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Measuring versus estimating net radiation and soil heat flux: Impact on Penman–Monteith reference ET estimates in semiarid regions

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ABSTRACT

The standardized ASCE Penman–Monteith and FAO-56 equations were used to estimate reference evapotranspiration (ET_0) using estimated and measured net radiation (R_n) and soil heat flux (G), based on hourly and daily meteorological data. The estimates were evaluated against lysimeter measurements. The results indicate that using measured or estimated values of R_n and G can have significant effect on the accuracy of the ET_0 estimations, especially when calculations were made on an hourly basis. The FAO-56 version performed very well during the irrigation season on a daily basis. The use of measured R_n and G did not improve ET_0 estimation on a daily basis, therefore, the use of estimated R_n and G appears to be dependable when calculations are based on 24-h weather data. When daily ET_0 was calculated from hourly estimations, the results were different depending on the version used. The ASCE version was more accurate, especially when R_n and G were measured. Therefore, measurement of R_n and G may have potential to improve estimation only when daily ET_0 is calculated from hourly estimations. The PM FAO-56 version was always a little less accurate than the ASCE version. For hourly calculations, using a constant surface resistance (as in FAO-56 version), the PM method underpredicted for high evaporative demand and vice versa. The ASCE version performed better than PM FAO-56 version when R_n and G were measured and estimated. Therefore, ASCE version tended to provide quite accurate values of hourly ET_0, even using estimated values of R_n and G. As conclusion, the methods proposed by FAO-56 for estimating R_n and G tended to produce accurate estimates for daily and hourly ET_0 under semiarid conditions and can be used with some degree of confidence for estimating ET_0. In addition, results suggest that the ASCE standardized equation on an hourly basis improved the accuracy of ET_0 estimation with respect to the FAO-56 version.

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1. Introduction

Accurate estimations of crop water requirements are necessary for planning and efficient use of water resources, mainly in arid or semiarid environments where agricultural consumptive uses are relatively high and lack of precipitation limits crop growth and yield. The standard method to quantify consumptive use of water by crops uses the concept of reference crop, defined as an "extensive surface of green grass of uniform height −8 to 15 cm tall—actively growing, completely shading the ground and not short of water" (Doorenbos and Pruitt, 1977) and as "a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23" (Allen et al., 1998). Reference crop evapotranspiration (ET_0) is computed and adjusted by an empirical crop coefficient (K_c) to produce an estimate of crop evapotranspiration (ET_c).

The most accurate way to measure ET_0 is by using weighing lysimeters or micrometeorological methods, but these procedures are no practical, as they are time consuming and expensive. ET_0 can be also estimated from climatic data. Some methods of estimation derive from sound physical principles governing the process, but most of them are empirical and usually rely on statistical correlations between ET_0 and one or more climatic variables (Sharma, 1985). The performance of different equations has been evaluated under different climate conditions (Allen et al., 1989; Katul et al., 1992; Amatya et al., 1995; Smith et al., 1996; Ventura et al., 1999; Berengena and Gavilán, 2005). These studies have indicated the superiority of the Penman–Monteith (PM) equation for estimating ET_0 over a wide range of climates (Jensen et al., 1990). That is why the PM equation is strongly recommended as the standard equation for estimating ET_0 by United Nations Food and Agriculture Organization (FAO) and by the American Society of Civil Engineers (ASCE) (Walter et al., 2001; ASCE-EWRI, 2005).

The application of PM equation requires measurements of solar radiation (R_s), temperature (T) and relative humidity (RH) of the air and wind speed (U). Besides, it requires measurements or estimates of net radiation (R_n), soil heat flux (G) and vapor pressure deficit (VPD). Procedures to estimate these parameters are described by different authors (Doorenbos and Pruitt, 1977; Jensen et al., 1990; Allen et al., 1998; Ortega-Farias et al., 2000; Irmak et al., 2003). In many cases, as they are simple empirical equations, the accuracy of the methods to estimate R_n and G affects the reliability of the ET_0 estimations (Batchelor, 1984). In addition, the use of different equations to estimate these parameters causes confusion among engineers and agronomists. Therefore, it is useful to evaluate the effects of using these equations on the accuracy of ET_0 estimates. The uncertainties in the ET_0 estimates can be minimized by measuring, instead of estimating, variables and parameters (Batchelor, 1984). However, different types of instruments may be used for this purpose, and their effect on accuracy of ET_0 due to instrumental errors is often unknown. Besides, they are expensive and are not frequently used in meteorological station networks. Another problem is that net radiometers and soil heat flux plates must be used on well-watered grass fields, which are difficult to find and to maintain as irrigated plots in arid and semiarid areas (Llasat and Snyder, 1998). Therefore, R_n and G are often estimated from other parameters.

