STANDARDIZED ASCE PENMAN-MONTEITH: IMPACT OF SUM-OF-HOURLY VS. 24-HOUR TIMESTEP COMPUTATIONS AT REFERENCE WEATHER STATION SITES

S. Irmak, T. A. Howell, R. G. Allen, J. O. Payero, D. L. Martin

ABSTRACT. *The standardized ASCE Penman-Monteith (ASCE-PM) model was used to estimate grass-reference evapotranspiration (ET_o) over a range of climates at seven locations based on hourly and 24 h weather data. Hourly ET_o computations were summed over 24 h periods and reported as sum-of-hourly (SOH). The SOH ASCE-PM ET_o values ($ET_{o,h,ASCE}$) were compared with the 24 h timestep ASCE-PM ET_o values ($ET_{o,d}$) and SOH ET_o values using the FAO Paper 56 Penman-Monteith (FAO56-PM) method ($ET_{o,h,FAO}$). The $ET_{o,h,ASCE}$ values were used as the basis for comparison. The $ET_{o,d}$ estimated higher than $ET_{o,h,ASCE}$ at all locations except one, and agreement between the computational timesteps was best in humid regions. The greatest differences between $ET_{o,d}$ and $ET_{o,h,ASCE}$ were in locations where strong, dry, hot winds cause advective increases in ET_o. Three locations showed considerable signs of advection. Some of the differences between the timesteps was attributed to uncertainties in predicting soil heat flux and to the difficulty of $ET_{o,d}$ to effectively account for abrupt diurnal changes in wind speed, air temperature, and vapor pressure deficit. The $ET_{o,h,FAO}$ values correlated well with $ET_{o,h,ASCE}$ values ($r^2 \geq 0.997$), but estimated lower than $ET_{o,h,ASCE}$ at all locations by 5% to 8%. This was due to the impact of higher surface resistance during daytime periods. Summing the ET_o values over a weekly, monthly, or annual basis generally reduced the differences between $ET_{o,d}$ and $ET_{o,h,ASCE}$. Summing the $ET_{o,d}$ values over multiple days and longer periods for peak ET_o months resulted in inconsistent differences between the two timesteps. The results suggest a potential improvement in accuracy when using the standardized ASCE-PM procedure applied hourly rather than daily. The hourly application helps to account for abrupt changes in atmospheric conditions on ET_o estimation in advective and other environments when hourly climate data are available.*

Keywords. *Evapotranspiration, Penman-Monteith, Sum-of-hourly, Weather station.*

In the U.S., water availability per capita has decreased more than 50%, from 10,600 m^3 $year^{-1}$ in 1950 to 5,600 m^3 $year^{-1}$ in 2000. The annual irretrievable total runoff volume (water flows to the sea) has increased from 155 km^3 $year^{-1}$ in 1980 to 194 km^3 $year^{-1}$ in 2000 (Mays, 1996). Withdrawal of freshwater resources for irrigation represents the largest of the country's water demands. Approximately 81% of the total consumptive water use in the U.S. is by irrigated agriculture and other agricultural operations (Solley et al., 1998). Thus, accurate and consistent determination of ET in irrigated agriculture is becoming increasingly important for better planning and efficient use of water resources, especially in arid or semi-arid environments where lack of precipitation usually limits crop growth and yield. Accurate quantification of ET is also crucial to irrigated crop production, water allocation, irrigation scheduling, evaluating the effects of changing land use on water yield, environmental assessment, and development of best management practices to protect surface and ground water quality.

The most common procedure for computing crop evapotranspiration (ET_c) is to adjust reference evapotranspiration (ET_o) using a crop coefficient (K_c, where $ET_c = ET_o \cdot K_c$). The K_c values represent the integrated effects of changes in leaf area, plant height, crop characteristics, irrigation method, rate of crop development, crop planting or sowing date, degree of canopy cover, canopy resistance, soil and climate conditions, and management practices (Doorenbos and Pruitt, 1977).

Because direct measurement of ET_o is difficult, time consuming, and costly, the most common procedure is to

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estimate ET_o using climatic data. Numerous methods have been introduced for computing ET_o, causing confusion among growers, consultants, extension educators, and decision and policymakers as to which method to select for ET_o estimation. Recently, the American Society of Civil Engineers (ASCE) Evapotranspiration in Irrigation and Hydrology Committee established a Task Committee on "Standardization of Reference Evapotranspiration Calculation" (Allen et al., 2000; Walter et al., 2001; Itenfisu et al., 2003). Based on Jensen et al. (1990), comparison of lysimeter-measured reference ET across various climates, and Task Committee experience, the Task Committee recommended the use of the ASCE-Penman-Monteith (PM) method, as simplified by FAO Paper No. 56 (FAO-56) (Allen et al., 1998), as the representation for reference ET. A reduced form of the ASCE-PM method was used as the basis for "standardized" ET_o computation. Equation parameters differ for hourly and 24 h (daily) data. Coefficients and parameters for a taller, rougher crop surface (0.5 m tall, like alfalfa) were also developed. A comparative analysis of a number of sites across the U.S. were reported and analyzed by Itenfisu et al. (2003). Itenfisu et al. (2003) made 24 h timestep and sum-of-hourly (SOH) comparisons among commonly used ET_o equations for 49 geographically diverse sites, for both short (grass) and tall (alfalfa) reference surfaces. The ASCE standardized ET_o equation, based on a surface resistance of 50 s m^{-1} during daytime and 200 s m^{-1} during nighttime, provided the best agreement with the full form of the ASCE-PM method applied on a daily basis. The advantages of adapting a specific procedure as a standardized method were discussed by Jensen et al. (1990), Allen et al. (1994a, 1994b), Hargreaves (1994), Allen et al. (2000), and Walter et al. (2001). Two important advantages are: providing commonality in computing ET_o, and enhancing the transferability of crop coefficients.

It is expected that the standardized ASCE-PM short reference ET (ET_{os}) or tall reference ET (ET_{rs}) method will gain acceptance and use in the U.S. A literature review reveals that the ET_o methods are being utilized mainly for computation with a 24 h timestep and not on an SOH basis. This might be because, in many cases, ET_o calculated on a 24 h timestep is considered to be sufficiently accurate for planning and designing irrigation and drainage infrastructure, irrigation scheduling, and other applications. Automated weather stations that collect weather data on an hourly basis may not present data in a quality controlled and readily accessible format to apply ET_o procedures on an SOH basis. Additionally, users may be uncertain about how to apply the ASCE-PM and FAO56-PM methods on an hourly basis and on accuracy improvement with SOH procedures. Nevertheless, availability of automated weather stations that collect hourly data is increasing, and it is important to assess the use of hourly data to compute ET_o on an SOH basis.

The Penman combination equation has continuously evolved. New forms of the equation are being used to estimate ET_o for an hourly or shorter time period. Van Bavel (1966) suggested that the Penman equation was only valid for instantaneous or hourly data. He argued that an SOH approach should provide a better representation of the effect of climatic conditions (solar radiation, air temperature, wind speed, and vapor pressure deficit) on daily ET_o. Allen et al. (2000) stated that "computing ET_o on an hourly or shorter timestep has advantages of improved accuracy in locations where large diurnal changes in wind speed and direction or cloudiness occur that are not typical of patterns at locations where 24 h ET_o methods have been developed." Allen (1994a) stated that "changes in dew point, wind speed, and cloudiness during the daytime can cause 24 h means to misrepresent evaporative power of the environment during parts of the day and may introduce error into the standardized combination equations when applied on a 24 h timestep basis." Tanner and Pelton (1960), Pruitt and Lourence (1966), and Van Bavel (1966) recommended the use of hourly data for daily ET_o estimation. Pruitt and Doorenbos (1977), Weiss (1982), Snyder and Pruitt (1985), and Ortega-Farias et al. (1995) pointed out that uncertainty exists when applying Penman-type equations using daily or longer-period mean weather data. Interactions between input parameters, including the day-night distribution of wind speed, vapor pressure deficit, and level of solar and/or net radiation, can produce errors in computation of daily ET_o. The magnitude of error depends on the trends and interactions among wind speed, vapor pressure deficit, temperature, and radiation during the 24 h period. Differences in ET_o computed using hourly and 24 h timesteps are likely larger in environments where strong advection occurs (for example, during hot, dry and windy summer months in arid or semi-arid climates) as opposed to humid or sub-humid locations where wind speeds are lower and advection is less severe.

The ASCE Environmental and Water Resources Institute ET Task Committee found that the SOH ET_o computed from the standardized procedure ranged from 0.94 to 1.07 of ET_o computed by the same procedure with a 24 h timestep for 49 locations across the U.S. (ASCE-EWRI, 2004). The average difference due to timestep length was 3.4%. The largest differences were in advective climates in southeastern Colorado, central Washington, and central Florida. The Task Committee found that the SOH ET_o from the FAO56-PM method ranged from 0.90 to 1.04 of ET_o computed by the standardized ASCE-PM on a daily timestep, with an average difference across the 49 locations of −4.2%. The FAO56-PM SOH ET_o method ranged from 0.88 to 0.97 of ET_o computed by the standardized ASCE-PM on an hourly timestep, with an average difference across the 49 locations of −5.2%. As indicated by these ratios, the lower daytime value for surface resistance used in the ASCE-EWRI standardization for hourly time periods (50 s m^{-1} during daytime and 200 s m^{-1} during nighttime) brought hourly ET_o computations, on average, to within 0.2% of daily timestep values across the 49 sites, whereas the FAO56-PM computed hourly using the 70 s m^{-1} for both daytime and nighttime periods predicted, on average, about 4% low.

The ASCE Task Committee and Itenfisu et al. (2003) evaluated differences in ET_o (and alfalfa reference ET, ET_r) caused by timestep and method over growing seasons and calendar years. However, they did not provide information on the possible causes of differences between the two ET_o computation procedures. In addition, evaluations of the difference in ET_o during the peak month is needed to assess the impact on peak values of reference ET that are needed for design and management of irrigation and drainage systems and water resources infrastructure. Furthermore, the variations between the hourly and daily timestep ET_o computations with location, especially in advective and non-advective regions, are not known. This study quantifies differences associated with using 24 h timestep ET_o, as

Table 1. Coordinates, elevation, reference surface, and years studied for each weather station site.

