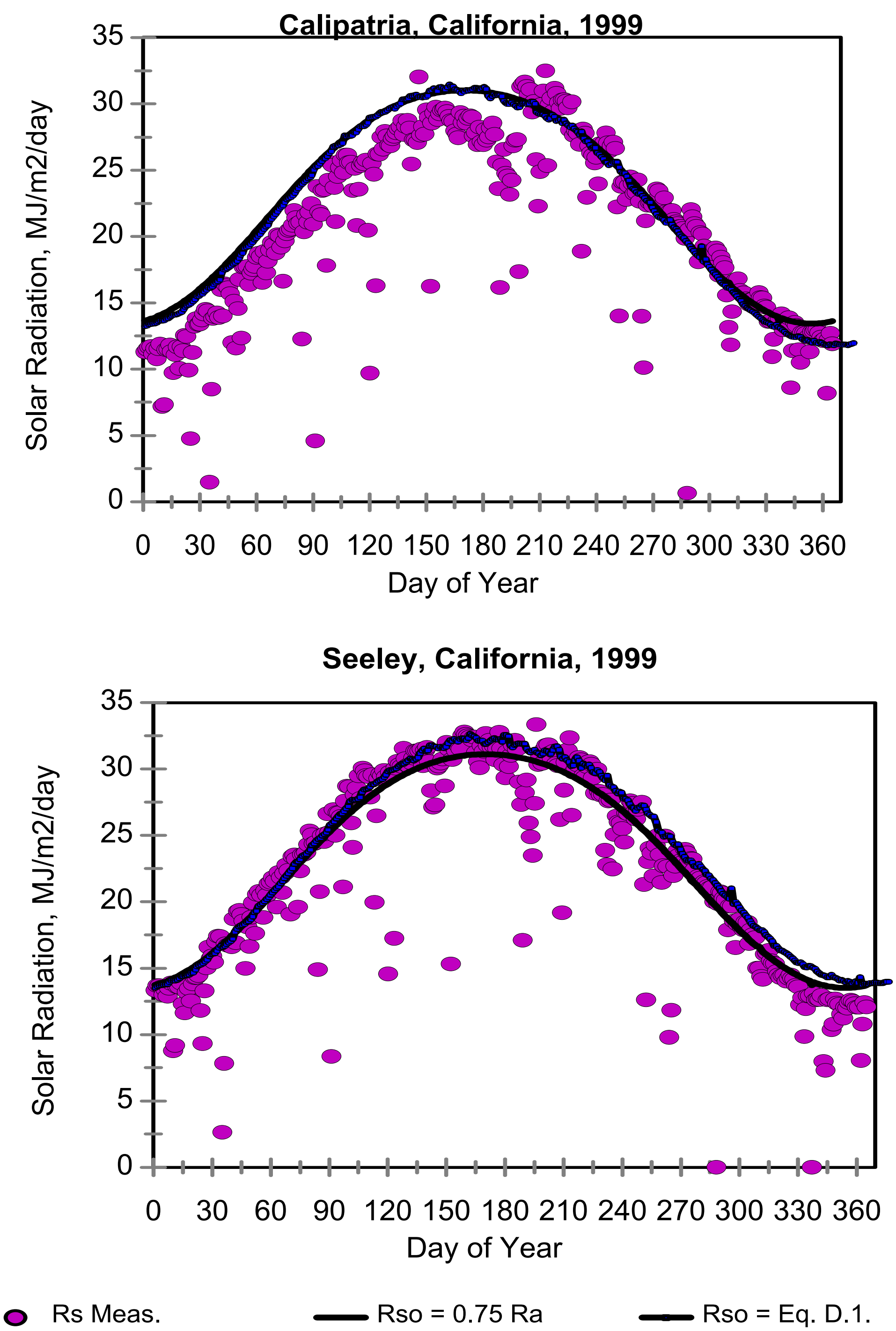


Figure D-1. Daily Measured R_s and Calculated R_{so} using Eq. 19 of the text and using Eq. D.1 – D.5 for Calipatria (top) and Seeley (bottom), California CIMIS stations in the Imperial Valley during 1999.

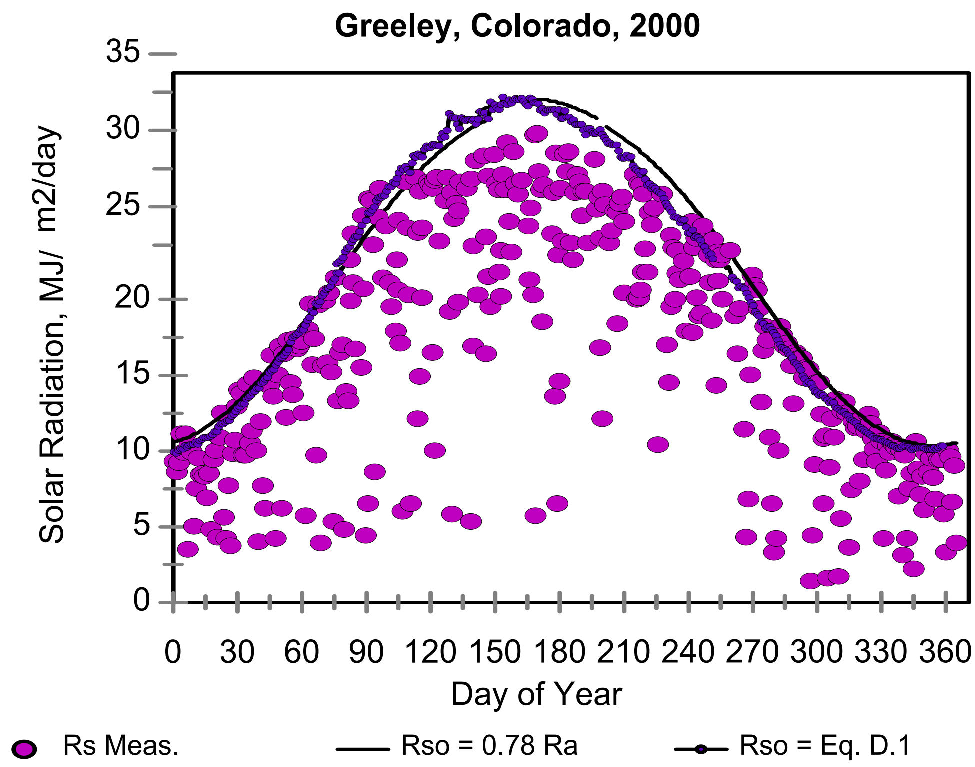


Figure D-2. Daily Measured Rs and Calculated Rso using Eq. 19 of the text and using Eq. D.1 – D.5 for Greely, Colorado during 2000.

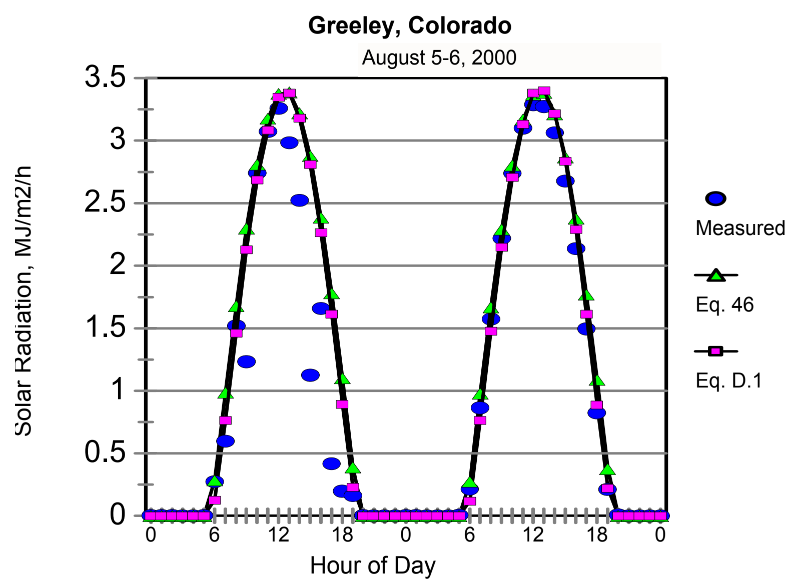


Figure D-3. Hourly measured solar radiation and clear-sky envelopes for two days in August, 2000 near Greeley, Colorado.

Net Radiation

Where net radiation data are measured, values can be compared with R_n estimated from solar radiation as a means of integrity assessment. One should not expect measured R_n to exactly agree with estimated R_n. However, significant variation between the two should be cause for a closer investigation of the measured data. Some net radiometers do not accurately measure the long wave component of net radiation. In addition, the R_n measurement should be made over a well-watered surface of clipped grass or full-cover alfalfa so that albedo is similar to that defined for ET_{sz}. A shift in the relationship between measured and estimated R_n may reflect a change in the quality or condition of the surface at the measurement site. Other measurement related factors that can shift the relationship between measured and estimated R_n include scratched or dirty radiometer domes, an off-level sensor, or condensation of moisture inside domes of the R_n sensor.

Figure D-4 shows hourly measured net radiation and net radiation calculated using the standardized net radiation procedure for one day at Kimberly, Idaho. Agreement between measured and calculated R_n is judged to be very good, even during nighttime periods.