The most accurate way to measure R_n is by using a four-component system, which measures short and long-wave radiation balances. Nevertheless, this system is very expensive, especially for weather station networks, with stations located in remote sites and designed to be nearly maintenance free (visited no more than two or three times per year) (Brotzge and Duchon, 2000). Net radiometers are the devices that measure R_n with a single instrument. These are cheaper than four-component systems, but they must be accurate and relatively maintenance free, especially if they are to be permanently deployed. These instruments generally use a thermopile sensor enclosed by hemispherical domes to protect them from environmental conditions. They generally use polyethylene domes to eliminate natural ventilation and reduce heat loss by thermal convection from the radiometer body (Field et al., 1992; Brotzge and Duchon, 2000). The main disadvantages of polyethylene domes are: (1) different transmissivity to different wavelengths of the radiation spectrum (Field et al., 1992; Halldin and Lindroth, 1992); (2) degradation over short-time periods of exposure (less than 3 months), requiring frequent substitution; (3) breaking of the domes, caused mainly by birds, and possible water entry inside the radiometer body, thus affecting the calibration of the system (Cobos and Baker, 2003). The domeless NR-Lite net radiometer (Kipp & Zonen) has been developed in order to reduce and simplify maintenance. This instrument differs from others in that the domes covering the thermopile sensor have been replaced with black Teflon coating. At the present time, it is the only domeless net radiometer commercially available. The manufacturer claims that this instrument is less accurate than the domed net radiometers normally used, mainly due to its loss of precision under high wind speeds. Nevertheless, a field evaluation of the accuracy of ET_0 estimates using both types of net radiometers is appropriate.

G is measured by using the combination method that combines soil heat storage with heat flux measurements (Fuchs, 1986). It requires soil temperature, soil moisture and heat flux plate measurements. However, this approach is vulnerable to errors in the input data set originating from errors in the calibration and placement depths of the sensors and from inhomogeneities of the soil profile (Liebethal et al., 2005). Therefore, it is common to estimate this flux from R_n (Clothier et al., 1986; Allen et al., 1998; Payero et al., 2005). An evaluation of ET_0 estimations using measured and estimated G is advisable.

The Agroclimatic Information Network of Andalusia, in Southern Spain, as part of the Irrigation Advisory Service of the regional government (Ruiz et al., 2005), calculates daily ET_0 using the Penman–Monteith equation FAO-56 version on a daily basis (Gavilán et al., 2003). Up till now, the ET_0 methods are being used mainly for computation on a daily basis because hourly data are not readily accessible. Fortunately, availability of automated weather stations that collect data every hour is increasing. Also, recent works suggest an improvement in accuracy when using the standardized ASCE Penman–Monteith equation on an hourly basis because this time step allows to account for the effects of diurnal changes in wind speed, air temperature and VPD (Irmak et al., 2005).

This equation, applied on an hourly basis, uses surface resistances (r_s) of 50 and 200 s m^{-1} for daytime and nighttime, respectively, in contrast to the FAO-56 version that is based on a r_s of 70 s m^{-1}. Therefore, a comparison between estimations in both hourly and daily basis using ASCE and FAO-56 versions would be advisable under our semiarid conditions using measured and estimated R_n and G.

The objective of this study was to evaluate ET$_0$ estimates using estimated and measured R_n and G, with mean daily and hourly meteorological data. Four years of meteorological and lysimeter data were used for the comparisons.