Study Site	Lat. (N)	Long. (W)	Elevation (m)	Reference Surface	Years Studied
Fort Pierce, Florida	27° 25′	80° 24′	8	Grass	2000
Bradenton, Florida	27° 27′	82° 28′	19	Grass	2000-2001
Bushland, Texas	35° 11′	102° 06′	1,169	Grass	1998-2000
North Platte, Nebraska	41° 05′	100° 46′	861	Grass/Alfalfa	1998-2002
Santa Rosa, California	38° 24′	122° 47′	24.4	Grass	2000-2003
Santa Barbara, California	34° 26′	119° 44′	76.2	Grass	2000-2003
Twitchell Island, California	38° 07′	121° 39′	−0.3	Grass	1998−2001

compared with SOH computations with the ASCE-PM and FAO56-PM methods for calendar years and peak months, for a selection of climates within the U.S.

MATERIALS AND METHODS

STUDY SITES AND CLIMATE DATA SOURCES

Grass-reference ET (ET$_o$) computations were made using carefully screened hourly weather data obtained from several regions having diverse climates. Study sites were located in a humid coastal region (Fort Pierce and Bradenton on the east and west coasts of Florida, respectively), semiarid temperate regions (Bushland, Texas, and North Platte, Nebraska), two Mediterranean-type regions along the west coast of California (Santa Rosa and Santa Barbara), and Twitchell Island, California (table 1). Hourly weather datasets for Fort Pierce and Bradenton were obtained from the University of Florida, Florida Automated Weather Network (FAWN) site (http://fawn.ifas.ufl.edu). Bushland datasets were measured by the USDA-ARS Conservation and Production Research Laboratory at their reference ET$_o$ research site at Bushland, Texas. North Platte datasets were collected at the University of Nebraska, West Central Research and Extension Center at North Platte by the High Plains Regional Climate Center (www.hprcc.unl.edu). Santa Rosa, Santa Barbara, and Twitchell Island datasets were obtained from the California Department of Water Resources (Snyder and Pruitt, 1985, 1992), California Irrigation Management Information System (CIMIS) website (www.cimis.water.ca.gov). Hourly weather variables included rainfall, maximum and minimum air temperatures, relative humidity, wind speed and direction, and solar radiation. Hourly net radiation and soil heat flux were only measured at Bushland for an irrigated cool season grass. The type of instrumentation and placement heights for each site are listed in table 2.

The study sites provided an opportunity to compare performance of the ASCE−PM and FAO56−PM ET$_o$ computation procedures, and hourly and daily timesteps, over a relatively wide range of climates for both dry and wet years and over a range of elevations. Annual rainfall amounts varied from 164 mm at North Platte, Nebraska, in 2002 to 1240 mm in Bradenton, Florida, in 2001, with North Platte and Bushland having the least and Bradenton and Santa Rosa having the highest amounts of rainfall. Elevations ranged from −0.3 m at Twitchell Island to 1169 m at Bushland.

DATA INTEGRITY AND QUALITY ANALYSES

The accuracy of ET$_o$ computations depends on the quality and integrity of the weather data used (Allen, 1996; Itenfisu et al., 2003). Data quality checks are, therefore, strongly recommended. Procedures for quality assessment of datasets used to compute ET$_o$ were outlined by Allen (1996), Allen et al. (1998), Temesgen et al. (1999), Walter et al. (2001), and Droogers and Allen (2002). An example of procedures to assess quality and integrity for a humid region (Florida) dataset was given by Irmak et al. (2003). In this study, quality and integrity checks were conducted for all datasets used. Only the datasets that passed the quality checks were used in analyses. Only one year of data (1998) passed the quality and integrity checks for the Fort Pierce station due to problems with solar radiation data. Five out of six years of data passed the quality checks for the North Platte site (one year was re−

Table 2. Instrument type and height at the study sites.

Variable[a]	Instrumentation[b]						
	Fort Pierce	Bradenton	Bushland	North Platte	Santa Rosa	Santa Barbara	Twitchell Island
R_s	LI200X pyranometer	LI200X pyranometer	Epply PSP	LI200X pyranometer	LI200S	LI200S	LI200S
R_n	Estimated by FAO56 and ASCE−EWRI	Estimated by FAO56 and ASCE−EWRI	REBS Q*7.1	Estimated by FAO56 and ASCE−EWRI	Estimated by FAO56 and ASCE−EWRI	Estimated by FAO56 and ASCE−EWRI	Estimated by FAO56 and ASCE−EWRI
T and RH	HMP probe, 1.5 m	HMP probe, 1.5 m	HMP45C probe	HMP35 probe	HMP35C probe, 1.5 m	HMP35C probe, 1.5 m	HMP35C probe, 1.5 m
U	Handar 425A, 10 m	Handar 425A, 10 m	Met−One anemo., 2 m	Met−One anemo., 3 m	Met−One anemo., 2 m	Met−One anemo., 2 m	Met−One anemo., 2 m
G	Estimated by FAO56 and ASCE−EWRI	Estimated by FAO56 and ASCE−EWRI	HFT−1	Estimated by FAO56 and ASCE−EWRI	Estimated by FAO56 and ASCE−EWRI	Estimated by FAO56 and ASCE−EWRI	Estimated by FAO56 and ASCE−EWRI
Rainfall	TE525MM tip. bucket	TE525MM tip. bucket	TE525MM tip. bucket	TE525MM tip. bucket	TE525MM tip. bucket	TE525MM tip. bucket	TE525MM tip. bucket

[a] R_s = solar radiation, R_n = net radiation, T = air temperature, RH = relative humidity, U = wind speed, and G = soil heat flux.

[b] LI200X and LI200S from LiCor Corp., Lincoln, Nebreaska; Epply PSP from The Epply Laboratory, Inc., Newport, Rhode Island; REBS Q*7.1 and HFT−1 from Radiation and Energy Balance Systems, Seattle, Washington; HMP, HMP45C, HMP35C, and Handar 425A from Vaisala Corp., Handar Business Unit, Sunnyvale, California; Met−One from Met−One, Grants Pass, Oregon; and TE525MM from Texas Electronics, Inc., Dallas, Texas.

jected because of solar radiation and relative humidity data). These were the only stations where any data were eliminated. The CIMIS datasets had the best quality and consistency. The CIMIS datasets are quality tested by the network using procedures developed by Snyder and Pruitt (1985) before posting for public use. In addition, the CIMIS network routinely replaces pyranometers and other sensors with recalibrated units.

The data quality checks were made on daily maximum ($T_{\max}$), average, and minimum ($T_{\min}$) air temperatures; daily maximum and minimum RH; and daily average dew point temperature (T_{dew}), daily solar radiation, and hourly net radiation (at Bushland only). The $T_{\max}$ and $T_{\min}$ values were compared to long-term temperature extremes. Following the procedures outlined by Allen (1996), Allen et al. (1998), Temesgen et al. (1999), Walter et al. (2001), and Droogers and Allen (2002), all datasets that were used in our analyses were acceptable for hourly ET_o comparisons and were judged to be of good quality and reasonably well reflective of "reference" environments.

PERFORMANCE AND STATISTICAL ANALYSES

The standardized ASCE-PM SOH ET_o computations were used as the basis for comparison of ET_o values. The reason for selecting the ASCE-PM method as the basis was because several studies (Allen et al., 1996; Ventura et al., 1999; Todorovic, 1999; Wright et al., 2000; Steduto et al., 2003) have shown that, in reality, for daytime hourly periods, r_s is less than 70 s m^{-1} for the standardized height of 0.12 m, which is used in the FAO56-PM for clipped grass, and that lower r_s values (e.g., 50 s m^{-1} used in the standardized ASCE-PM method) would better represent clipped grass hourly r_s values under the field conditions. The hourly ASCE-PM ET_o values were summed over each day to obtain daily values of ET_o ($\text{ET}_{\text{o,h,ASCE}}$, where "h" stands for sum-of-hourly). Daytime and nighttime ET_o values were summed. Comparisons and statistical analyses between daily values of the SOH ASCE ET_o ($\text{ET}_{\text{o,h,ASCE}}$), 24 h timestep ASCE ($\text{ET}_{\text{o,d}}$, where "d" stands for daily), and the SOH FAO56-PM ET_o ($\text{ET}_{\text{o,h,FAO}}$) were conducted for all study years and growing seasons listed in table 1. Comparative and statistical analyses were performed for the peak ET_o months. The root mean squared difference (RMSD) was used as a criterion to judge the accuracy and reliability of the methods. The standard deviation (SD) between the SOH and 24 h timestep ET_o values were also considered. The SD values were calculated to measure how widely the ET_o values were dispersed from the average (mean ET_o) value. The RMSD between the ET_o values was calculated as:

$$\text{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[y_i^{\left(\text{ET}_{\text{o,h,ASCE}}\right)} - y_i^{\left(\text{ET}_{\text{o,d}}\right) - or - \left(\text{ET}_{\text{o,h,FAO}}\right)}\right]^2} \tag{1}$$

where n is the number of observations, $y_i^{(\text{ETo,h,ASCE})}$ is the standardized sum-of-hourly ASCE-PM ET_o, and $y_i^{(\text{ETo,d})-\,or\,-(\text{ETo,h,FAO})}$ is either the sum-of-hourly FAO56-PM or 24 h ASCE-PM ET_o values.

Because it is an indication of both bias and variance from the 1:1 line, the RMSD provides an effective measure of how well datasets compare. Low RMSD values indicate better agreement. A paired sample *t*-test (two-sample for means) was performed to identify whether $\text{ET}_{\text{o,d}}$ and $\text{ET}_{\text{o,h,FAO}}$ values were significantly different from the $\text{ET}_{\text{o,h}}$ values at the 5% significance level. The null hypothesis was that the $\text{ET}_{\text{o,d}}$ and $\text{ET}_{\text{o,h,FAO}}$ values came from the same population as the $\text{ET}_{\text{o,h,ASCE}}$ values and that the hypothesized (null hypothesis) mean difference between ET_o values was zero. The mean ratio (mean of years studied) for $\text{ET}_{\text{o,d}}$ and $\text{ET}_{\text{o,h,FAO}}$ to $\text{ET}_{\text{o,h,ASCE}}$ (% difference) was calculated and used to judge performances. The coefficient of determination, slope, and intercept of the linear regressions between the ET_o computation procedures were calculated. The same analyses were conducted to quantify and analyze the differences and performances for peak ET_o months. The performance indicators were also calculated for multiple days (3-day sum) and longer periods (weekly, monthly, and annual sum) and analyzed to assess whether differences exist between daily and longer periods in comparisons of ET_o.