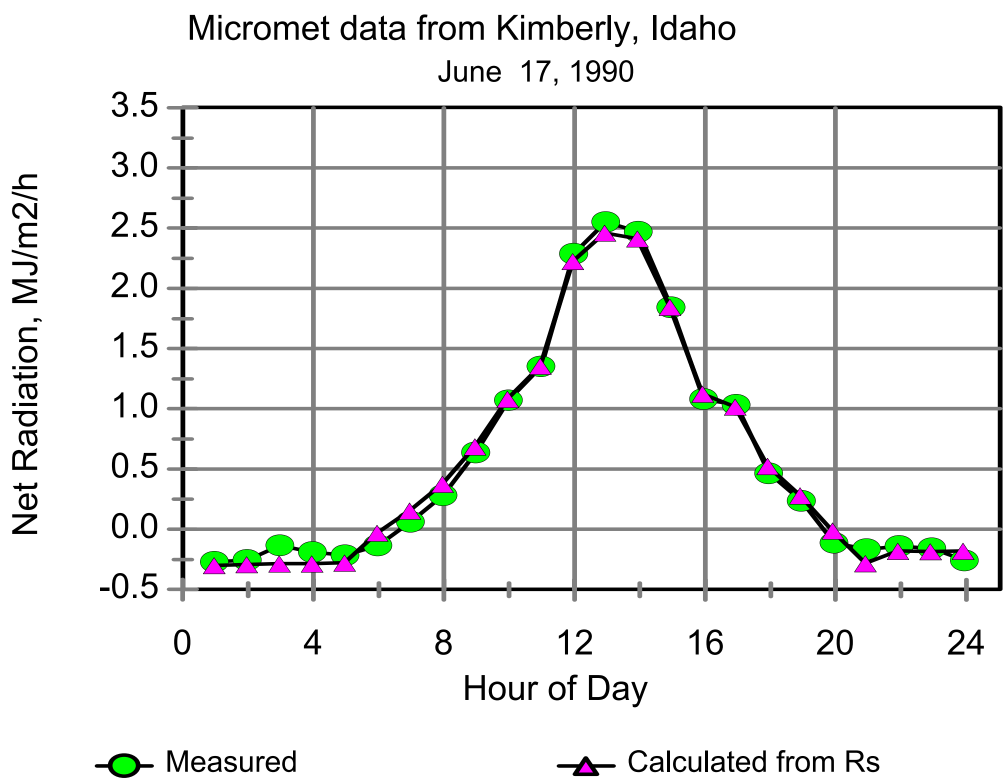


Figure D-4. Measured and calculated hourly net radiation for one day at Kimberly, Idaho over clipped grass (R_n was calculated using Eq. 42-60). Data courtesy of Dr. J.L. Wright, USDA-ARS, Kimberly.

HUMIDITY AND AIR TEMPERATURE

RELATIVE HUMIDITY

Humidity and temperature data should be screened to identify questionable or erroneous data prior to use. A portion of the screening process involves the user having a sense of reasonable or unreasonable values. For example, relative humidity (RH) values of less than 5 to 10% in arid regions and 30% in subhumid regions are uncommon and may indicate problems with the sensor. Similarly, RH values in excess of 100% do not occur in the natural environment and may indicate that the sensor is out of calibration. The accuracy of most electronic RH sensors is generally within +/- 5% RH; thus, recorded RH values in excess of 105% provide good evidence that the sensor is out of calibration.

All RH values in excess of 100% should be set equal to 100% prior to use in the ET_{sz} computation process. Use of this simple adjustment procedure does not alleviate sensor calibration errors in recorded RH data that lie below 100%. One should use RH data sets containing values in excess of 100% with caution. Furthermore, RH values in excess of 100%, if not accompanied by a QC flag, may indicate that the data set has not been subjected to rigorous QC.

If hourly data are available, it is advisable to examine the diurnal variation of RH on selected days to ensure that RH approaches maximum and minimum levels during the coolest and warmest portions of the day, respectively. Hourly time series of RH should also be examined for the presence of spikes and spurious values of RH that may indicate sensor malfunction. Finally, one should check RH data on several days with heavy and/or sustained precipitation events or when dew or fog events are known to have occurred. Relative humidity should approach 90-100% during a sustained precipitation, fog, or dew event, and should approach 100% in the evening hours following a heavy rain event.

DEW-POINT TEMPERATURE

Dew-point temperature (T_{dew}), as calculated from RH, may be reported in lieu of RH for some data sets. Any errors in RH will affect e_a (since e_a = RH*e_s(T)/100), and thus the computed T_{dew}. Values for T_{dew} should be compared to minimum temperatures (T_{min}). In humid regions, T_{min} will approach T_{dew} on many days. Exceptions occur on days that feature a change in air mass (e.g., frontal passage), or high winds and/or cloudiness at night. T_{dew} may approach T_{min} in arid and semiarid environments if nighttime winds are light and measurements are made over a surface meeting the reference definition. It is not uncommon in arid and semiarid regions to have T_{dew} 2 to 5 ^oC lower than T_{min} under reference conditions (see discussion below) and well below T_{min} if the measurement site is subjected to local aridity. If T_{dew} regularly exceeds T_{min}, then the T_{dew} sensor may be out of calibration. Such data should be examined closely and possibly adjusted prior to use (see Appendix E).

When it is not observed, T_{dew} can be computed from e_a by[1]

$$T_{dew} = \frac{116.91 + 237.3\ \ln(e_a)}{16.78 - \ln(e_a)} \tag{D.7a}$$

where:

T_{dew} = dew point temperature [^oC]
e_a = actual vapor pressure [kPa]

For the case of measurements with an Assmann-style psychrometer, T_{dew} can be calculated from

$$T_{dew} = \left(112 + 0.9\,T_{wet}\right)\left(\frac{e_a}{e^o\left(T_{wet}\right)}\right)^{1/8} - 112 + 0.1\,T_{wet} \qquad \text{D.7b)}$$

[1] Reference: Bosen (1958); Jensen *et al.* (1990)

where:

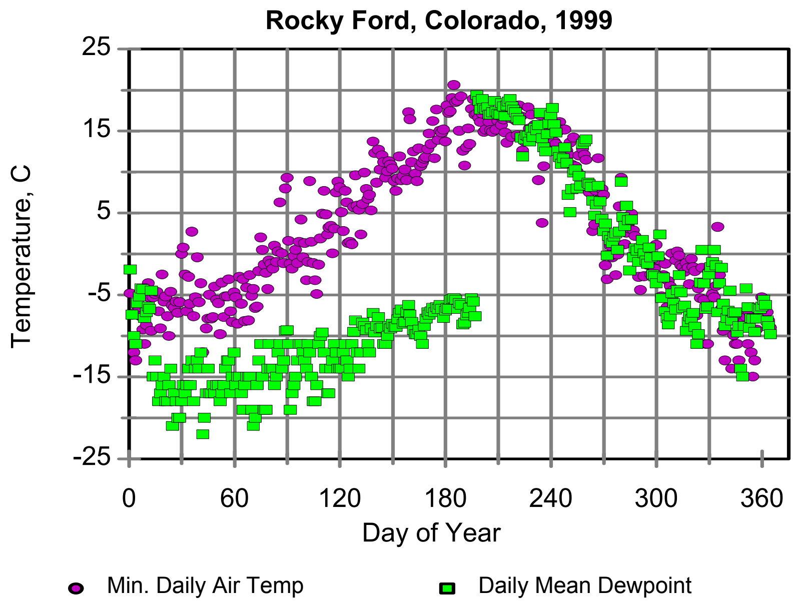
T_{wet}	= wet bulb temperature [°C]
e_a	= actual vapor pressure [kPa]

Figure D-5 illustrates the use of T_{min} and T_{dew} comparisons and use of plots of daily RH_{max} and RH_{min} to detect errors in hygrometer data from an AWS in SE Colorado. The large shifts in mean daily T_{dew} relative to T_{min} at days 15 and 200 are obvious. Following day 200, the data began to follow an expected pattern and relationship with T_{min}, with T_{dew} in close proximity to T_{min}. Similar obvious shifts in RH_{max} and RH_{min} are apparent also (bottom plot of Figure D-5). During the last half of the year, values for RH_{max} exceeded 100% by a small amount. However, these errors in RH are considered to be small relative to those occurring during the first part of the year, where the T_{dew} data required substantial correction.

Figure D-6 shows T_{dew} and T_{min} for the same station and year as in Figure D-5, but following correction of T_{dew} using the following relationship:

$$T_{dew} = T_{min} - (T_{min} - T_{dew})_{station\ 2} \qquad \text{(D.8)}$$

where $(T_{min} - T_{dew})_{station\ 2}$ is the measured difference between T_{min} and T_{dew} at an AWS about 50 km distant on the same day. The use of $(T_{min} - T_{dew})_{station\ 2}$ preserved the difference observed between T_{min} and T_{dew} at the adjacent station, and therefore the relative dryness of the air mass, but adjusted for differences in minimum daily air temperature between the two sites. The resulting plots of T_{min} and T_{dew} in Fig. D-6 illustrate good continuity of the relationship between T_{min} and T_{dew} for the corrected period (days 15 – 200) and original observations following day 200. The occasionally low values for T_{dew} during days 15 – 200 were present in the data set for station 2.



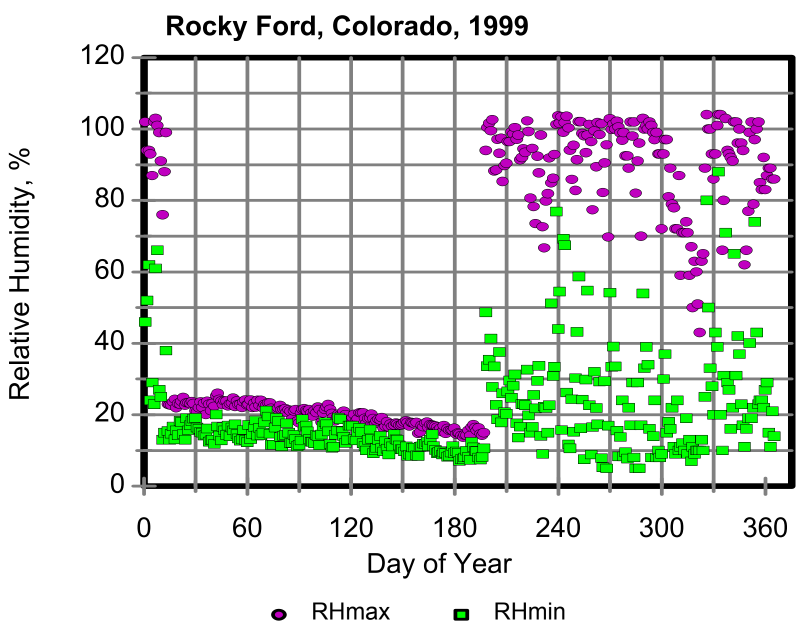


Figure D-5. Measured daily minimum air temperature and mean daily dewpoint temperature (top) and daily maximum and minimum relative humidity (bottom) recorded for Rocky Ford, Colorado during 1999.