2. Materials and methods

2.1. *Site description and dates of measurements*

The study was carried out at the Experimental Station of the "Alameda del Obispo" (37°51′N, 4°51′W, 110 m above mean see level) located at the IFAPA Agricultural Training and Research Center, near Córdoba, Southern Spain, in the Guadalquivir Valley. The climate in the experimental site is Mediterranean semiarid. Mean annual ET$_0$ is 1387 mm, whereas mean annual precipitation is 536 mm. The mean annual maximum and minimum daily air temperatures are 24.6 and 10.7 °C, respectively, and the annual average wind speed at 2 m height is 1.7 m s^{-1}. Mean annual relative humidity is 62%. The experimental data were collected from June through September during the 1999, 2000 and 2001 irrigation seasons and throughout the whole year during 2004, on a rectangular grass (*Festuca arundinacea* Schreb) plot of about 1.3 ha (120 m × 110 m), which was used as a reference surface for ET$_0$ measurements. During the irrigation season, the plot was irrigated twice per week (Monday and Friday) to fulfill the crop water requirements, and it was mowed on Mondays, just before watering, to keep the grass about 12 cm high (between 10 and 15 cm) while collecting the experimental data (Wednesdays and Thursdays). The grass cover is typically fertilized three times per year with nitrogen–phosphorus–potassium fertilizer. The grass thatch (dead, decaying leaves) is removed once each year during spring time.

2.2. *Weighing lysimeter*

ET$_0$ was measured by a high precision weighing lysimeter located at the center of the field. The lysimeter tank has a surface of 6 m^2 (3 × 2) and a depth of 1.5 m. It is supported by a counter-weighted platform scale able to detect about 0.1 kg weight variation (equivalent to 0.02 mm depth of water over the lysimeter). The lysimeter weight was sensed by a load cell (model TSF-P, Epel Ind. S.A.) connected to a datalogger CR510 (Campbell Scientific, CSI), which was programmed to store the weight every hour during 1999 and every half-hour during 2000, 2001 and 2004. The outputs were obtained as the average of 120 readings taken every 2 s over a 4-min period centered at the respective sampling times, so that fluctuations in weight due to wind friction on the lysimeter surface were smoothed. The load cell was calibrated each year at the beginning of the irrigation season. For the analysis, the irrigation and mowing days were discarded, as well as those days when vegetation moisture might alter the standard reference conditions. During the experiments, visible differences between the grass inside and outside the lysimeter were not apparent at all.

2.3. *Meteorological measurements*

An automatic weather station controlled by a programmable CR10X datalogger (CSI) was located on the grass field 30 m from the lysimeter. The station consisted of sensors to measure air temperature and relative humidity (HMP45A probe, Vaisala), solar radiation (pyranometer CM 6B, Kipp & Zonen), and wind speed and direction (anemometer A100R and wind vane W200P, Vector Inst.). Temperature–humidity probe and wind sensors were placed 1.5 and 2.0 m above the surface, respectively. From 1999 to 2001, R_n was measured by a domed net radiometer Q-7.1 (Radiation and Energy Balance Systems, REBS) and by a domeless net radiometer NR-Lite (Kipp & Zonen). During 2004 only the NR-Lite net radiometer was used in the experiment. G was obtained from the readings of two soil heat flux plates (HFP01, Hukseflux) buried at a depth of 80 mm. G at the surface was determined by correcting the flux at 80 mm depth for soil heat storage above the plates, calculated from temperature changes in the soil volume above the heat flux plates ("combination approach"). Four soil thermocouples (TCAV) were installed so that a pair of them was used to obtain the average temperature of the soil layer above one heat plate, and the other one, above the second plate; they were located at 20 and 60 mm depth. Flux plates were located about 1.5 m apart from each other. The heat flux at 80 mm depth was calculated from the average outputs of the two plates. Hourly and semi-hourly mean values were registered during 1999 and from 2000 to 2004, respectively.

Measurements of net radiometers were corrected for wind effects according to the manufacturer recommendations. NR-Lite outputs were previously corrected by a 10% increase (Brotzge and Duchon, 2000), as recommended by the manufacturer based on results obtained from a field comparison made by these authors. Domes of Q-7.1 net radiometer were periodically replaced according to manufacturer recommendations, and never were exposed either to irrigation water. R_n was measured at a height of 1.30 m in both cases, so that the measurements represented the same source areas.