REFERENCE ET COMPUTATION

Hourly and 24 h Timestep ASCE-PM ET_o Computations

The standardized ASCE-PM equation is intended to simplify and clarify the application of the method and associated equations for computing aerodynamic and bulk surface resistance (r_a and r_s, respectively). Equations were combined into a single expression for both grass and alfalfa-reference surfaces and for a 24 h or an hourly timestep by varying coefficients (Walter et al., 2001; Itenfisu et al., 2003). Computation of standardized short grass ET_o with a 24 h timestep uses a grass height of 0.12 m and an r_s value of 70 s m^{-1}, which is the same as for the FAO56-PM equation (Allen et al., 1998). For hourly timesteps, r_s is set to 50 s m^{-1} for daytime hours and to 200 s m^{-1} for nighttime hours. The standardized ASCE-PM equation is:

$$\text{ET}_\text{o} = \frac{0.408\Delta(R_\text{n} - G) + \gamma \dfrac{C_\text{n}}{T + 273} U_2\,(e_\text{s} - e_\text{a})}{\left[\Delta + \gamma(1 + C_\text{d} U_2)\right]} \tag{2}$$

where

ET_o = standardized grass-reference ET (mm d^{-1} or mm h^{-1})

Δ = slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1})

R_n = calculated net radiation at the crop surface (MJ m^{-2} d^{-1} for 24 h timesteps, or MJ m^{-2} h^{-1} for hourly timesteps)

G = heat flux density at the soil surface (MJ m^{-2} d^{-1} for 24 h timesteps, or MJ m^{-2} h^{-1} for hourly timesteps)

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 = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

$e_\text{s} - e_\text{a}$ = vapor pressure deficit (kPa)

γ = psychrometric constant (kPa °C^{-1})

C_n = numerator constant that changes with reference surface and calculation timestep (900 °C mm s^3 Mg^{-1} d^{-1} for 24 h timesteps, and 37 °C mm s^3 Mg^{-1} h^{-1} for hourly timesteps for the grass-reference surface)

C_d = denominator constant that changes with reference surface and calculation timestep (0.34 s m^{-1} for 24 h timesteps, 0.24 s m^{-1} for hourly timesteps during daytime, and 0.96 s m^{-1} for hourly nighttime for the grass-reference surface)
0.408 = coefficient having units of m^2 mm MJ^{-1}.

The values for C_n and C_d associated with r_s, r_a, reference crop height, and zero plane displacement height for computing tall (alfalfa) reference ET (ET$_r$) are discussed by Walter et al. (2001), Itenfisu et al. (2003), and ASCE-EWRI (2004). In this study, all ET$_o$ computations were made using REF-ET software (version 2.0; Allen, 2001). The current version of REF-ET provides standardized ET$_o$ or ET$_r$ computations by 17 commonly used equations with hourly, daily, or monthly timesteps. The two primary objectives of the REF-ET software are to: (1) provide standardized ET$_o$ and ET$_r$ computations following ASCE-EWRI (2004) that can be compared with other ET computer programs for various weather datasets, and (2) provide standardized ET$_o$ and ET$_r$ computations using data from a variety of data file types, data unit types, and timesteps. REF-ET has been used as the standardized ET$_o$ and ET$_r$ computation tool to calibrate and/or validate other ET$_o$ and ET$_r$ spreadsheets and computer software. In REF-ET, daily values for Δ, R_n, e_s, and e_a were calculated using the equations (albedo, $\alpha = 0.23$) given by Allen et al. (1998) and ASCE-EWRI (2004). Measured RH$_{max}$, RH$_{min}$, T_{max}, and T_{min} values were used to calculate e_a and e_s for 24 h timesteps. The Stefan-Boltzmann constant (σ) for the calculation of the net outgoing longwave radiation (R_{nl}) was taken as 4.901×10^{-9} MJ K^{-4} m^{-2} d^{-1}. A value of 1.013×10^{-3} MJ kg^{-1} °C^{-1} that represents an average value of specific heat (c_p) at constant temperature was used in the calculations. The latent heat of vaporization (λ) was taken as 2.45 MJ kg^{-1} following FAO56 and ASCE-EWRI (2004). The psychrometric constant (γ) was computed as a function of atmospheric pressure (P), λ, c_p, and ratio of molecular weight of water vapor to dry air ($\varepsilon = 0.622$) for each study site. Atmospheric pressure (P) was calculated as a function of station elevation (z). Soil heat flux density (G) was assumed to be zero for the 24 h timestep. Wind speed measurements were made at a height of 10 m at the Florida stations, as noted in table 2. REF-ET converts wind speeds measured other than at 2 m height to 2 m wind speed values using equation 47 in Allen et al. (1998).

Hourly and 24 h Timestep FAO56-PM ET$_o$ Computations

The 24 h form and coefficients for the FAO56-PM (ET$_{o,d}$) method are the same as for the ASCE standardized equation (eq. 2), where $C_n = 900$ and $C_d = 0.34$. The form of the FAO56-PM equation for hourly timestep (Allen et al., 1994a; Allen et al., 1998) is:

$$\mathrm{ET_o} = \frac{0.408\Delta(R_n - G) + \gamma \frac{37}{T_h + 273} U_2 \left[e_{s(T_h)} - e_a\right]}{\left[\Delta + \gamma(1 + 0.34U_2)\right]} \qquad (3)$$

where ET$_o$ is in mm h^{-1}, R_n and G are in MJ m^{-2} h^{-1}, T_h is the mean hourly air temperature (°C), $e_{s(T_h)}$ is the saturation vapor pressure at air temperature T_h, e_a is the average hourly actual vapor pressure, and U_2 is the hourly wind speed (m s^{-1} at 2 m).

The ASCE-PM and FAO56-PM equations use essentially the same procedures for computing hourly and 24 h values of G, R_n, and other parameters. Although measured R_n and G values were available for Bushland, in order to retain the consistency of comparisons of ET$_o$ computations, R_n and G were estimated using measured R_s, T, and humidity data for both ASCE-PM and FAO56-PM equations for all locations. The hourly G in both the ASCE-PM and FAO56-PM equations is estimated as a function of R_n for day and nighttime as (ASCE-EWRI, 2004):

$$G_{\text{h-daytime}} = 0.1 \cdot R_n \qquad (4)$$

$$G_{\text{h-nighttime}} = 0.5 \cdot R_n \qquad (5)$$

For hourly computations in REF-ET, the Stefan-Boltzmann constant was taken as 2.043×10^{-10} MJ m^{-2} h^{-1} in the computation of R_{nl}. The extraterrestrial radiation (R_a) was computed using equation 28 of Allen et al. (1998). In hourly computation of R_a, the inverse relative distance factor for the earth-sun (d_r), solar declination (δ), latitude (φ), solar time angle at the beginning of period (ω_1), at the midpoint (ω), and at the end of the period (ω_2), seasonal correction factor (S_c), and coefficient b were computed on an hourly basis. Following ASCE-EWRI (2004) guidelines, in hourly ET$_o$ computation, daytime is defined as occurring when the average R_n during an hourly period is greater than zero. During the computation of hourly R_n, the ratio of incoming solar radiation to clear sky solar radiation (R_s/R_{so}), which provides an indication of cloud cover, was limited to less than or equal to 1.0 during all periods, and the ratio R_s/R_{so} during a time period occurring 2 to 3 h before sunset was used to compute the R_n during nighttime. This latter procedure assumes that cloud cover during nighttime is similar to that 2 to 3 h before sunset. The SOH ET$_o$ utilized hourly computed ET$_o$ data that were summed over the 24 h time period. Hourly ET$_o$ values were permitted to be negative, reflecting either dew or errors in estimating hourly R_n or G or parameter inaccuracies. For more detailed information on the computation of hourly and 24 h timestep ET$_o$, refer to the REF-ET user manual (Allen, 2001) and ASCE-EWRI (2004).

RESULTS AND DISCUSSION

COMPARISON OF 24 h TIMESTEP (ET$_{O,D}$) AND SOH ASCE-PM ET$_O$ (ET$_{O,H,ASCE}$)

Figure 1 shows relationships between ET$_{o,d}$ and ET$_{o,h,ASCE}$ values for Bradenton, Fort Pierce, Santa Rosa, Santa Barbara, Twitchell Island, North Platte, and Bushland. Tables 3 and 4 summarize performance indicators and statistical analyses, and population statistics and t-test results, respectively. Although the relationship between the ET$_{o,d}$ and ET$_{o,h,ASCE}$ showed variation with location, the relationship was good at all locations. As an example, humid locations (Fort Pierce and Bradenton) had the lowest RMSD values (0.25 and 0.31 mm d^{-1}, respectively) among all sites, and North Platte and Bushland had the highest (table 3). The average ratio of ET$_{o,d}$ to ET$_{o,h,ASCE}$ ranged from 0.97 at Santa Barbara to 1.09 at North Platte, indicating that the ET$_{o,d}$ estimated 2.7% lower than ET$_{o,h,ASCE}$ at Santa Barbara and estimated 9% higher at North Platte for the calendar year (table 3). Bushland had similar results to North Platte, with the ET$_{o,d}$ estimating 8% higher than ET$_{o,h,ASCE}$ at Bushland