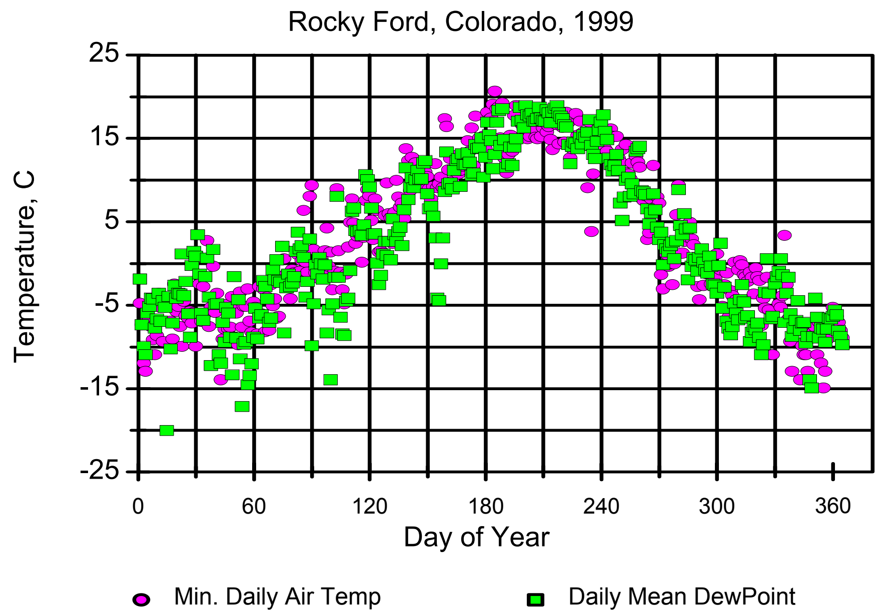


Figure D-6. Measured daily minimum air temperature and mean daily dewpoint temperature for Rocky Ford, Colorado during 1999, where T_{dew} for days 15 to 200 was replaced by estimates using Eq. D-8.

Plots of hourly or shorter period T_{dew} data may assist in identifying problems in T_{dew} data. Dew point and vapor pressure are relatively conservative parameters and often exhibit little change over a day, especially in humid regions. Often, T_{dew} will increase somewhat during midmorning due to evaporation of water and increased capacity for the air to contain vapor (see for example, Fig. D-7 and D-10). Dew point will then stabilize or decline slightly during the mid-day hours as the vapor near the surface gets mixed into a progressively deeper boundary layer. Hourly variation in T_{dew} is greater in semiarid and arid settings, especially in areas prone to strong regional advection. However, large changes in T_{dew} during the day, except under circumstances such as a change in air mass (e.g., frontal activity or sea/land breeze) or large change in wind direction, could signal an error or bias in the T_{dew} measurement. It is common in the western Great Plains of the U.S. to have distinct drylines, which extend either N-S or NE-SW. A dryline, which is an atmospheric transition zone having large gradients in vapor content, may move during the day, with larger T_{dew} values in front of the dryline (typically the eastern side) and with substantially smaller T_{dew} values behind the dryline (typically the western side). Allen (1996) provides illustrative plots of hourly T_{dew} data and expected trends over time.

AIR TEMPERATURE

In general, air temperature is the simplest and most consistent weather parameter to measure and the parameter most likely to be of highest quality, provided it is measured in a reference-type of environment. Air temperature extremes in a data set should be compared to historical record extremes, if such data are available for locations near the site. Temperatures that routinely exceed the record extremes for a location indicate a problem with either the sensor or with the radiation shield used to house the sensor. Sensors mounted in non-aspirated radiation shields may produce erroneously high temperatures on days having light winds due to solar heating of the shield (Gill, 1983). Consistently hot temperatures from a sensor mounted in an aspirated radiation shield may indicate problems with the ventilation system. An effective check for spuriously high or low temperature extremes is to compare the average of the daily extremes (T_{max} and T_{min}) with the mean daily temperature as averaged by the data logger for the day. Many automated weather stations now generate a recorded average temperature for the 24-hr period that can be used in this comparison. Differences between the average computed from the temperature extremes and the recorded 24-hr average for the day will generally run within 2 ^{o}C. Temperature data should be subjected to closer scrutiny on days when the two averages deviate by more than 3 ^{o}C. Precipitation events, air mass changes, and unusual wind conditions can cause deviations in excess of 3 ^{o}C.

When hourly temperature data are available, it is advisable to plot the diel (hourly) temperature trend on selected dates to ensure that temperatures attain maximum and minimum values at the appropriate time of the day. For most locations, minimum temperatures occur shortly before sunrise, and maximum temperatures occur in mid-afternoon (1400-1600). It is also important to examine diel temperature profiles for spikes or spurious temperatures that could indicate a malfunctioning sensor.

Figure D-7 illustrates hourly measurements of both air temperature and dewpoint temperature during a single day over a grassed surface near Kimberly, Idaho. Measurements were made using electronic instrumentation and dual measurements using independent systems from different manufacturers were used for purposes of data back-up and redundancy. The two air temperature sensors (TC = thermocouple and RMY = RM Young chilled mirror system) tracked

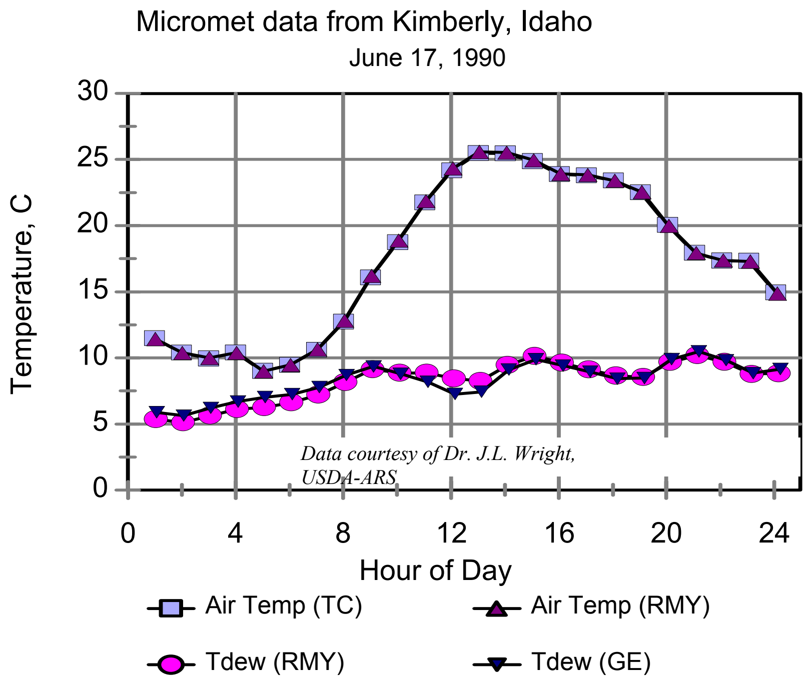


Figure D-7. Hourly air temperature and measured dewpoint temperature from dual sensor systems near Kimberly, Idaho, July 17, 1990. Data courtesy of Dr. J.L. Wright, USDA-ARS, Kimberly, Idaho.

each other consistently throughout the 24-hour period. The two dewpoint temperature measurements (RMY = RM Young chilled mirror system and GE = General Eastern chilled mirror system) tracked each other closely throughout the period. The closeness of the data measurements from two independent, colocated systems is useful in confirming the accuracy of the data and the proper functioning of both instrument systems. In addition to validation of the air temperature and measured dewpoint temperatures, the data in Fig. D-7 show that minimum daily air temperature, recorded as 9.0 ^{o}C at about 5 am was about 3 ^{o}C above the dewpoint temperature (6.2 ^{o}C) measured at the same time. This difference is in line with that expected from a well-watered reference environment as discussed in the following section.

IMPACT OF NON-REFERENCE WEATHER STATION SITE ON TEMPERATURE AND HUMIDITY

Temperature and humidity data that pass QC checks still may not be acceptable for use in estimating ET_{ref}. The moisture status of the underlying surface impacts both temperature and humidity, and data collected away from well-watered vegetation (e.g., at airports or over dry, paved, and fallow surfaces) can be negatively influenced by the local aridity, especially in arid and semiarid climates. Data from dry or urban settings may cause overestimation of ET_{os} or ET_{rs} due to air temperature measurements that are too high and humidity measurements that are too low, relative to the reference condition. Under these "arid" measurement conditions, the ET_{os} and ET_{rs} calculations are reflective of the "ambient" and "non-reference" environment (i.e., where average net rainfall plus irrigation is substantially less than ET_o or ET_r). However, they may over-predict ET_{os} and ET_{rs} for a well-watered setting. An extreme example of the impact of local aridity on ET_{os} was observed in a study near Parker, AZ, (Brown, 2001) where weather stations were installed in adjacent 15-ha fields containing irrigated alfalfa and fallow ground. Data from each station were used to estimate ET_{os} using the ET_{sz} equation. Monthly totals of ET_{os} computed using the fallow station data set exceeded similar ET_{os} totals computed using the alfalfa data set by 18-26% during months of June through September (Figure D-8).

Often, an assessment of RH, T_{dew}, and e_a can indicate whether meteorological data were collected in a reference environment. Under reference conditions, RH_{max} generally exceeds 90% and may approach 100% during early morning hours, provided skies are clear and winds are light (Allen, 1996). Minimum temperatures under these circumstances will approach T_{dew}. One can therefore plot and then visually scan plots of RH_{max} or average (or early morning) T_{dew} and T_{min} as a function of time to determine if humidity data reflect the reference condition.