2.4. *Data integrity and quality analysis*

Accuracy of ET$_0$ calculations depends on quality and integrity of meteorological data used (Allen et al., 1996). Therefore, data quality control is necessary. Different procedures for quality assurance are described by Meek and Hatfield (1994), Allen (1996), Shafer et al. (2000) and Feng et al. (2004). In this work, integrity of meteorological data was evaluated for all values used and only those that passed the test were used in the analysis. Different tests were performed for temperature, relative humidity, solar radiation and net radiation. A range test based on monthly climate extremes in Córdoba, furnished by the Spanish National Meteorological Institute (INM) was applied. Temperature observations were evaluated using this range test.

RH data were also screened by applying a range test, flagging these values outside the range 5–100%. A specific test was performed for R_s measurements, according to Allen et al. (1996). The method compared measured R_s against computed short wave radiation expected under clear sky conditions (R_{so}). Daily values of R_{so} were calculated as a function of the site elevation and extraterrestrial radiation (R_a). On a completely clear day, R_s values should closely follow the R_{so} tendency and then, solar radiation values that were consistently above or below R_{so} on clear days were flagged. Days for which one or more observations were flagged or not available were excluded in the analysis.

2.5. *Net radiation and soil heat flux estimations*

R_n was estimated using measured R_s, T and actual vapor pressure data according to Allen et al. (1998) on both hourly and daily time step basis. R_n was calculated as the difference between incoming net short-wave irradiance (R_{ns}) and the outgoing net long-wave irradiance (R_{nl}):

$$R_n = R_{ns} - R_{nl} \tag{1}$$

R_{ns} was calculated as

$$R_{ns} = (1 - \alpha)R_s \tag{2}$$

where α is the albedo or canopy reflection coefficient, which was set to 0.23 for our reference crop (Allen et al., 1998).

R_{nl} is computed as

$$R_{nl} = \sigma\left[\frac{T_{max}^4 + T_{min}^4}{2}\right](0.34 - 0.14(e_a)^{1/2})\left(\frac{1.35R_s}{R_{so} - 0.35}\right) \tag{3}$$

where σ is the Stephan–Boltzmann constant (4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1}); T_{max} and T_{min} are the maximum and minimum absolute temperatures (K). For hourly calculations, T_{max} and T_{min} were replaced by the corresponding hourly mean temperature and $\sigma = 2.042 \times 10^{-10}$ MJ K^{-4} m^{-2} h^{-1}; e_a the actual vapor pressure (kPa); R_{so} is the clear-sky solar irradiance (MJ m^{-2} day^{-1} or MJ m^{-2} h^{-1}), calculated as

$$R_{so} = (0.75 + 2 \times 10^{-5}z)R_a \tag{4}$$

where z is the elevation of the site above mean sea level (m) and R_a is the extraterrestrial solar irradiance (MJ m^{-2} day^{-1}).

For daily calculations, G may be ignored ($G \cong 0$). Hourly means of G were estimated as a function of R_n for day and nighttime periods as

$$G_{h\,daytime} = 0.1R_n \tag{5}$$

$$G_{h\,nighttime} = 0.5R_n \tag{6}$$

2.6. *Reference ET equations*

2.6.1. *ASCE Penman–Monteith (ASCE-PM) ET$_0$ equation*

The standardized ASCE-PM equation is an attempt to simplify and clarify the application of the Penman–Monteith equation, using a single expression for both grass and alfalfa reference surfaces and for daily or hourly time step. For grass, this version assumes r_s values of 50 s m^{-1} during the daytime and 200 s m^{-1} at night for hourly time steps, and 70 s m^{-1} for daily time steps. The standardized ASCE-PM equation is expressed as

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma(C_n/(T_a + 273))U_2(e_s - e_a)}{\Delta + \gamma(1 + C_d U_2)} \tag{7}$$

where ET$_0$ is the reference evapotranspiration (mm h^{-1} or mm day^{-1}); Δ the slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1}); R_n the net radiation (MJ m^{-2} h^{-1} or MJ m^{-2} day^{-1} for hourly and daily time step, respectively); G the soil heat flux (MJ m^{-2} h^{-1} or MJ m^{-2} day^{-1} for hourly and daily time step, respectively); γ the psycrometric constant (kPa °C^{-1}); T the mean hourly or daily air temperature (°C); U_2 the mean hourly or daily wind speed at 2 m height (m s^{-1}); e_s the saturation pressure deficit (kPa); e_a the actual pressure deficit (kPa); C_n and C_d are the numerator and denominator constant for a reference type and calculation time step. For grass reference surface, ASCE-PM has C_n values of 900 and 37 for daily and hourly time steps, respectively. C_d has a fixed value of 0.34 for the daily time step and values of 0.24 and 0.96 during the daytime and the nighttime, respectively, for hourly time steps. Daytime is defined as occurring when the average R_n during an hourly period is greater than zero.