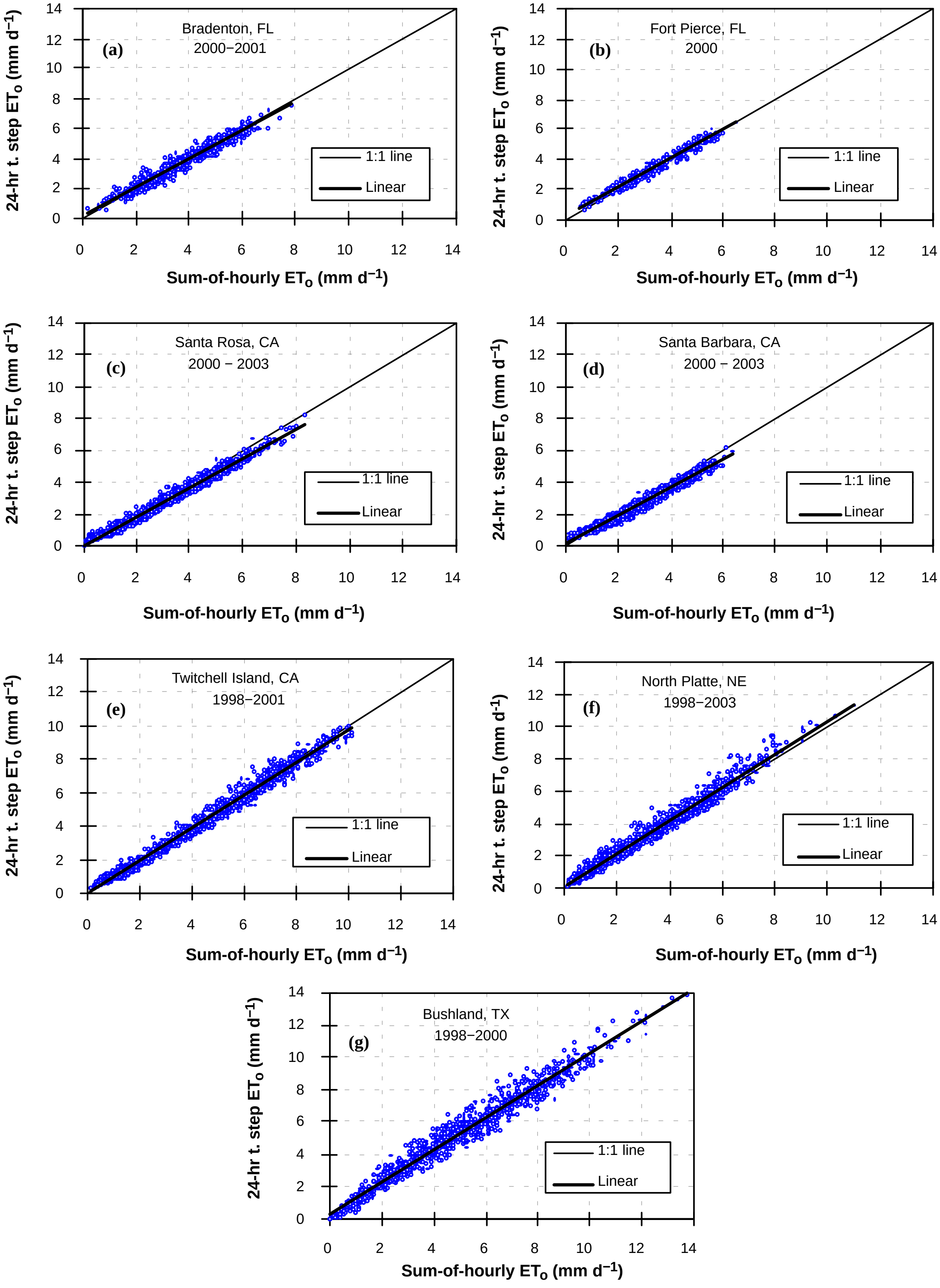

Figure 1. Relationship between the 24 h timestep ASCE-PM ET$_o$ (ET$_{o,d}$) and sum-of-hourly (SOH) ASCE-PM ET$_o$ (ET$_{o,h,ASCE}$). Daytime and nighttime hourly ET$_o$ values were considered in daily SOH computations.

(RMSD = 0.55 mm d^{-1}) (table 3). When calculations for the April-October (growing season) period were considered at North Platte and Bushland (Florida sites have essentially a 12-month growing period), the ratios of ET$_{o,d}$ to ET$_{o,h,ASCE}$ were 1.08 and 1.05, and RMSD values were 0.42 and 0.56 mm d^{-1}, respectively. This compares with ratios found by ASCE-EWRI (2004) for ET$_{o,d}$ to ET$_{o,h,ASCE}$ of 1.07 for Bushland 1997 and 1998 datasets and about 1.04 at Champion, Nebraska, during 1997 and 1998. Champion is about 120 km SW of North Platte. Ortega-Farias et al. (1995) compared ET$_o$ estimated using the hourly Penman model (Penman, 1963) (with wind function developed by Pruitt and Doorenbos, 1977) versus ET$_o$ measured using a Bowen ratio energy balance system and found that the hourly Penman-

Table 3. Number of observations (*n*), root mean squared difference (RMSD), average ratio of $\mathrm{ET_{o,d}}$ to $\mathrm{ET_{o,h,ASCE}}$, and regression coefficients between the $\mathrm{ET_{o,d}}$ and $\mathrm{ET_{o,h,ASCE}}$ values for the calendar year.

Site	Number of Observations (*n*)	RMSD of Daily Estimate (mm d^{-1})[a]	Average Ratio $\mathrm{ET_{o,d}/ET_{o,h,ASCE}}$	Slope[b]	Intercept[b]	r^2 [b]
Bradenton	731	0.31 (1.36)	1.01	0.957	0.145	0.947
Fort Pierce	366	0.25 (1.28)	1.03	0.949	0.234	0.965
Santa Rosa	1,461	0.36 (1.77)	1.00	0.905	0.07	0.982
Santa Barbara	1,461	0.34 (1.33)	0.97	0.887	0.126	0.969
Twitchell Island	1,461	0.32 (2.61)	1.02	0.974	0.03	0.987
North Platte (CY)[c]	1,826	0.37 (2.24)	1.09	1.022	0.08	0.979
Bushland (CY)	1,096	0.55 (2.75)	1.08	0.993	0.308	0.970
North Platte (GS)	1,221	0.42 (2.15)	1.08	1.027	0.09	0.972
Bushland (GS)	611	0.56 (2.52)	1.05	0.980	0.370	0.961

[a] RMSD values were calculated using the number of observations (*n*) in column 2. Values in parentheses indicate standard deviations between the $\mathrm{ET_{o,d}}$ and $\mathrm{ET_{o,h,ASCE}}$ values.

[b] Regression coefficients where $\mathrm{ET_{o,d}} = \mathrm{slope} \cdot \mathrm{ET_{o,h,ASCE}} + \mathrm{intercept}$.

[c] CY is the entire calendar year, and GS is the growing season (taken as April-October for North Platte and Bushland).

Monteith equation estimated 5.2% higher than hourly measured $\mathrm{ET_o}$. The higher estimation by $\mathrm{ET_{o,d}}$ in our study ranged from 2% at Twitchell Island to 9% at North Platte. Average ratios of $\mathrm{ET_{o,d}}$ to $\mathrm{ET_{o,h,ASCE}}$ were close to 1.0 for the Florida and California stations, ranging from 0.97 to 1.03 with less scatter around the 1:1 line (figs. 1a through 1e). The $\mathrm{ET_{o,d}}$ values were significantly different ($P < 0.05$) from the $\mathrm{ET_{o,h,ASCE}}$ values (table 4). The null hypothesis was rejected for all locations. It is important to note in figure 1 that because of the effect of maritime environment of Twitchell Island, a large sea/ocean influence, with cooler temperatures, higher relative humidity and, thus, lower $\mathrm{ET_o}$ would be expected for this location. However, Twitchell Island has much higher $\mathrm{ET_o}$ values than Santa Rosa and Santa Barbara (fig. 1e vs. figs. 1c and 1d). Thus, Santa Rosa and Santa Barbara have probably more influence from the ocean than Twitchell Island, which is situated more inland, and may not be truly representative of an island.

The results of comparisons of impact of time period on calculation of $\mathrm{ET_o}$, especially the average ratio and RMSD values, are in general agreement with those obtained by Itenfisu et al. (2003) and ASCE-EWRI (2004). Itenfisu et al. (2003) reported that the average ratio between the 24 h timestep versus SOH for a variety of Penman-type combination equations varied from a minimum of 0.81 to a maximum of 1.14 among 76 site-years. Our average ratio ranged from 0.97 to 1.09. Itenfisu et al. (2003) reported that the ASCE-PM and FAO56-PM equation forms that use the same resistance values for hourly as for 24 h timestep tended to estimate lower $\mathrm{ET_o}$ when applied hourly and summed daily than when applied to 24 h timesteps. Ventura et al. (1999) compared the hourly FAO56-PM and lysimeter-measured $\mathrm{ET_o}$ values at locations in California and Italy. They reported similar RMSD values (0.26 mm d^{-1}) found in our study between the hourly Penman-Monteith and lysimeter-measured $\mathrm{ET_o}$. The lower RMSD in their study may be due to their assumption that nighttime hourly $\mathrm{ET_o}$ values, when $R_n < 0$, are insignificant and were set equal to zero. However, this assumption would probably not be valid at some locations, as some locations can have appreciable vapor pressure deficit during nighttime and emission of heat from soil to support nighttime ET. Nighttime $\mathrm{ET_o}$ is also likely to occur if the soil and grass surface are wet from irrigation or rainfall or if there is a warm air advection. These conditions are not uncommon in the arid/semi-arid regions of Nebraska and Texas where strong and warm air advection occurs during hot summer nights, contributing to evaporative losses.

It is important to emphasize the possible consequences of higher or lower estimations by the $\mathrm{ET_{o,d}}$ method as compared with the standardized $\mathrm{ET_{o,h,ASCE}}$ method. If we consider that 1 mm of water in a 1 ha field will add up to 10 m^3 of water, even a small higher or lower estimation of $\mathrm{ET_o}$ or $\mathrm{ET_r}$ (e.g., 0.3 mm d^{-1}) will cause a total of 3 m^3 of either over- or underirrigation application in the same area. It will cause a 300 m^3 of over- or underirrigation in a 100 ha field. If these values were to be considered on a watershed or regional scale, the impact of accurate determination of $\mathrm{ET_o}$ or $\mathrm{ET_r}$ on managing, planning, and allocating water resources and on the hydrologic water balances would be better appreciated. In either case, the growers, ecosystems, and regions will be negatively affected. Lower estimations of ET will cause growers to underirrigate and this might impose stresses on the crops, thus negatively affecting plant growth and yield quantity and/or quality. Higher estimations of the ET will

Table 4. Statistics and results of paired sample *t*-tests (two-sample for means) for the $\mathrm{ET_{o,d}}$ versus $\mathrm{ET_{o,h,ASCE}}$ (mm d^{-1}) values ($\alpha = 0.05$) for the calendar year.