For example, Figure D-9a shows daily T_{min} and T_{dew} for the year 2000 for the agricultural weather station near Greeley, Colorado. Mean daily T_{dew} (calculated from daily average measured vapor pressure) follows T_{min} relatively closely throughout the year, and is generally within a few degrees Celsius of T_{min}. Figure D-9b shows daily maximum and minimum RH for 2000 at Greeley. The RH_{max} tends toward 90 to 100% during many days. Minimum relative humidity (RH_{min}) runs a little below the expected 25 to 35% range for a reference setting in a semi-arid environment (Allen, Brockway and Wright, 1983; Allen 1996, Allen et al., 1996). Overall, the humidity and air temperature data at Greeley during 2000 are judged to be relatively accurate and reflective of a "reference" condition.

If RH_{max} is consistently below 80% for a substantial portion of the growing season record, or if T_{dew} deviates more than 3–4 ^{o}C less than T_{min} for a substantial portion of the growing season record, then the humidity data should be subjected to further scrutiny. Among the factors to investigate are: 1) type, maintenance, and calibration of the RH or T_{dew} equipment; 2) presence of cloudiness or wind flow at night, which tend to reduce RH_{max}; and 3) that the site may not be representative of well-watered conditions. Historically, humidity has been among the most difficult routine meteorological parameters to accurately measure. The quality of RH measurements has improved in recent years due to improvements in sensor technology. Prior to 1990, many agricultural weather networks used polystyrene humidity sensors. These sensors degraded rather quickly in agricultural environments (Howell at al., 1984; Brown et al., 1987), and RH measurement errors in excess of 5% RH were common under the best of circumstances (Brown et al., 1987). Most networks now utilize thin-film capacitance RH sensors that are stable for periods in excess of one year and accurate to within 2-3% RH if properly maintained and calibrated (Tanner, 2001).

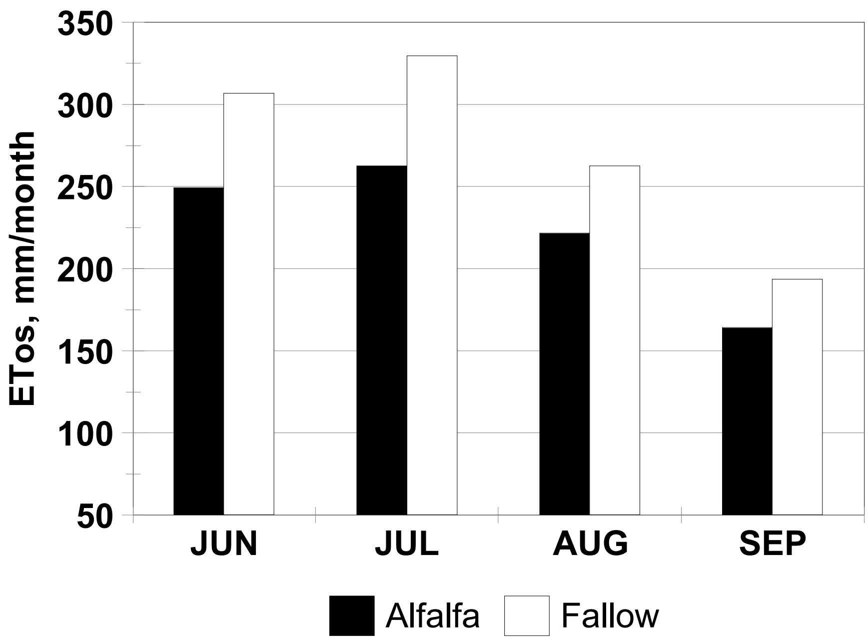
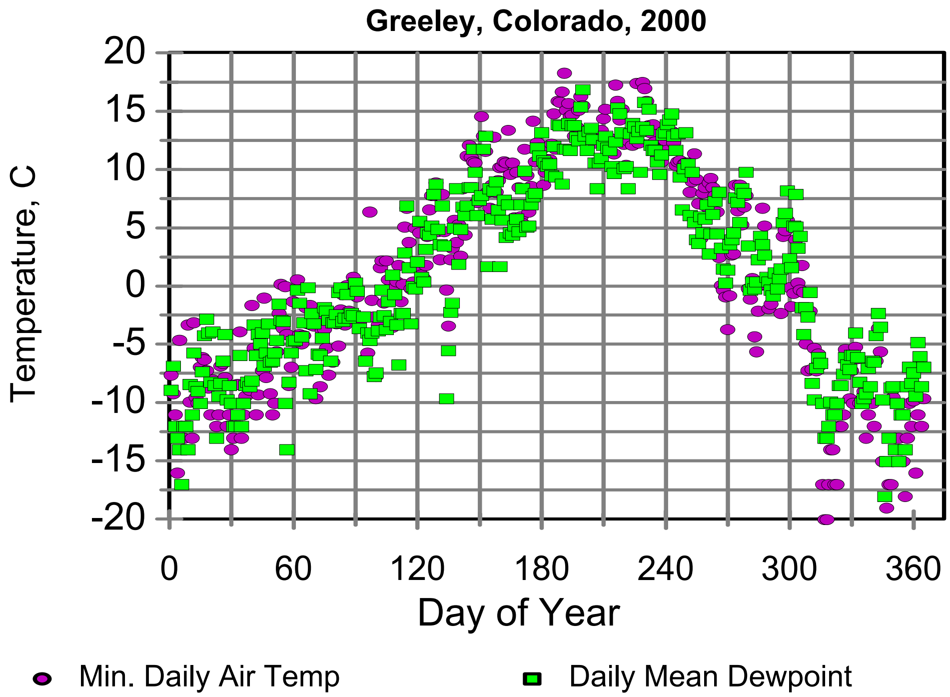


Figure D-8. ET_{os} by month for the summer of 2000 at Parker, AZ computed using meteorological data collected under reference (alfalfa) and non-reference (fallow) conditions.



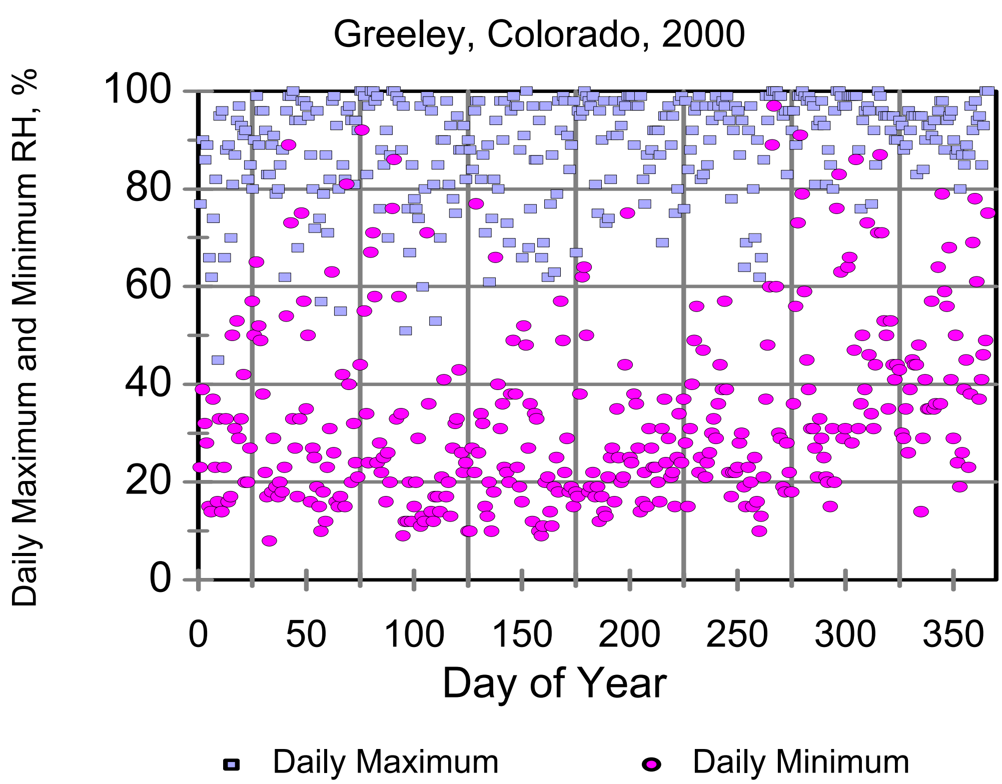


Figure D-9. a) Daily minimum air temperature and daily mean dew point temperature vs. day of the year and b) daily maximum and daily minimum relative humidity vs. day of the year for Greeley, Colorado, during 2000.

Psychrometers, dewcells, and chilled mirror hygrometers can provide high quality humidity data, as shown in Fig. D-7, provided the sensors receive proper maintenance and are operated within the design range. These sensors are not in widespread use for general climate monitoring in remote, automated weather stations due to cost and maintenance factors. The RH and T_{dew} assessments described here may not be effective at identifying reference environments in regions prone to cloudiness and large nighttime winds. Cloudiness lowers net loss of long-wave radiation at night, which inhibits cooling and may prevent T_{min} from approaching T_{dew} at night. High nighttime wind speed enhances the transfer of sensible heat and dry air to the surface, slowing the rate of cooling and preventing full humidification of the atmospheric boundary layer above well-watered surfaces.

Often, dewpoint temperature is consistent between locations having similar surface conditions. For example, Fig. D-10 shows hourly dewpoint temperatures for four Agrimet weather stations (data courtesy of U.S. Bureau of Reclamation) in southern Idaho that are up to 140 km apart. However, the recorded dewpoint temperatures and their trend during the day are largely consistent. These four stations (Rexburg, Monteview, Ashton, and Aberdeen) are situated in irrigated agricultural settings. Dewpoint data taken from a desert weather station (Flint Creek, Idaho, lat. 42.08^o, long. 112.18^o) is substantially lower, averaging 11 ^oC below the average for the four Agrimet stations. Air temperature at Flint Creek averaged 4 ^oC above the Agrimet stations over the 24-hour period. The impact of aridity on both dewpoint temperature and air temperature at Flint Creek is obvious and is manifested in erroneously high ET_{ref} estimates if applied without correction.