2.6.2. *FAO56 Penman–Monteith (FAO56-PM) ET$_0$ equation*

The FAO56-PM assumes a constant r_s value of 70 s m^{-1} for both hourly and daily time steps. Therefore, for grass reference, FAO56-PM equation has C_n values of 900 and 37 for daily and hourly time steps, respectively, and a constant C_d value of 0.34 for both daytime and nighttime. Both ASCE and FAO-56 PM equations use the same procedures for computing hourly and daily values of G, R_n and other parameters (ASCE-EWRI, 2005).

2.7. *Evaluation of equation performance*

ET$_0$ estimated was compared against the lysimeter measurements by using simple linear regression and other statistics given by Willmot (1982). For the simple regression, the model $y = a + bx$ was used, where y is the estimated ET$_0$, x the measured ET$_0$, a the intercept and b is the slope. For the error analysis the following statistics were used:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{ET}_{0\,est} - \mathrm{ET}_{0\,meas})^2} \tag{8}$$

$$\mathrm{RE} = \frac{\mathrm{RMSE}}{\overline{\mathrm{ET}_{0\,meas}}} \times 100 \tag{9}$$

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}(\mathrm{ET}_{0\,est} - \mathrm{ET}_{0\,meas}) \tag{10}$$

where RMSE is the root mean square error, n the number of observations, ET$_{0\ est}$ and ET$_{0\ meas}$ the estimated and measured ET$_0$ rate (mm day^{-1} or mm h^{-1}), RE the relative error (%), MBE the mean bias error (mm day^{-1} or mm h^{-1}) and $\overline{\mathrm{ET}_{0\,meas}}$ is the average measured ET$_0$.

Table 1 – Summary of statistics from comparison between R_n measured by two net radiometers ($R_{n\,meas}$) and estimated ($R_{n\,est}$) from FAO-56 procedure, for 1999–2001 data set

Net radiometer	N	$\overline{R_{n\,meas}}$ (MJ m^{-2} day^{-1})	$\overline{R_{n\,est}}/\overline{R_{n\,meas}}$	a (MJ m^{-2} day^{-1})	b	r^2	RMSE (MJ m^{-2} day^{-1})	MBE (MJ m^{-2} day^{-1})	RE (%)
Daily data set									
Q-7.1	88	15.34	0.93	−2.08	1.06	0.88	1.39	−1.11	9.1
NR-Lite	88	13.86	1.03	−0.44	1.06	0.92	0.79	0.37	5.7
Net radiometer	N	$\overline{R_{n\,meas}}$ (W m^{-2})	$\overline{R_{n\,est}}/\overline{R_{n\,meas}}$	a (W m^{-2})	b	r^2	RMSE (W m^{-2})	MBE (W m^{-2})	RE (%)
Hourly data set									
Q-7.1	2520	178.71	0.95	−18.16	1.05	0.99	24.56	−9.5	13.7
NR-Lite	2208	161.59	1.04	−3.96	1.06	0.99	28.04	6.2	17.3

$R_{n\,meas}$ was taken as the independent variable. N: number of observations; a: intercept; b: regression coefficient; r^2: coefficient of determination; RMSE: root mean square error; MBE: mean bias error.

3. Results and discussion

3.1. Measured and estimated R_n and G and their effects on ET_0 estimates

The purpose of this study was not to prove the superiority of one net radiometer over the other, but to quantify the impact over ET_0 estimates resulting from the use of two frequently used net radiometers. Results of the comparison between measured and estimated R_n mean rate were different depending on the averaging period. When it was done on a daily basis, R_n measured by NR-Lite and estimated by FAO56 procedure compared rather well, with a good correlation ($r^2 = 0.92$) and a RE smaller than 6% (Table 1). The average ratio of FAO56 to NR-Lite and the bias were 1.03 and 0.37 MJ m^{-2} day^{-1}, respectively, and a small overestimation for high R_n values was observed. When comparison was made between R_n measurements by Q-7.1 and estimated values, the agreement was rather poor, with higher RE and scatter. r^2 and RE were 0.88 and 9.1%, respectively. The average ratio and the bias of FAO56 to Q-7.1 were 0.93 and −1.11 MJ m^{-2} day^{-1}. In this case, the method underestimated measured R_n especially for medium R_n values.