	Mean		Variance			*t*-test (one tail)		
Study Site	$\mathrm{ET_{o,h,ASCE}}$	$\mathrm{ET_{o,d}}$	$\mathrm{ET_{o,h,ASCE}}$	$\mathrm{ET_{o,d}}$	*df* [a]	t_{computed}	t_{critical}	$P_{(0.05)}$[b]
Bradenton	3.67	3.72	1.71	1.75	730	−3.5	1.64	*
Fort Pierce	3.49	3.54	1.71	1.59	365	−4.3	1.64	*
Santa Rosa	3.00	2.79	3.42	2.85	1,460	28.3	1.64	*
Santa Barbara	2.92	2.72	1.95	1.58	1,460	28.8	1.64	*
Twitchell Island	4.16	4.08	6.97	6.69	1,460	10.1	1.64	*
North Platte	3.11	3.28	4.82	5.24	1,825	−20.8	1.64	*
Bushland	4.73	5.00	7.51	7.64	1,095	−18.8	1.64	*

[a] *df* = degrees of freedom ($n - 1$).

[b] * = significant at the 5% significance level.

cause overirrigation and wasting of water resources, with attendant increase in nutrient and pesticide leaching to the groundwater or other water bodies.

COMPARISON OF $ET_{O,D}$ AND $ET_{O,H,ASCE}$ FOR PEAK ET MONTH

Analyses for the peak ET_o month are summarized in table 5. The month of peak ET_o was selected as the month having a maximum monthly total ET_o and not the month when the maximum daily ET_o occurred. The reason that there is more than one peak ET_o month for Santa Rosa, Twitchell Island, North Platte, and Bushland, as shown in table 5, is because the maximum monthly total ET_o did not occur in the same month in the study years. For example, at North Platte, the maximum monthly total peak ET_o occurred in May 1998, in June 2000, in July 2001, and in August 2002. Thus, the RMSD, average ratio of $ET_{o,d}$ to $ET_{o,h,ASCE}$, slope, intercept, and r^2 values in table 5 are the average of these peak ET_o months for Santa Rosa, Twitchell Island, North Platte, and Bushland. The agreement between $ET_{o,d}$ and $ET_{o,h,ASCE}$ for the peak months exhibited variation from one location to another, although ratios were still close to 1.0. For example, the RMSD values for Bushland, North Platte, and Santa Rosa were lower (0.36, 0.30, and 0.30 mm d^{-1}) for peak ET_o months than for the entire year (0.56, 0.37, and 0.36 mm d^{-1}). In general, the $ET_{o,d}$ computation procedure estimated higher than the $ET_{o,h,ASCE}$ during the calendar year (table 3) and estimated lower during the peak summer months at four of seven locations, with the ratio of $ET_{o,d}$ to $ET_{o,h,ASCE}$ timestep ranging from 0.95 to 1.05. On average, the $ET_{o,d}$ was 4.2% higher than $ET_{o,h,ASCE}$ at Bushland, and 5.1% higher at North Platte during the peak month (table 5). These findings are in agreement with Itenfisu et al. (2003), who observed that $ET_{o,h,ASCE}$ values were higher than daily values for 45 of 76 site-locations for growing seasons, but were lower at Bushland and North Platte.

QUANTIFICATION OF ADVECTION AND ITS EFFECT ON $ET_{O,D}$ VS. $ET_{O,H,ASCE}$

Figures 1a through 1g appear to show that the magnitude of the estimation by the $ET_{o,d}$ procedure relative to $ET_{o,h,ASCE}$ is somewhat greater at higher ET_o rates. For example, although there is a good correlation between the two computation procedures between the ET_o range from 0 to approximately 7 mm d^{-1} in North Platte, the estimation by the $ET_{o,d}$ procedure from 7 to 11 mm d^{-1} is greater than the $ET_{o,h,ASCE}$ procedure, and the regression line deviates from the 1:1 line more in that range than in the 0 to 7 mm d^{-1} range.

The presence of sensible heat advection was evaluated at each location by examining when the latent heat (LE, represented here by ET_o) was greater than available energy ($R_n - G$) (Rosenberg et al., 1983). Figure 2 contains plots showing the ratio of $ET_{o,h,ASCE}$, expressed as latent heat from a green grass surface, to net radiation on a 24 h basis for each study site. The advection was quantified for the traditional growing seasons (from March through September for California stations and from April through October for North Platte and Bushland). The growing season for Florida stations was assumed to be year round. Ratios closer to or greater than unity (1.0) indicate a high likelihood of advection of sensible heat as manifested in ET_o and reflect unrestricted evaporative losses (consumption of energy rather than generation). In humid locations (Bradenton and Fort Pierce), the ratio followed a consistent line fluctuating within a very narrow range from 0.4 to 0.5 and always running well below the unity line, indicating very little advection. This is expected due to the nature of humid climates. Similar results, albeit with higher ratios, were found for the California stations except Twitchell Island, where the ratio of ET_o to R_n was usually higher than for other California and Florida stations. The two Great Plains stations (North Platte and Bushland) had the largest deviation between the $ET_{o,d}$ and $ET_{o,h,ASCE}$ values and indicated a number of days (approximately 40 days) when daily ET_o exceeded daily available energy. Although ET_o/R_n ratios for most days were below unity, ratios were much closer to unity as compared with other stations. In addition to effects of advective anomalies on differences between the $ET_{o,d}$ and $ET_{o,h,ASCE}$ estimates, differences between the two timesteps may have stemmed from uncertainties associated with estimating soil heat flux (G) as a function of R_n. Analyses at Bushland using measured vs. estimated G showed that using $G = 0.1 \cdot R_n$ for daytime and $G = 0.5 \cdot R_n$ for nighttime periods impacts positively on the computation of $ET_{o,h,ASCE}$. For example, figure 3 shows a plot of hourly $ET_{o,h,ASCE}$ computed using measured R_n and G versus ET_o values computed using estimated R_n and G for Bushland (n = 26,298). Measured R_n and G were only available for Bushland. The relationship between the two ET_o values was good, with $r^2 = 0.988$. The relationship between the two ET_o values had an RMSD value of 0.03 mm h^{-1} and SD of 0.25 mm h^{-1}, with the ratio of ET_o with estimated R_n and G to ET_o with measured R_n and G averaging 0.94. Using estimated R_n and G estimated 6% lower than when ET_o was computed using measured R_n and G (fig. 3).

Table 5. Peak month ET_o statistics between $ET_{o,d}$ and $ET_{o,h,ASCE}$ values.

Study Site	n	Peak ET_o Month	Mean Value for $ET_{o,h,ASCE}$ (mm d^{-1})	RMSD of Daily Estimate[a] (mm d^{-1})	Average Ratio $ET_{o,d}/ET_{o,h,ASCE}$	Slope[b]	Int.[b]	r^2 [b]
Bradenton	31	May	5.61	0.23 (0.43)	0.98	0.771	1.139	0.863
Fort Pierce	31	May	5.07	0.29 (0.64)	1.00	0.857	0.694	0.810
Santa Rosa	92	June-July-Aug.	4.81; 4.97; 4.18	0.30 (0.56)	0.95	0.820	0.606	0.956
Santa Barbara	31	Aug.	4.09	0.22 (0.57)	0.95	0.883	0.279	0.990
Twitchell Island	61	June-July	7.34; 7.37	0.22 (0.61)	0.98	0.975	0.040	0.924
North Platte	123	May-June-July-Aug.	4.42; 5.70; 5.84; 4.98	0.30 (0.98)	1.05	1.050	−0.03	0.965
Bushland	61	June-July	7.10; 7.47	0.36 (1.01)	1.04	0.908	0.942	0.946

[a] RMSD values (mm d^{-1}) were calculated using the number of observations (n) in column 2. Values in parentheses indicate standard deviations between the ASCE-PM 24 h and SOH timestep ET_o.

[b] Regression coefficients where $ET_{o,d} = \text{slope} \cdot ET_{o,h,ASCE} + \text{intercept}$.