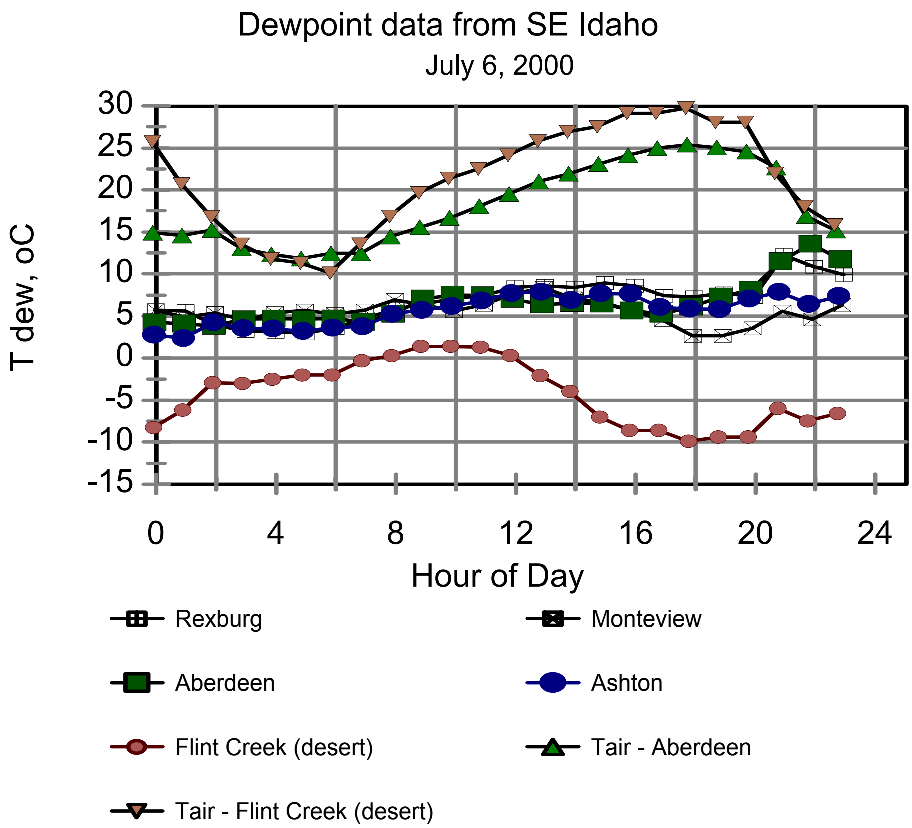


Figure D-10. Hourly dewpoint from four irrigated regions of southeast Idaho and from a desert weather station (Flint Creek) on July 6, 2000. Also shown are air temperatures at Aberdeen and Flint Creek.

Adjustment of temperature and/or humidity data may be warranted when the weather station site is known to be in an arid setting, or when assessment of humidity data indicates aridity is impacting the site. Allen and Pruitt (1986) and Allen (1996) suggested simple, empirical adjustment procedures to make "non-reference" weather data more representative of well-watered reference conditions. Allen and Gichuki (1989) and Ley et al. (1996) suggested more sophisticated approaches. Annex 6 of FAO-56 includes procedures for evaluating and adjusting humidity and air temperature data for aridity of the weather station site.

ESTIMATING T_{DEW} USING T_{MIN}

Often, substituting $T_{dew} = T_{min} - K_o$ for measured T_{dew}, (i.e., using Eq. E.1 of Appendix E), can improve estimates of daily ET_{os} and ET_{rs} when data are from a non-reference, arid setting. In arid and semiarid regions, it is best to check with the source of weather data to determine if K_o values have been developed for the area. For example, in Arizona the value of K_o was found to vary from 2-5 ^oC over the course of a year. When local information on K_o is not available, a K_o in the range of 2-4 ^oC is recommended for semiarid and arid regions (Allen, 1996). In humid regions where T_{dew} approaches T_{min} on most nights, K_o is set equal to 0 ^oC.

Using minimum air temperature measurements from a non-reference setting to predict dew point temperature (via Eq. E. 1) will tend to overestimate the true T_{dew} and e_a that would occur under reference conditions, because measured T_{min} will be higher in the dry setting than in a reference setting. However, because e_s in the Penman-Monteith equation would be predicted using the same T_{min} values used to predict T_{dew}, e_s and e_a will be nearly equally "inflated." Therefore, the e_s - e_a difference in the standardized ET_{ref} equation in general agrees with the e_s - e_a difference that would be anticipated for the reference condition. As a consequence, a more accurate estimate for ET_{os} or ET_{rs} may result than if the actual measurement of T_{dew} from the arid setting had been used. When humidity is adjusted using $T_{dew} = T_{min} - K_o$, no further adjustment is needed to the air temperature data set to account for effects of aridity of the weather measurement site.

Use of the $T_{dew} = T_{min} - K_o$ adjustment also produces a slight upward bias in computed net radiation (R_n). As indicated above, the adjustment inflates e_a above levels expected for reference conditions. This error in e_a causes atmospheric long-wave radiation to be overestimated, which in turn causes a 1-3% overestimation in R_n.

DISCUSSION

The impacts of aridity upon data collected at an automated weather station received considerable consideration and deliberation by Task Committee members. The availability of experimental data that were collected specifically for evaluating impacts of aridity on weather data was a constraint. Brown (2001) data, however, demonstrate that significant error in predicted ET_{sz} can occur under very arid conditions. The magnitude of expected error under more moderate climates and the typical patchwork of irrigated and non-irrigated fields should be less.

Important questions concern the magnitude of errors in ET_{sz} associated with non-ideal sites (i.e., those lacking substantial transpiring vegetation). How well does a station represent the average expected ET over an adjacent irrigated green crop? The TC has attempted to provide guidelines for the user of AWS data to adjust for, or evaluate, the probable error associated with data from an AWS based on the data it provides. Making a simple check by substituting dew point based on minimum air temperature minus a constant will indicate if there is a potential problem. Analysis of T_{min}-T_{dew} relationship from nearby stations can provide valuable insight as to whether data are representative of the reference condition.

WIND SPEED

Accuracy of wind speed measurements is difficult to assess unless duplicate instruments are used. Nevertheless, one should visually inspect wind records for the presence of consistently low wind speed values that may indicate a malfunctioning or failed anemometer or the presence of ice if air temperatures are near or below 0 °C. Consistent and low wind speeds can indicate dirty anemometer bearings that will increase the anemometer wind speed threshold and might eventually seize and stop the anemometer altogether. Wind speeds from failed anemometers will usually appear as small, constant values (less than 0.5 m s^{-1} or the wind speed threshold for a new anemometer) if the anemometer is monitored with a data logger.

Maximum wind speed data, if available, can assist in the assessment of low wind speed data. With a failed anemometer, recorded maximum and mean wind speeds will often be equal. Gust factor (ratio of maximum wind speed (m s^{-1}) to mean daily wind speed (m s^{-1})) is a useful index for checking anemometer measurements. If plotting the gust factor over time indicates a period of excessively large values, then the anemometer may be malfunctioning. For example, Figure D-11a shows data from an anemometer that was malfunctioning between Day 109 to 117 due to bearing contamination. Gust factors often increase as contamination increases the friction in the bearings. The increasing bearing friction has a greater impact on cup rotation at small as opposed to large wind speeds and thus causes an increase in the ratio of maximum to mean wind speed The gust factor will exhibit a sudden drop to 1.0 when the anemometer seizes or fails electronically.

Any appreciable period having daily mean wind speeds of less than 1.0 m s^{-1} should be viewed with caution. Aside from exceptionally calm periods or anemometer problems, other possible reasons for daily wind speeds of less than 1.0 m s^{-1} would include excessive vegetation height at the station or the presence of blocking structures in the nearby landscape (e.g., solid fences or buildings).

Data from a nearby station may also assist in the assessment of wind speeds at a particular site. In some cases, winds at two nearby locations are related which indicates the ratio of the wind speeds at the two locations will remain nearly constant. By plotting this ratio over time, one can identify a problem anemometer. A sudden and consistent change in the ratio often indicates a failed anemometer; a gradual change in ratio may indicate growing contamination in the bearings (Figure D-11b).

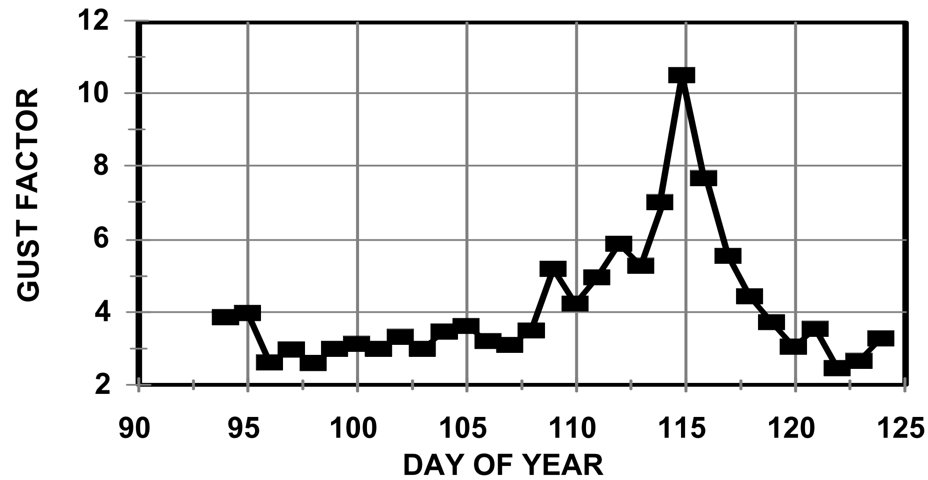


Figure D-11.a) Plot showing the increase in the gust factor at Eloy, AZ during a period when an anemometer was failing due to bearing contamination.