Results were different when comparisons were made on an hourly basis. A good correlation was observed in both cases, with r^2 higher than 0.99 (Table 1). Nevertheless, hourly R_n values estimated by FAO56 procedure were smaller than Q-7.1 R_n measurements. The average ratio and the bias of FAO56 to Q-7.1 were 0.95 and −9.5 W m^{-2}, respectively, and the RMSE amounted to 24.56 W m^{-2}. On the contrary, FAO56 procedure overestimated NR-Lite R_n measurements by 4% on the average, with RMSE and bias amounting to 28.04 and 6.2 W m^{-2}, respectively. The use of these different measurements or estimations may introduce bias in ET_0 estimations, especially when daily ET_0 is obtained from aggregation of hourly values, as it will be seen later.

Contribution of G to energy balance is significant for time steps smaller than 24 h. However, it is not common to have

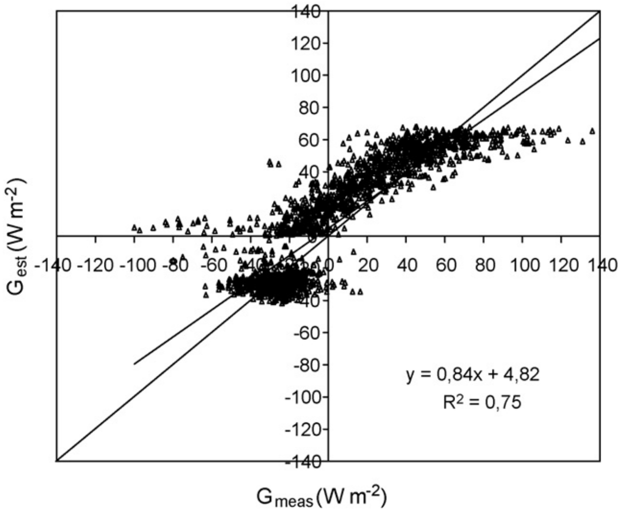

Fig. 1 – Comparison of hourly average soil heat flux measured (G_{meas}) and estimated (G_{est}) according to the FAO-56 procedure for 1999–2001 data set.

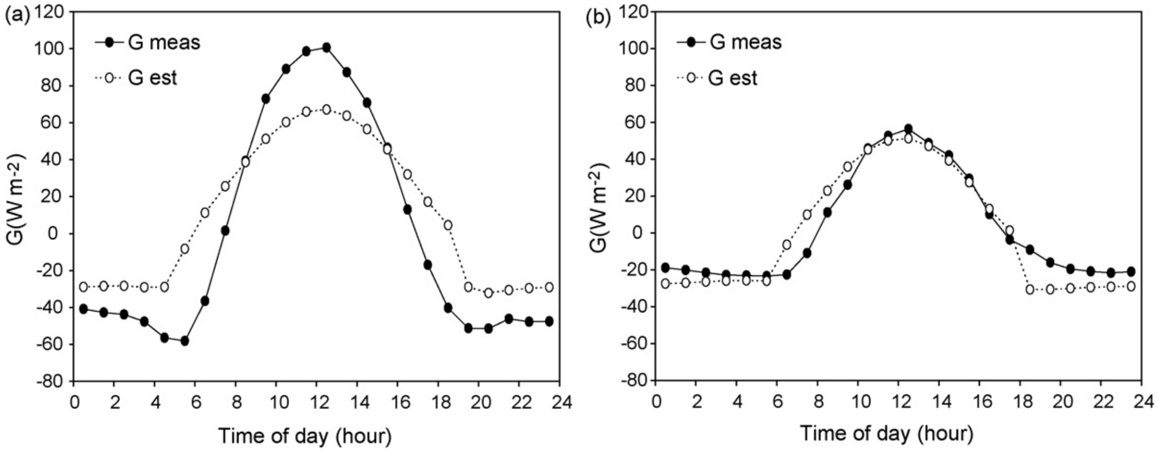

Fig. 2 – Daily pattern of measured (G_{meas}) and estimated (G_{est}) soil heat flux during DOY 157 (a) and 268 (b) in 1999.