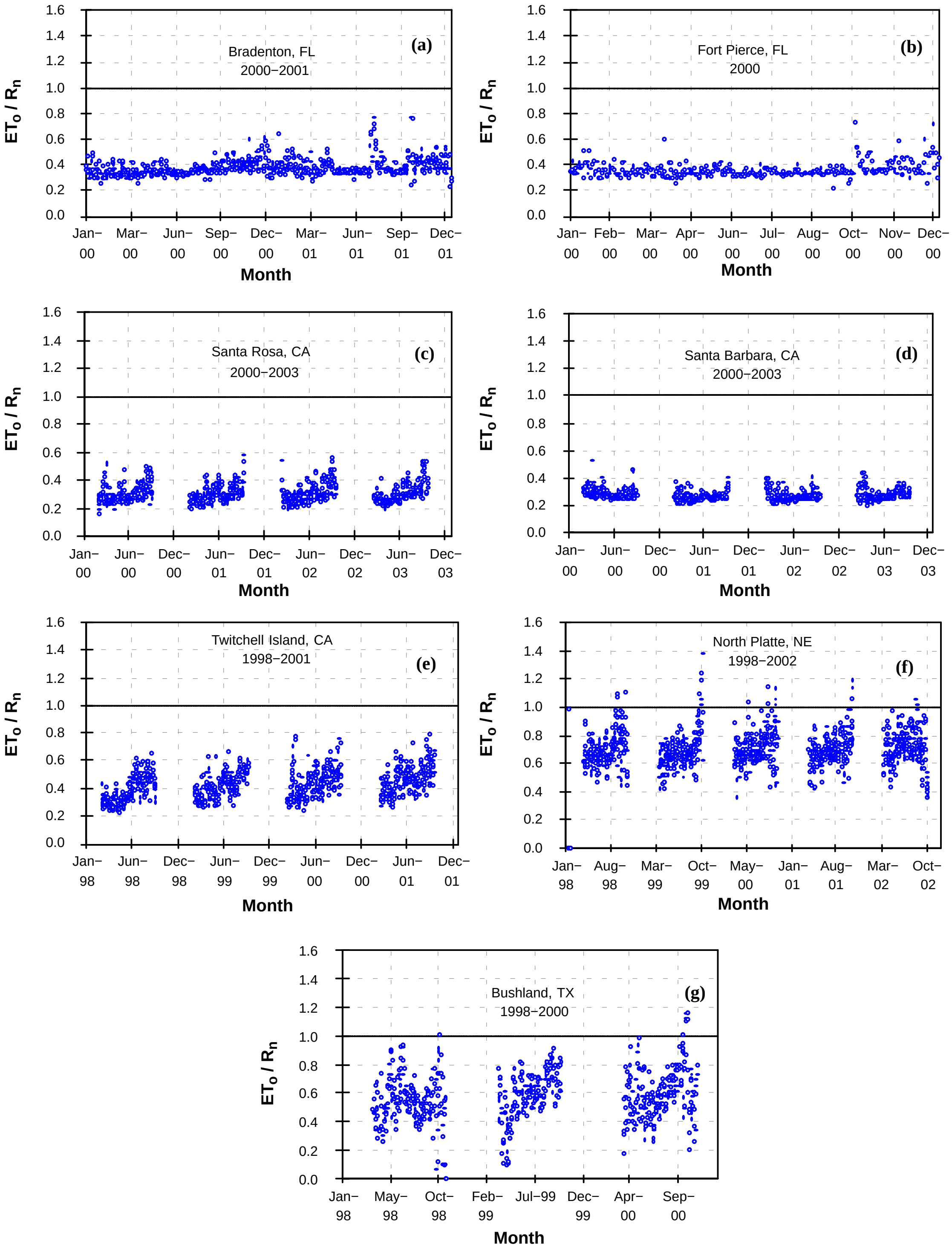

Figure 2. Daily ratios of reference evapotranspiration (ET$_o$), computed with 24 h timestep ASCE-PM (ET$_{o,d}$), to net radiation (R_n) to assess the advective conditions.

These RMSD and SD values are not large for ET$_{o,h,ASCE}$ values. However, they would have some impact when the hourly ET$_o$ values are summed. The difference between the two ET$_o$ values was significant ($P < 0.05$; $t_{critical} = 1.64$, $t_{computed} = -42.3$).

To demonstrate the uncertainties involved in estimating G, hourly measured vs. estimated G values for Bushland are plotted in figure 4 (n = 26,298). Measured G values in figure 4 were corrected for the heat storage changes in the soil layer above the plates, assuming constant water content in the upper layer of the soil profile. The following equations were used to correct the measured G values (Payero et al., 2001):

$$G = SHF + S \tag{6}$$

$$S = (T_i - T_{i-1}) \cdot D \cdot C_s / t \tag{7}$$

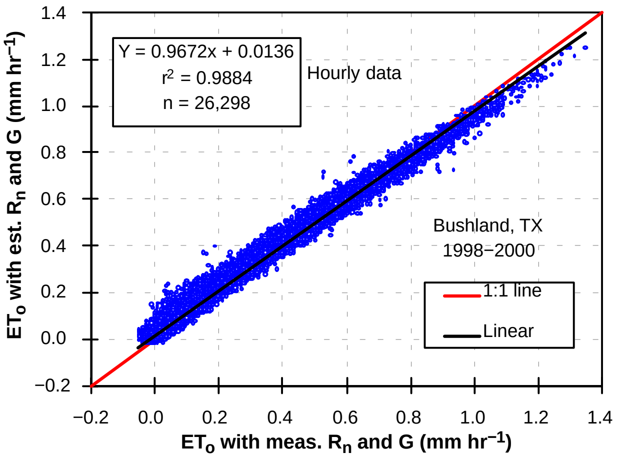

Figure 3. Relationship between ET_o computed using measured R_n and G vs. ET_o computed using estimated R_n and G for Bushland, Texas.

where

G = corrected measured soil heat flux (MJ m^{-2} h^{-1})
SHF = measured soil heat flux (MJ m^{-2} h^{-1})
S = change in stored heat above the soil heat flux plates (MJ m^{-2} h^{-1})
T_i = current soil temperature, measured at approximately 0.02 to 0.03 m below the soil surface (°C)
T_{i-1} = previous hour's soil temperature (°C)
D = depth to soil heat flux plate from the soil surface (0.05 m)
C_s = soil heat capacity (1.93 MJ m^{-3} K^{-1} for quartz constituent soils (Hillel, 1998) assuming the soil is at or near field capacity)
t = time interval (h).

At Bushland, the soil temperature and G measurements were made at four locations under the fescue grass. An average of the four measurements was used in the analyses (fig. 4).

The agreement between the measured and estimated (as fractions of R_n) G values in figure 4 is poor, with RMSD averaging 0.09 MJ m^{-2} h^{-1} and SD averaging 0.08 MJ m^{-2} h^{-1} and with a low r^2 of 0.275. Overall, using a constant G/R_n ratio ($G = 0.1 \cdot R_n$ and $G = 0.5 \cdot R_n$ for daytime and nighttime, respectively) for a given day resulted in large discrepancies from the measured values and might have introduced appreciable bias into the relationship. Although the fixed fractions of R_n are widely used in the estimations of G, Camuffo and Bernardi (1982) showed this ratio to vary considerably during the day. One of the issues with using a fixed fraction of R_n to estimate G is that the relationship between G and R_n suffers from hysteresis effects (Payero et al., 2001). Therefore, to avoid the hysteresis issue, G equations in remote sensing are usually derived using observations near noon hours, and therefore are not representative of diurnal patterns. Ventura et al. (1999) found that although daytime G is assumed to be 10% of R_n in the hourly FAO56-PM equation, the measured G under grass in California that was never shorter than 0.10 m was between 3% and 5% of R_n. Payero et al. (2001) developed an alternative improved model to estimate hourly G as a function of R_n and surface temperature for reference grass and for heights between 0.1 and 0.2 m. It is possible that the grass vegetation at Bushland had significant buildup of thatch (dead grass residue). A thick thatch will serve as an insulator, thereby reducing G. The 0.1 G to R_n ratio used in the ET_{os} standardization is for a low-thatch surface.

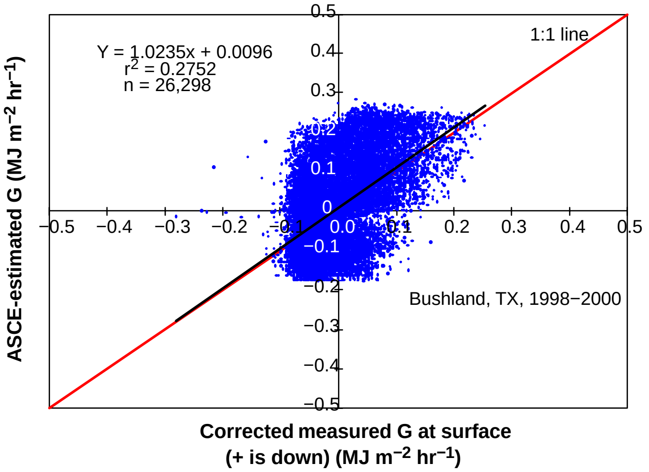

Figure 4. Relationship between hourly measured and estimated G ($G = 0.1 \cdot R_n$ for daytime and $G = 0.5 \cdot R_n$ for nighttime) for Bushland, Texas.

The $ET_{o,d}$ method estimated higher ET_o values than the $ET_{o,h,ASCE}$ method. The higher estimation by the $ET_{o,d}$ method as compared to the $ET_{o,h,ASCE}$ in North Platte and Bushland (figs. 1f and 1g, respectively) is possibly due to the impacts of estimating ET_o in the advective environments of these locations. Extremely high-quality lysimeter data are needed to be able to more conclusively assess the magnitude of the effect of advection on the relationship between the $ET_{o,d}$ and $ET_{o,h,ASCE}$ in advective environments.

COMPARISON OF SOH ASCE-PM ($ET_{O,H,ASCE}$) AND SOH FAO56-PM ($ET_{O,H,FAO}$) METHODS

The standardized ASCE-PM ET_o calculation for hourly or shorter timesteps differs from the FAO56-PM method in that the former uses coefficients representing $r_s = 50$ s m^{-1} during daytime and $r_s = 200$ s m^{-1} during nighttime, whereas the latter method uses coefficients representing $r_s = 70$ s m^{-1} for both daytime and nighttime. The relationships between the $ET_{o,h,ASCE}$ and $ET_{o,h,FAO}$ values are shown in figure 5. The performance indicators and regression parameters are given in table 6, and the statistical analyses between the two methods are reported in table 7. There was a good correlation between the $ET_{o,h,ASCE}$ and $ET_{o,h,FAO}$ values at all locations (fig. 5) with $r^2 \geq 0.997$. The RMSD between the $ET_{o,h,ASCE}$ and $ET_{o,h,FAO}$ values were considerably lower than those obtained by using the 24 h timestep (table 6), with Bradenton and Santa Barbara having the lowest RMSD values (0.16 and 0.17 mm d^{-1}). Twitchell Island and Bushland had the highest RMSD values (0.29 and 0.28 mm d^{-1}, respectively). The $ET_{o,h,FAO}$ method estimated lower than the standardized $ET_{o,h,ASCE}$ method at all locations and for all years due to the higher daytime r_s. Lower estimation is reflected in the average ratio of $ET_{o,h,FAO}$ to $ET_{o,h,ASCE}$ values in table 6. Estimations by the $ET_{o,h,FAO}$ ranged from −4.9% at North Platte to −8.1% in Santa Rosa relative to the $ET_{o,h,ASCE}$. The rates of lower estimation by the $ET_{o,h,FAO}$ method are in agreement with those reported by ASCE-EWRI (2004). ASCE-EWRI (2004) reported an average ratio of $ET_{o,h,FAO}$ to $ET_{o,h,ASCE}$ to range from 0.906 to 0.975 with an average of 0.947 for 49 sites. The average ratio of the seven sites in