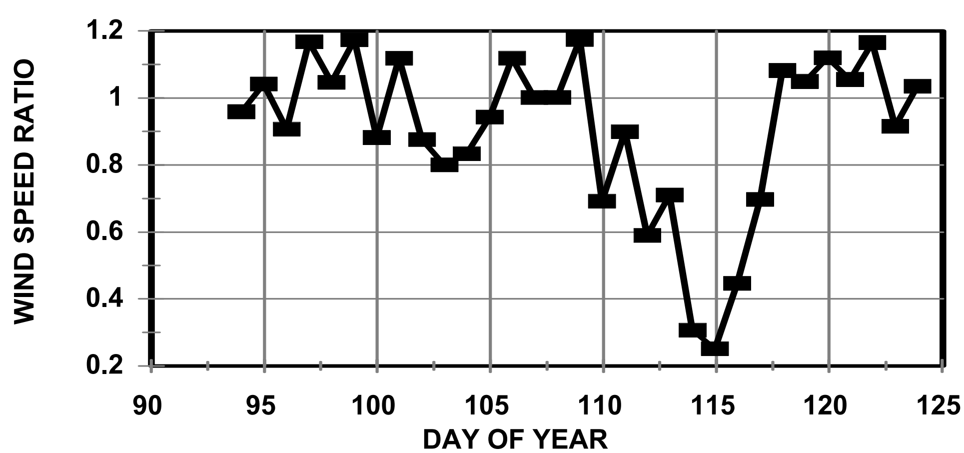


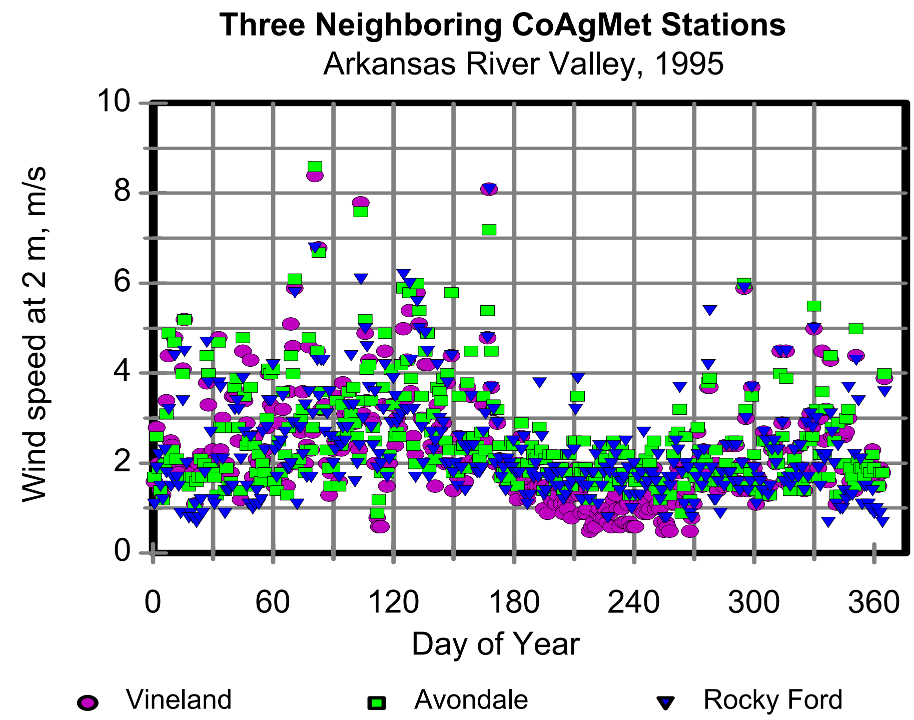
Figure D-11b) Ratio of daily mean wind speeds at Eloy, AZ to those at Maricopa, AZ during the period of anemometer failure described in a).

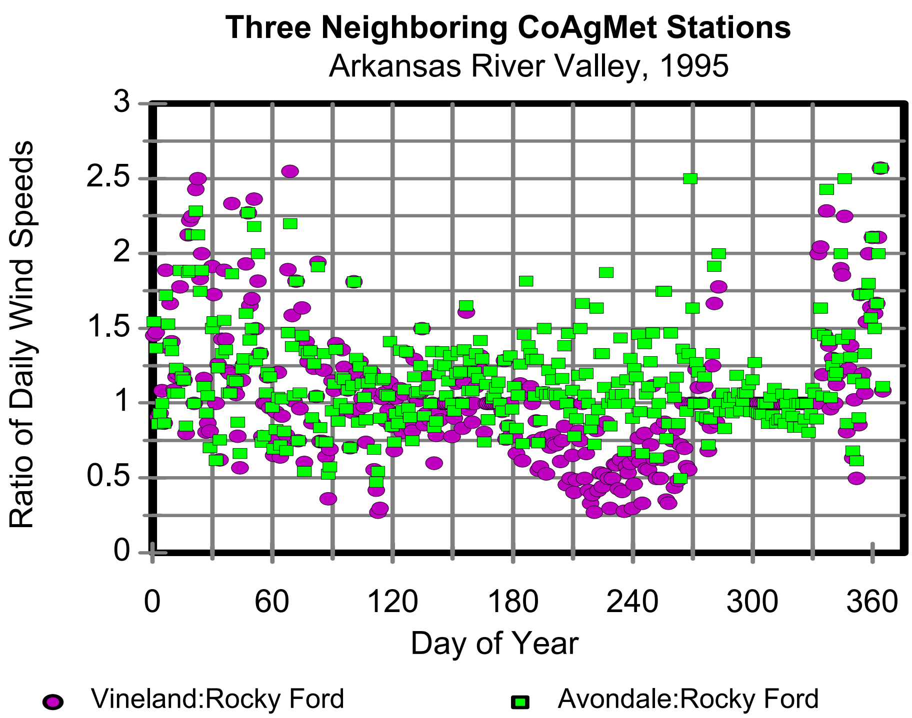
As an illustration of comparing wind speed data from two or more locations, daily wind speed data from three neighboring CoAgMet AWS stations located in the Arkansas River Valley of Colorado are plotted in Figure D-12a. The Vineland and Avondale stations are within 15 km (10 miles) of one another and the Rocky Ford station is about 60 km (40 miles) further east. All stations are located in agricultural environments and wind was measured at 2 m above the ground. The similarity in wind speed records is apparent. The Vineland station had some fields of corn planted near the weather station during 1995 (personal commun., R.Allen, 2001) that impeded wind speed measurements during late summer. This is evident in viewing the daily wind plot in Figure D-12a, where daily wind speeds for Vineland fell below those at Avondale and Rocky Ford from day 190 through day 270. Ratios of wind speed for Vineland to wind speed at Rocky Ford show a similar pattern (Figure D-12b), with ratios routinely falling below 0.7 during the period from day 210 through day 270. Ratios of wind speed for Avondale to Rocky Ford followed a consistent average of 1.0 all year, with some inconsistencies during winter months. This example illustrates the use of data from neighboring stations to discern shifts or anomalies in a data set.

A good preventive maintenance program is required to keep anemometers functioning at peak performance levels. Weather station anemometers should be replaced with newly reconditioned (new bearings) and calibrated anemometers at regular intervals. An annual replacement in light to normal wind regions or semi-annual replacement in windy regions should be considered for anemometers located in agricultural settings. Some providers of weather data employ a standard practice of replacing anemometers on a regularly scheduled basis. The replacement schedule is typically based on local experience or recommendations of the manufacturer and may be as short as six months. An alternative technique for evaluating anemometers involves redundancy in instrumentation and requires placement of a second anemometer[2] of the same design, but with fresh bearings, at the weather station for a three or four day period at least once each year, and comparing recorded values. Variations between recordings can signal a need to replace bearings, switches, or other parts.

Wind speeds over non-reference surfaces may exhibit a systematic upward bias relative to wind speeds measured over reference surfaces. Vegetation in excess of the recommended reference-surface height will impose a greater frictional drag on the near surface atmosphere and reduce wind speed relative to the reference condition. Smooth, dry surfaces will generate an opposite bias; wind speeds over these surfaces will generally be higher than those measured over reference surfaces. Allen and Wright (1997) have suggested procedures for adjusting non-reference wind speed data to better represent reference conditions; however, these procedures are somewhat complicated and have not been validated for a wide range of conditions.

[2] If a second data logger is used to record the temporary anemometer, one should be careful to synchronize data logger clocks. Also, one should be careful that adjacent anemometers do not interfere with one another's wind stream.


Three Neighboring CoAgMet Stations
Arkansas River Valley, 1995
Wind speed at 2 m, m/s
10
8
6
4
2
0
0
60
120
180
240
300
360
Day of Year
Vineland
Avondale
Rocky Ford


Three Neighboring CoAgMet Stations
Arkansas River Valley, 1995
Ratio of Daily Wind Speeds
3
2.5
2
1.5
1
0.5
0
0
60
120
180
240
300
360
Day of Year
Vineland:Rocky Ford
Avondale:Rocky Ford

APPENDIX E

ESTIMATING MISSING CLIMATIC DATA

TABLE OF CONTENTS

INTRODUCTION

The calculation of reference evapotranspiration with the standardized ASCE Penman-Monteith reference ET equation requires air temperature, vapor pressure, radiation, and wind speed data. The climate data should reflect the environment within the area for which an estimate of ET is required. If some of the required weather data are missing or do not accurately represent an irrigated site/region or are erroneous, then it may be possible that data may be estimated in order to apply the equation. The quality of calculated reference ET values depend on the quality of weather data. If the estimated missing data are reasonably representative of a site within an irrigated area, then it is likely that the calculated reference ET values from the standardized equation will be more reliable than estimates made using other more empirical methods. This appendix provides procedures for estimating solar radiation, vapor pressure, and wind speed data when they are missing or of questionable quality. Users should employ some type of "flagging" procedure to clearly identify data that have been estimated.