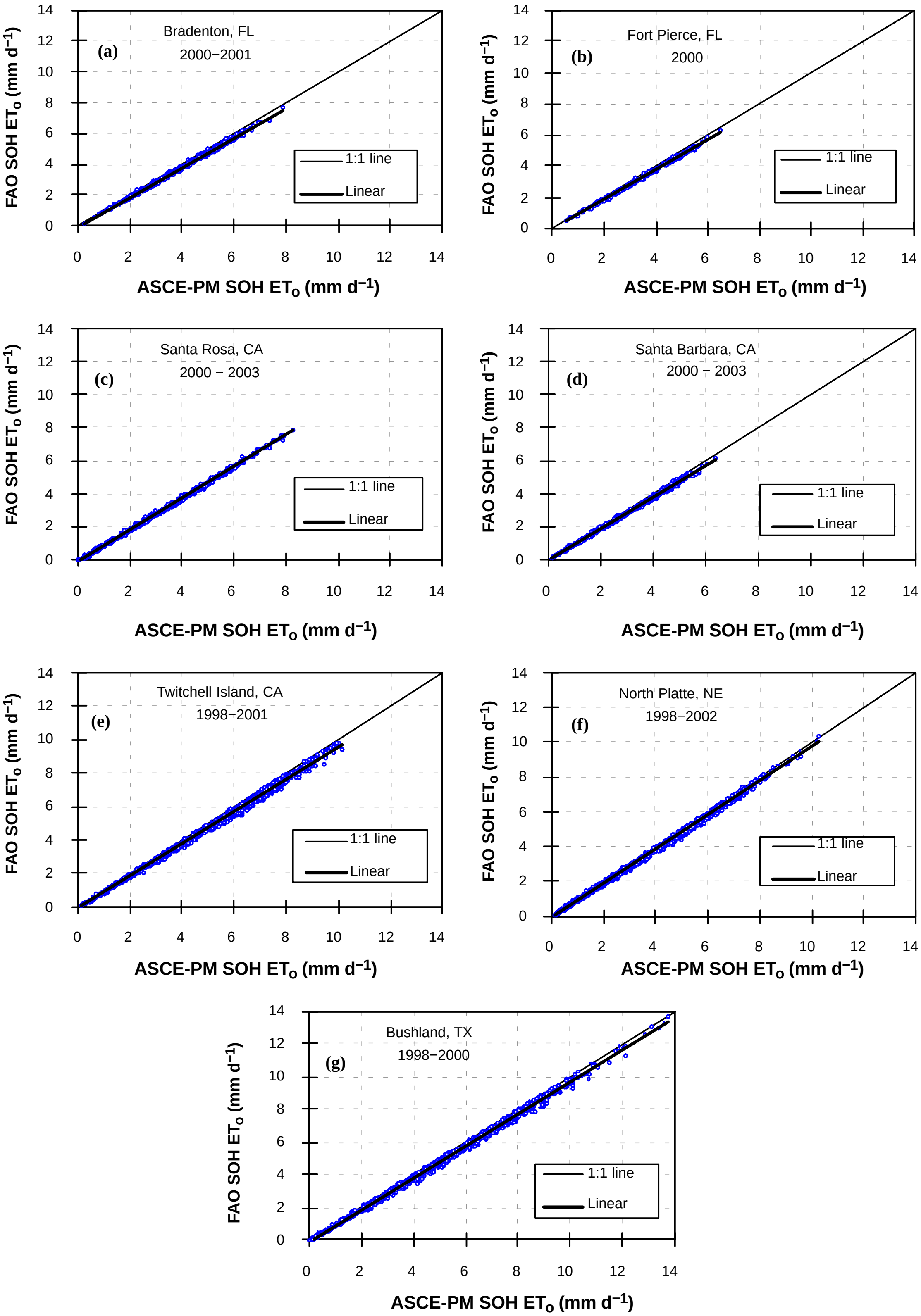

Figure 5. Relationship between the SOH ASCE-PM ET$_o$ (ET$_{o,h,ASCE}$) and SOH FAO56-PM ET$_o$ (ET$_{o,h,FAO}$).

this study is 0.940 (table 6). The ET$_{o,h,FAO}$ values were significantly different ($P < 0.05$) from the ET$_{o,h,ASCE}$ values for the seven locations (table 7). The underestimation by the ET$_{o,h,FAO}$ method was due to the 70 s m^{-1} r_s used by this method during daytime, as opposed to the 50 s m^{-1} r_s value used by the ET$_{o,h,ASCE}$ method. All other terms in the two methods are identical. The higher value for r_s (200 s m^{-1}) used by the ASCE-PM during nighttime tends to lower nighttime ET$_o$ estimates and therefore counters some of the increase in daytime estimates. However, nighttime ET$_o$ is generally small, so complete countering is rare.

Table 6. Performance indicators between $ET_{o,h,ASCE}$ and $ET_{o,h,FAO}$ values for the calendar year.

Study Site	n	RMSD of Daily Estimate (mm d^{-1})[a]	Average Ratio $ET_{o,h,FAO}/ET_{o,h,ASCE}$	Slope[b]	Intercept[b]	r^2 [b]
Bradenton	731	0.16 (1.35)	0.95	0.965	−0.05	0.998
Fort Pierce	366	0.21 (1.28)	0.93	0.953	−0.03	0.998
Santa Rosa	1,461	0.23 (1.81)	0.92	0.950	−0.05	0.999
Santa Barbara	1,461	0.17 (1.37)	0.95	0.949	−0.04	0.997
Twitchell Island	1,461	0.29 (2.59)	0.94	0.958	−0.05	0.997
North Platte	1,826	0.18 (2.16)	0.95	0.971	−0.05	0.998
Bushland	1,096	0.28 (2.71)	0.94	0.972	−0.09	0.997

[a] RMSD values were calculated using the number of observations (n) in column 2. Values in parentheses indicate standard deviations.

[b] Regression coefficients where $ET_{o,h,FAO}$ = slope·$ET_{o,h,ASCE}$ + intercept.

Table 7. Statistical analyses (paired sample *t*-test; two-sample for means) between the $ET_{o,h,ASCE}$ versus $ET_{o,h,FAO}$ (mm d^{-1}) values ($\alpha = 0.05$) for the calendar year.

	Mean		Variance			*t*-test (one tail)		
Study Site	$ET_{o,h,ASCE}$	$ET_{o,h,FAO}$	$ET_{o,h,ASCE}$	$ET_{o,h,FAO}$	*df* [a]	$t_{computed}$	$t_{critical}$	$P_{(0.05)}$[b]
Bradenton	3.77	3.58	1.89	1.76	730	60.9	1.64	*
Fort Pierce	3.49	3.30	1.71	1.56	365	42.3	1.64	*
Santa Rosa	3.00	2.80	3.42	3.09	1,460	69.4	1.64	*
Santa Barbara	2.92	2.77	1.95	1.78	1,460	69.4	1.64	*
Twitchell Island	4.16	3.93	6.97	6.41	1,460	50.6	1.64	*
North Platte	3.11	2.98	4.81	4.54	1,825	54.0	1.64	*
Bushland	4.73	4.50	7.51	7.12	1,095	44.8	1.64	*

[a] *df* = degrees of freedom (n − 1).

[b] * = significant at the 5% significance level.

Table 8. Performance indicators between $ET_{o,d}$ and $ET_{o,h,ASCE}$ values for multiple days and longer periods (n = 52 for weekly, n = 12 for monthly, and n = 1 to 5, depending on the years studied for a given location, for annual analyses).

	$ET_{o,d}$ versus $ET_{o,h,ASCE}$											
	Weekly Sum					Monthly Sum					Annual Sum	
Site	RMSD[a] (mm $week^{-1}$)	Avg. Ratio[b]	Slope[c]	Int.[c]	r^2	RMSD[a] (mm mo^{-1})	Avg. Ratio[b]	Slope[c]	Int.[c]	r^2	RMSD[a] (mm $year^{-1}$)	Avg. Ratio[b]
Bradenton	1.0 (7.8)	1.01	1.02	−0.25	0.99	3.5 (33.2)	1.01	1.04	−3.12	0.99	18.4 (13.0)	1.01
Fort Pierce	1.0 (7.3)	1.02	1.00	0.45	0.98	3.4 (29.6)	1.02	−1.01	0.008	0.99	20.2 (14.2)	1.02
Santa Rosa	1.8 (11.1)	0.95	0.92	0.27	0.99	6.7 (46.0)	0.94	0.95	−0.82	0.99	65.3 (46.2)	0.94
Santa Barbara	2.0 (8.4)	0.92	0.94	−0.36	0.98	7.8 (34.6)	0.92	0.98	−5.05	0.99	85.5 (60.4)	0.93
Twitchell Island	1.3 (16.1)	1.01	0.98	−0.01	0.99	4.3 (68.8)	0.99	0.98	−0.70	0.99	32.1 (22.7)	0.98
North Platte	1.6 (13.5)	1.07	1.03	0.50	0.99	5.9 (54.5)	1.07	1.03	2.46	0.99	58.6 (41.4)	1.05
Bushland	1.6 (19.3)	1.03	0.97	1.21	0.99	5.4 (79.9)	1.03	0.97	5.41	0.99	9.29 (6.60)	1.00

[a] Root mean squared difference (RMSD) of weekly (mm $week^{-1}$), monthly (mm $month^{-1}$), and annual (mm $year^{-1}$) sum estimates. Values in parentheses indicate standard deviations between the 24 h and SOH timestep ASCE-PM ET_o.

[b] Average ratio of $ET_{o,d}$ to $ET_{o,h,ASCE}$.

[c] Regression coefficients where $ET_{o,d}$ = slope·$ET_{o,h,ASCE}$ + intercept.