MINIMUM DATA REQUIREMENTS

Many of the suggested procedures for estimating missing data rely upon measured maximum and minimum air temperatures. Therefore daily maximum and minimum air temperature, or at the very least, daily mean air temperatures are considered to be the absolute minimum data requirements necessary to apply the standardized Penman-Monteith method. In situations where solar radiation, humidity and wind speed data are available, but air temperature data are missing, temperature may be estimated from a nearby weather station site using some form of regression or interpolation/extrapolation procedure. Estimated temperature data should not be used at a site if the temperature data are subsequently used to estimate humidity and solar radiation data, as the resulting ET_{ref} would essentially have been calculated using no local data.

ESTIMATING MISSING HUMIDITY DATA

Where daily humidity data are missing or are of questionable quality, vapor pressure, e_a, can be estimated for the reference environment by assuming that dew-point temperature (T_{dew}) is near the daily minimum air temperature (T_{min}):

$$T_{dew} = T_{min} - K_o \quad \text{(E.1)}$$

where K_o is approximately 2 to 4 ^oC in dry (arid and semiarid) climates and K_o is approximately 0 ^oC in humid to subhumid climates. Background on this relationship is discussed in Appendix D and an illustration of the trend for close proximity between T_{dew} and T_{min} is provided. Further discussion and caveats of this relationship are given in Allen (1996) and Allen et al., (1998).

An alternative to applying Eq. E.1 is to assume that relative humidity, RH, approaches 90 to 100% during early morning hours (before sunrise) over well-watered (i.e. reference) settings (as illustrated in Figure D-2b), so that the assumption that RH_{max} ~ 90% or RH_{max} ~ 100% can be employed. Daily vapor pressure is then calculated using the estimated RH_{max} and measured T_{min} in Eq. 12 of the text.

When humidity data are available from a nearby station, for example within 100 km, the user may elect to predict T_{dew} for a site having no humidity data or having faulty data using Eq. D.8 of Appendix D. This relationship presumes that differences between T_{dew} and T_{min} are similar between stations. Similar results and estimates of humidity can be obtained by transferring RH measurements between locations and calculating e_a using the transferred RH data and local air temperature (using Eq. 7 and 11-13 or Eq. 37 and 41 in the text). It is recommended that similarity in relationships between T_{dew} and T_{min} or in RH be confirmed using temporary measurement of humidity or by analysis of data from adjacent stations.

By definition, reference ET_{os}, or ET_{rs}, is ET from an extensive surface of well-watered vegetation. Therefore, when humidity data are available from only a site which is known to deviate substantially from a reference environment, then use of "adjusted" dew-point temperature in the standardized PM equation may produce more reliable and representative reference ET than those obtained using humidity data from the non-reference site. Further information and recommendations on coping with impacts of weather station environment are given in Appendix D. The user should "flag" any estimated humidity data and describe the procedures that were used.

ESTIMATING MISSING RADIATION DATA

Solar Radiation Data Derived From Observed Sunshine Hours

If observed hours of sunshine are measured, solar radiation for 24-hour and longer time periods can be calculated using the Angstrom formula, which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \tag{E.2}$$

where

- R_s = solar or shortwave radiation [MJ m^{-2} day^{-1}],
- n = actual duration of sunshine [hour],
- N = maximum possible duration of sunshine or daylight hours [hour],
- n/N = relative sunshine duration [-],
- R_a = extraterrestrial radiation [MJ m^{-2} day^{-1}],
- a_s = constant expressing the fraction of extraterrestrial radiation reaching the earth's surface on overcast days ($n = 0$),
- b_s = constant expressing the additional fraction of extraterrestrial radiation reaching the earth's surface on a clear day,
- a_s+b_s = fraction of extraterrestrial radiation reaching the earth's surface on a clear day ($n = N$).

R_s is expressed in Eq. E.2 in MJ m^{-2} day^{-1} for R_a in MJ m^{-2} day^{-1}. Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month), the Angstrom values a_s and b_s will vary. Where no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values $a_s = 0.25$ and $b_s = 0.50$ from FAO-24 and FAO-56 are recommended.

The potential daylight hours, N, are given by:

$$N = \frac{24}{\pi} \omega_s \tag{E.3}$$

where ω_s is the sunset hour angle in radians and is calculated using Eq. 27 or 28 in the text.

Solar Radiation Data From a Nearby Weather Station

For 24-hour and longer time periods, solar radiation can be relatively similar over large areas. Similarity in solar radiation depends on (i) the size of the region; (ii) the air masses governing rainfall and cloudiness being nearly identical within the region; and (iii) the physiography of the region being nearly homogenous. Differences in relief strongly influence the movement of air masses and development of cloud systems, so that these should be negligible if radiation data are to be transferred between locations.

Generally, daily calculations of reference ET using estimated radiation data are justified when utilized as a sum or as an average over a multiple-day period. This is the case for the computation of total evapotranspiration demand between successive irrigations or when planning irrigation schedules. Under these conditions, the relative error for one day may be compensated by an error for another day within the time period. Daily estimates should not be utilized as true daily estimates but only as averages over the period under consideration.

Solar Radiation Data Derived From Air Temperature

Solar radiation can be estimated based on an empirical equation derived using the difference between maximum and minimum air temperature and extraterrestrial solar radiation. The difference between the maximum and minimum air temperature is related to the degree of cloud cover at a location. Clear-sky conditions result in higher air temperatures during the day (i.e., T_{max}) than under cloudy conditions because the atmosphere is transparent to incoming solar radiation. Clear-sky conditions result in relatively lower air temperatures during nighttime (i.e., T_{min}) than under cloudy conditions because less outgoing long-wave radiation is absorbed and reemitted by the atmosphere. On the other hand, under overcast conditions, T_{max} is often lower than for clear days because a significant portion of the incoming solar radiation never reaches the earth's surface and is absorbed and reflected by the clouds. Similarly, T_{min} will be relatively higher because cloud cover acts as an absorbing and reemitting blanket and therefore decreases the net outgoing long-wave radiation.

Therefore, the difference between the maximum and minimum air temperature (T_{max} - T_{min}) can be used as an indicator of the fraction of extraterrestrial radiation that reaches the earth's surface. This principle has been utilized by Hargreaves and Samani (1982) to develop estimates of ET_o using only air temperature data.

The Hargreaves-Samani style of radiation prediction formula has the form:

$$R_s = k_{Rs} \sqrt{(T_{max} - T_{min})}\, R_a \qquad \text{(E.4)}$$

where

R_a = extraterrestrial radiation [MJ m^{-2} d^{-1}],
T_{max} = maximum air temperature [°C],
T_{min} = minimum air temperature [°C],
k_{Rs} = adjustment coefficient (0.16 .. 0.19) [$°C^{-0.5}$].

The adjustment coefficient k_{Rs} is empirical and differs for 'interior' or 'coastal' regions[1]:

- for 'interior' locations, defined as where the local land mass dominates and air masses are not strongly influenced by a large water body, $k_{Rs} \cong 0.16$;
- for 'coastal' locations, situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby water body, $k_{Rs} \cong 0.19$.

R_s predicted by Eq. E.4 should be limited to $\leq R_{so}$ which is the R_s for a cloud-free day. The temperature difference method is recommended for locations where it is not appropriate to import radiation data from a regional station, either because homogeneous climate conditions do not occur, or because data for the region are lacking. For island conditions, the methodology is not appropriate due to moderating effects of the surrounding water body. Allen (1997) provides examples for applying Eq. E.4 to predict daily and monthly values for solar radiation and procedures for site specific auto-calibration of k_{Rs}.

MISSING WIND SPEED DATA

Wind Speed Data From a Nearby Weather Station

Extrapolating wind speed data from a nearby agricultural weather station, as for radiation data, relies on the assumption that the airflow is relatively similar within a relatively 'homogeneous' region. There is generally relatively large variation in wind speed through the course of a day, which can translate into substantial differences in concurrent measurements of wind speed at two locations. However, when averaged over times periods of one day or longer, differences between locations become smaller.

Data from a weather station may be extrapolated to a nearby location where ET_{ref} is to be predicted if the governing air masses are of the same origin and where the same weather frontal systems govern the regional air flow. The surrounding relief of the two locations should be similar. In areas having large differences in relief, density-induced "drainage" of air and orographic shielding can cause substantial differences in observed wind speed over relatively short distances. Where short periods of wind data are available for the location, ratios of wind speed between two locations can be established and used to estimate wind data for the data-short location.

Wind speed data from airports in the U.S. typically are measured at a height of 10 m. In arid and semiarid areas, the airport anemometer is often surrounded by non-irrigated, short grass. Measured wind speed adjusted from a height of 10 m to 2 m using the logarithmic wind profile will typically exceed the wind speed over an irrigated area during the growing season because of large differences in vegetation roughness and the damping effect caused by the heat sink as water evaporates.

When extrapolating wind speed data from another station, trends in other meteorological parameters and relief should be compared. Strong winds are often associated with low relative humidity and light winds are common with high relative humidity. Thus, trends in variation of daily maximum and minimum relative humidity should be similar in both locations. In mountainous areas, data should

[1] The values presented here for K_{Rs} are based on work by Hargreaves and Samani (1982) and Allen (1995) and were

not be extrapolated from the nearest station but from nearby stations with similar elevation, surrounding vegetation, and exposure to the dominant winds. The pairing of stations may vary from one season to another, depending on the dominant winds.

Empirical Estimates of Monthly Wind Speed

The variation in average wind speed between monthly periods is often relatively small and fluctuates around average values. Therefore, in situations of no, or faulty, wind speed data, monthly values of wind speed may be estimated based on general information available for the regional climate, taking seasonal changes into account. Or, if regional information is unavailable, general values for wind speed suggested in Table E-1 can be employed. Caution should be exercised.

TABLE E-1
General classes of wind speed data (taken from FAO-56)

Description	mean wind speed at 2 m
light wind	... ≤ 1.0 m s^{-1}
light to moderate wind	1–3 m s^{-1}
moderate to strong wind	3–5 m s^{-1}
strong wind	... ≥ 5.0 m s^{-1}

A preliminary value of 2 m s^{-1} can be used as a first estimate of 2-m wind speed for an agricultural setting. This value is based on an average computed from over 2 000 weather stations around the globe (Allen et al., 1998).