MULTIPLE DAYS AND LONGER-TERM COMPARISONS OF $ET_{O,D}$ AND $ET_{O,H,ASCE}$ FOR CALENDAR YEAR AND PEAK ET_O MONTH

Field-scale irrigation systems, such as a center pivot in a fine-textured soil (e.g., silty-loam or clay), require from 3 to 7 days to complete one irrigation cycle. The application depth for this system may be a sum of 3 or more days of daily ET. In this case, the sum of daily ET_o for multiple days and longer periods (i.e., weekly, monthly, and annual) becomes important. Table 8 shows the comparison statistics between the $ET_{o,d}$ and $ET_{o,h,ASCE}$ values on a weekly, monthly, and annual sum basis. This process would help to assess whether summing daily ET_o values over longer periods would reduce the risk of using daily ($ET_{o,d}$) values as compared with the ET_o values computed on an SOH basis. In general, the results in table 8 show that summing the ET_o values over a weekly, monthly, and annual basis somewhat reduced the differences between the $ET_{o,d}$ and $ET_{o,h,ASCE}$ values as compared with the values reported in table 3. However, the differences were not reduced with similar magnitudes at all locations. For example, at Fort Pierce, the r^2 increased from 0.965 to 0.990 (table 3 vs. table 8), the average ratio decreased from 1.03 to 1.02 (table 3 vs. table 8) with data points scattering closer to 1:1 line when ET_o values were summed on a weekly (7 day) period. Similar results were obtained when the ET_o values were summed over monthly period. However, a difference of 1.0 mm $week^{-1}$, 3.5 mm $month^{-1}$, and 18.4 mm $year^{-1}$ still exists between the $ET_{o,d}$ and $ET_{o,h,ASCE}$ values when daily ET_o values were summed over a weekly, monthly, and annual basis, respectively (table 8). The differences between the two ET_o timesteps showed significant variations from one location to another. For example, at Santa Barbara and Santa Rosa, the differences on an annual basis were 85.5 and 65.3 mm $year^{-1}$, respectively, while at Bradenton, the difference on an annual basis was 18.4 mm $year^{-1}$. The 85.5 and 65.3 mm of water will make a considerable difference in terms of designing and planning of irrigation and drainage systems and other water storage infrastructure. These differences suggest that using a 24 h timestep rather than the SOH timestep would result in underestimations of ET_o of as much as 6% to 8% based on the weekly, monthly, and annual average ratios given in table 8, and this may cause improper design of water management infrastructure. The Santa Rosa and Santa Barbara stations resulted in the largest weekly and monthly differences among all stations (table 8). The Bushland station resulted in the smallest difference (9.29 mm year^{-1}) between the two ET_o computation procedures on an annual basis.

Table 9 summarizes the performance indicators to assess the differences between $ET_{o,d}$ and $ET_{o,h,ASCE}$ values when the ET_o values were summed over 3-day, weekly, and monthly periods in peak ET months. The peak ET_o month for each location is given in table 5. When the $ET_{o,d}$ values were summed over a 3-day period for the peak ET_o months, the differences between the two computation timesteps showed considerable variations with location. In some locations, the differences between the two timesteps were lower than the values reported in table 5. However, in some locations, the differences were higher than they were for the daily comparisons. For example, when the $ET_{o,d}$ values were summed for a 3-day period, the differences were lower (higher r^2 between the $ET_{o,d}$ and $ET_{o,h,ASCE}$ values) at Bradenton, Santa Rosa, and Twitchell Island, whereas the differences were higher (lower r^2 values, higher deviation) at Fort Pierce, North Platte, and Bushland (table 9). Summing the ET_o values over a 3-day period did not change the errors associated with using the 24 h timestep procedure at Santa Barbara (table 9). Similar results were obtained for the weekly and monthly sum comparisons (table 9). The largest 3-day, weekly, and monthly differences between the $ET_{o,d}$ and $ET_{o,h,ASCE}$ values were at North Platte and Santa Rosa, whereas the smallest differences were at Bradenton. These results suggest that summing the $ET_{o,d}$ values over multiple days and longer periods for the peak ET_o months resulted in inconsistent differences with location. In some locations (Fort Pierce, North Platte, and Bushland), there is a risk associated with summing the $ET_{o,d}$ values over multiple days in peak ET_o months as compared with using the $ET_{o,h,ASCE}$ values. However, summing the $ET_{o,d}$ values over multiple days improved (lower RMSD and higher r^2, table 9) the relationship between the two ET_o computation procedures at Bradenton, Santa Rosa, and Twitchell Island for the peak ET_o months. The comparisons between the $ET_{o,h,ASCE}$ and $ET_{o,h,FAO}$ values were not made for multiple days or longer periods. This is because the $ET_{o,h,FAO}$ values were consistently below the $ET_{o,h,ASCE}$ values (fig. 5) at all locations. Over the multiple days and longer periods, the magnitude of the difference between the two computation procedures would be steadily increasing over the 3-day, weekly, monthly, and annual sum basis, with the $ET_{o,h,FAO}$ values consistently running below the $ET_{o,h,ASCE}$ values at all locations.

SUMMARY AND CONCLUSIONS

The standardized hourly ASCE-PM model was evaluated to assess differences between using a 24 h computation timestep for ET_o ($ET_{o,d}$) as compared with the sum-of-hourly (SOH) ET_o ($ET_{o,h,ASCE}$) in different climates. The SOH FAO56-PM ET_o values ($ET_{o,h,FAO}$) were also compared against $ET_{o,h,ASCE}$ values. The agreement between the $ET_{o,h,ASCE}$ and $ET_{o,d}$ procedure was reasonable at most locations. However, our results on comparisons between the $ET_{o,d}$ versus $ET_{o,h,ASCE}$ values indicated that there are significant differences between the two sets of ET_o values. The differences between the two ET_o computation procedures were attributed partly to uncertainties in using constant ratios of G to R_n in the hourly computation timesteps and possibly to the inability of the 24 h timestep computation procedure to account for the effect of abnormal diurnal changes in wind speed, air temperature, and vapor pressure deficit. Differences between the two calculation timesteps ranged from −2.7 to +9% (24 h less SOH) on an annual basis and from −5.2 to +5.1% for peak ET_o months. At Bushland, the RMSD was 0.56 mm d^{-1}.

In general, summing the ET_o values over a weekly, monthly, and annual basis (for the calendar year) somewhat reduced the differences between the $ET_{o,d}$ and $ET_{o,h,ASCE}$ ET_o values. However, the differences were not reduced with similar magnitudes at all locations. The differences suggested that using a 24 h timestep rather than the SOH approach would result in underestimations of ET_o of as much as 6% to 8% depending on the location. Summing the $ET_{o,d}$ values over multiple days and longer periods for the peak ET_o

Table 9. Performance indicators between $ET_{o,d}$ and $ET_{o,h,ASCE}$ values for multiple days for peak ET_o months (n = 10 for 3-day, n = 4 for weekly, and n = 1 to 4 (depending on the years studied for a given location) for monthly analyses).

	$ET_{o,d}$ versus $ET_{o,h,ASCE}$											
	Three-Day Sum					Weekly Sum					Monthly Sum	
Site	RMSD[a] (mm 3d^{-1})	Avg. Ratio[b]	Slope[c]	Int.[c]	r^2	RMSD[a] (mm week^{-1})	Avg. Ratio[b]	Slope[c]	Int.[c]	r^2	RMSD[a] (mm mo^{-1})	Avg. Ratio[b]
Bradenton	0.42 (1.29)	1.00	0.96	0.67	0.90	0.67 (1.91)	1.00	0.97	1.10	0.87	1.24 (0.88)	1.00
Fort Pierce	0.73 (1.49)	1.00	0.88	1.81	0.77	1.44 (2.48)	1.00	1.00	−0.33	0.68	1.02 (0.72)	0.99
Santa Rosa	0.76 (1.22)	0.96	0.77	2.70	0.96	1.75 (2.57)	0.95	0.74	7.10	0.98	6.93 (4.90)	0.95
Santa Barbara	0.61 (1.81)	0.96	0.85	1.19	0.99	1.37 (2.46)	0.95	0.92	0.95	0.98	5.30 (3.75)	0.96
Twitchell Island	0.44 (0.80)	0.99	0.85	3.00	0.79	0.93 (1.55)	0.99	0.84	7.81	0.74	2.47 (1.75)	0.99
North Platte	0.98 (1.82)	1.05	1.05	0.01	0.97	2.20 (3.12)	1.05	1.11	−2.44	0.97	9.77 (6.91)	1.05
Bushland	0.61 (1.44)	1.02	0.84	0.98	0.98	1.32 (2.13)	1.02	0.87	8.02	0.99	5.96 (4.22)	1.02

[a] Root mean square difference (RMSD) of 3-day (mm 3-days^{-1}), weekly (mm week^{-1}), and monthly (mm month^{-1}) sum estimates. Values in parenthesis indicate standard deviations between the 24 h and SOH timestep ASCE-PM ET_o.

[b] Average ratio of $ET_{o,d}$ to $ET_{o,h,ASCE}$.

[c] Regression coefficients where $ET_{o,d}$ = slope·$ET_{o,h,ASCE}$ + intercept.

months resulted in inconsistent differences with location. In some locations (Fort Pierce, North Platte, and Bushland), there is a risk associated with summing the two $ET_{o,d}$ values over multiple days in peak ET_o months as compared with using the $ET_{o,h,ASCE}$ values. However, summing the $ET_{o,d}$ values over multiple days for the peak ET_o months improved (lower RMSD and higher r^2) the relationship between the two ET_o computation procedures at Bradenton, Santa Rosa, and Twitchell Island, and did not change the differences at Santa Barbara.

The $ET_{o,h,FAO}$ values agreed well with the $ET_{o,h,ASCE}$ values in all cases, with $r^2 \geq 0.997$ and low RMSD values (ranging from 0.16 mm d^{-1} at Bradenton to 0.29 mm d^{-1} at Twitchell Island). Although the $ET_{o,h,FAO}$ produced acceptable ET_o estimates, it estimated lower than the $ET_{o,h,ASCE}$ as −8.1% at Santa Rosa and −4.9% at North Platte. A substantial portion of the low estimation by the $ET_{o,h,FAO}$ method was due to the use of higher surface resistance (70 s m^{-1}) during daytime periods in the hourly timestep application as compared to the hourly standardized ASCE-PM, which uses 50 s m^{-1} resistance during daytime and 200 s m^{-1} during nighttime. Results suggest the benefit and potentially improved accuracy of using the standardized ASCE-PM procedure applied hourly as opposed to applying it with a 24 h timestep basis. The hourly application helps to account for impacts of abrupt diurnal changes in atmospheric conditions on ET_o estimation in advective and other environments, when hourly climate data are available.

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