In general, estimated wind speed at 2 m should be limited to about $u_2 \geq 0.5$ m s^{-1} when used to calculate standardized reference ET. This lower limit accounts for the influence of boundary layer instability caused by buoyancy of air in promoting exchange of heat and vapor at the surface when air is calm. This effect occurs when the wind speed is small and buoyancy of warm air induces air exchange at the surface.

As with humidity and solar radiation data, estimated wind speed data should be flagged in the data set and the user should describe procedures that were used to make the estimates.

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reported in FAO-56.

MISSING MAXIMUM OR MINIMUM AIR TEMPERATURE DATA

Some weather data sets contain daily mean air temperature summaries, but do not contain values for maximum and minimum air temperature. Daily maximum and minimum air temperatures are used in the standardized reference ET procedure for calculating net radiation and the saturation vapor pressure. During the process of calculating daily ET_{ref} using data sets where T_{max} and T_{min} are not available, but where daily mean air temperature and solar radiation data are available, accuracy of calculations for net radiation and saturation vapor pressure can be improved by estimating values for T_{max} and/or T_{min} by inverting Eq. E.4 and solving for T_{max} - T_{min}:

$$(T_{max} - T_{min}) = \left(\frac{R_s}{k_{Rs} \; R_a} \right)^2 \tag{E.5a}$$

where

R_a = extraterrestrial radiation [MJ m^{-2} d^{-1}],
T_{max} = maximum air temperature [°C],
T_{min} = minimum air temperature [°C],
k_{Rs} = adjustment coefficient, defined previously [$°C^{-0.5}$].

Values for T_{max} and/or T_{min} can be estimated using $T_{max} - T_{min}$ from E.5a as:

$$T_{max} = T_{mean} + \frac{(T_{max} - T_{min})}{2} \tag{E.5b}$$

$$T_{min} = T_{mean} - \frac{(T_{max} - T_{min})}{2} \tag{E.5c}$$

The estimated values for T_{max} and T_{min} should be clearly identified in the data set as estimated values.

APPENDIX F

Summary of

Reference Evapotranspiration Comparisons

Table F-1. Summary of weather station sites used in the study (listed from east to west longitude).

Site-Year Index	State	SITE	Longitude (degrees)	Latitude (degrees)	Elevation (m)	Mean Annual Precip.	Years (19--)	Peak-Month Mean ASCE-PM ET_o (mm d^{-1})	
								Year 1	Year 2
1	NY	Willsboro	73.38	44.38	43	760	98	3.79	
2, 3	NY	Valatie	73.68	42.43	76	910	97 98	3.90	3.89
4, 5	NY	Ithaca	76.45	42.45	123	910	97 98	3.82	3.88
6	SC	Florence	79.81	34.24	40	1120	86	5.91	
7	FL	Fort Pierce	80.44	27.57	7	1422	99	4.68	
8, 9	FL	Lake Alfred	81.89	28.03	46	1270	98 99	5.66	4.88
10, 11	GA	Blairsville	83.93	34.84	584	1307	97 98	4.48	4.63
12, 13	GA	Griffin	84.28	33.26	282	1447	97 98	5.05	5.99
14, 15	GA	Attapulgus	84.49	30.76	37	1460	97 98	4.54	6.29
16	IL	Bondville	88.37	40.00	213	1008	99	5.18	
17	IL	Belleville	89.88	38.52	133	974	99	5.53	
18	IL	Monmouth	90.73	40.92	229	942	99	5.23	
19, 20	OK	Wister	94.68	34.98	143	1188	97 98	5.13	6.03
21, 22	NE	Mead	96.30	41.08	366	743	97 98	5.15	4.57
23, 24	OK	Marena	97.21	36.06	331	889	97 98	5.63	6.84
25, 26	NE	Clay Center	98.08	40.31	552	685	97 98	5.46	5.15
27, 28	OK	Apache	98.29	34.91	440	757	97 98	6.59	8.60
29, 30	NE	Champion	101.43	40.22	1029	482	97 98	6.64	6.18
31, 32	OK	Goodwell	101.60	36.60	996	447	97 98	8.56	9.68
33, 34	TX	Bushland	102.05	35.11	1170	505	97 98	7.36	9.34
35, 36	TX	Dalhart	102.32	36.20	1228	467	97 98	6.44	7.30
37, 38	CO	Ovid	102.45	40.97	1089	448	98 99	5.50	6.08
39, 40	CO	Rocky Ford	104.00	38.00	1274	279	97 99	7.08	8.02
41, 42	CO	Wiggins	104.06	40.31	1367	353	97 98	5.88	5.93
43	CO	Fort Collins	105.00	40.60	1527	383	95	5.58	
44, 45	CO	Loveland	105.11	40.40	1540	406	97 98	5.59	5.30
46, 47	CO	Center	106	38	2348	178	97 99	5.62	5.96
48, 49	CO	Colton	106	39	2743	279	82 83	4.65	4.69
50, 51	CO	Portis	106	39	2895	279	82 83	4.38	4.30
52, 53	CO	Fruita	109	39	1377	228	97 99	7.87	6.75
54, 55	CO	Yellow Jacket	109	37	2252	406	97 99	5.92	5.96
56, 57	AZ	Tucson	110.94	32.28	713	300	97 98	8.54	8.21
58, 59	ID	Ashton	111.47	44.03	1615	430	97 98	4.96	5.70
60, 61	UT	Logan	111.80	41.60	1350	433	89 90	6.21	5.77
62, 63	AZ	Phoenix Encanto	112.10	33.48	335	175	97 98	7.49	7.60
64, 65	MT	St. Ignatius	114.10	47.31	896	360	97 98	4.52	5.27
66, 67	MT	Creston	114.13	48.19	899	390	97 98	4.16	4.73
68, 69	MT	Ronan	114.28	47.54	927	380	97 98	4.31	4.70
70, 71	ID	Twin Falls	114.35	42.61	1195	222	97 98	5.69	6.44
72, 73	ID	Parma	116.93	43.80	703	237	97 98	5.66	6.10
74	WA	Paterson	119.49	45.94	109	152	98	6.65	
75	CA	Fresno	119.70	36.80	103	269	98	7.11	
76	WA	Gramling	119.73	46.29	386	178	98	7.42	
77	WA	Roza	119.73	46.29	343	178	98	5.96	
78	CA	Santa Maria	120.40	35.00	82	314	98	4.42	
79	CA	Davis	121.80	38.50	18	461	98	6.71	
80	WA	Puyallup	122.30	47.10	61	1016	98	3.48	
81	WA	Grayland	124.00	46.78	2	2032	98	2.78	
	82	Haga	124.50	42.50	9	1778	99	3.32	

Table F-2. Statistical summary of the comparisons between various reference ET methods, using growing-season results from 82 site-years of daily and 76 site-years of hourly data.

METHOD	RATIO				RMSD (mm d^{-1})				RMSD as % of Mean Daily ET
	Max	Min	Mean	Std Dev	Max	Min	Mean	Std Dev	
Daily ET_o vs. Daily ASCE-PM ET_o									
FAO56-PM	1.004	0.982	0.994	0.006	0.155	0.005	0.039	0.035	0.8
ASCE Stand'zed	1.007	0.982	0.995	0.006	0.146	0.008	0.041	0.032	0.9
1963 Penman	1.201	0.995	1.072	0.036	0.772	0.167	0.430	0.092	10.4
Hargreaves	1.430	0.791	1.057	0.127	2.235	0.439	0.927	0.308	22.2
Daily ET_r vs. Daily ASCE-PM ET_r									
ASCE Stand'zed	1.025	0.974	0.998	0.010	0.300	0.014	0.069	0.058	1.28
1982 Kim Penman	1.118	0.892	0.988	0.043	1.706	0.169	0.662	0.267	12.2
Sum-of-Hourly ET_o vs. Daily ET_o (within method)									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
FAO56-PM	1.043	0.901	0.958	0.032	0.829	0.197	0.365	0.137	8.5
ASCE Stand'zed	1.081	0.941	1.012	0.028	0.663	0.228	0.334	0.084	7.7
1963 Penman	1.182	0.955	1.047	0.036	1.373	0.185	0.429	0.179	8.9
Sum-of-Hourly ET_r vs. Daily ET_r (within method)									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.931	1.022	0.037	1.048	0.315	0.540	0.152	9.6
1982 Kim Penman	1.054	0.910	0.976	0.032	1.008	0.322	0.539	0.071	10.1
Sum-of-Hourly ET_o vs. Daily ASCE-PM ET_o									
ASCE-PM	1.047	0.903	0.960	0.033	0.829	0.197	0.362	0.133	8.4
FAO56-PM	1.041	0.896	0.952	0.034	0.889	0.200	0.389	0.152	8.9
ASCE Stand'zed	1.080	0.937	1.007	0.029	0.678	0.235	0.335	0.086	8.0
1963 Penman	1.225	1.039	1.124	0.043	1.186	0.326	0.684	0.152	16.3
CIMIS Penman	1.220	0.969	1.080	0.047	0.966	0.290	0.579	0.137	13.9
Sum-of-Hourly ET_r vs. Daily ASCE-PM ET_r									
ASCE-PM	1.042	0.875	0.944	0.039	1.367	0.232	0.568	0.237	10.3
ASCE Stand'zed	1.108	0.933	1.020	0.037	1.067	0.331	0.532	0.144	9.41
1982 Kim Penman	1.138	0.855	0.963	0.059	1.923	0.416	0.759	0.304	13.8

Table F-3 (a, b) to F-10 (a, b). Yearly and growing season ratio table summaries. These 16 tables are formatted and can be printed from Excel. (see ETo and ETr comparison excel tables named “ETo rato tables Appendix F 3-6(updated with peak ETo).xls” and “ETr rato tables Appendix F 7-10(Updated with Peak ETr).xls”).