this information available in weather station networks because its calculation requires data from soil heat flux plates, soil temperature sensors and a measurement or estimate of soil water content, and these are not routinely measured by standard meteorological stations. Therefore, in most cases, G is estimated from standard weather station data, usually as a fraction of R_n. Different procedures have been proposed for estimating this component of the energy balance (Clothier et al., 1986; Choudhury et al., 1987; Payero et al., 2005). In this work, G was calculated according to Allen et al. (1998) making a distinction between daylight and nighttime hours. Table 2 summarizes the comparisons between hourly measured and estimated G. The correlation between measured and estimated values was not very high, with coefficients of determination ranging from 0.75 to 0.53 and RMSE amounting to 19.26 and 23.42 W m^{-2} (for 1999–2001 and 2004 data set, respectively) (Table 2 and Fig. 1). The RMSE are similar to those reported by Irmak et al. (2005) for Bushland, Texas, where RMSE was 25 W m^{-2}. However, our r^2 were higher than their r^2, which was 0.2752. From May to September, estimated values

Table 2 – Summary of statistics from comparison between hourly measured (G_{meas}) and estimated (G_{est}) soil heat flux

Data set	N	a (W m^{-2})	b	r^2	RMSE (W m^{-2})	MBE (W m^{-2})
1999–2001	2016	4.82	0.84	0.75	19.26	4.64
2004	8784	−0.72	0.76	0.53	23.42	−0.43

Measured G_{meas} was taken as independent variable. N: number of observations; a: intercept; b: regression coefficient; r^2: coefficient of determination; RMSE: root mean square error; MBE: mean bias error.

Table 3 – Summary of statistics from comparison between estimated Penman–Monteith daily ET_0 ($ET_{0\ est}$) and measured lysimeter ET_0 ($ET_{0\ meas}$) for 1999–2001 data set

Method	N	$\overline{ET_{0\ meas}}$ (mm day^{-1})	$\overline{ET_{0\ est}}/\overline{ET_{0\ meas}}$	a (mm day^{-1})	b	r^2	RMSE (mm day^{-1})	MBE (mm day^{-1})	RE (%)
FAO56$_1$	81	7.1	1.04	1.11	0.88	0.91	0.47	0.26	6.6
FAO56$_2$	81	7.1	0.98	0.83	0.87	0.90	0.45	−0.13	6.3
FAO56$_3$	81	7.1	0.99	0.91	0.86	0.89	0.43	−0.07	6.1
FAO56$_4$	81	7.1	1.00	1.11	0.85	0.92	0.39	0.02	5.5
FAO56$_5$	81	7.1	0.95	0.82	0.83	0.90	0.57	−0.37	8.0
FAO56$_6$	81	7.1	0.95	1.21	0.78	0.90	0.56	−0.34	7.8
ASCE$_1$	81	7.1	1.02	0.98	0.88	0.93	0.38	0.14	5.4
ASCE$_2$	81	7.1	0.96	0.68	0.87	0.92	0.46	−0.25	6.5
ASCE$_3$	81	7.1	0.97	1.12	0.82	0.92	0.45	−0.19	6.3

Measured ET_0 was taken as the independent variable. N: number of observations; a: intercept; b: regression coefficient; r^2: coefficient of determination; RMSE: root mean square error; MBE: mean bias error; RE; relative error. *Note*: FAO56$_1$, FAO56$_2$ and FAO56$_3$: estimated FAO-56 daily ET_0 on a daily basis, with R_n measured by Q-7.1, NR-Lite, and estimated, respectively; FAO56$_4$, FAO56$_5$, FAO56$_6$: estimated FAO-56 daily ET_0 on an hourly basis, with R_n measured by Q-7.1, NR-Lite and estimated, respectively; ASCE$_1$, ASCE$_2$, ASCE$_3$: estimated ASCE-PM daily ET_0 on an hourly basis, with R_n measured by Q-7.1, NR-Lite and estimated, respectively. G was measured for FAO56$_1$, FAO56$_2$, FAO56$_4$, FAO56$_5$, ASCE$_1$ and ASCE$_2$, and estimated for FAO56$_3$, FAO56$_6$ and ASCE$_3$.

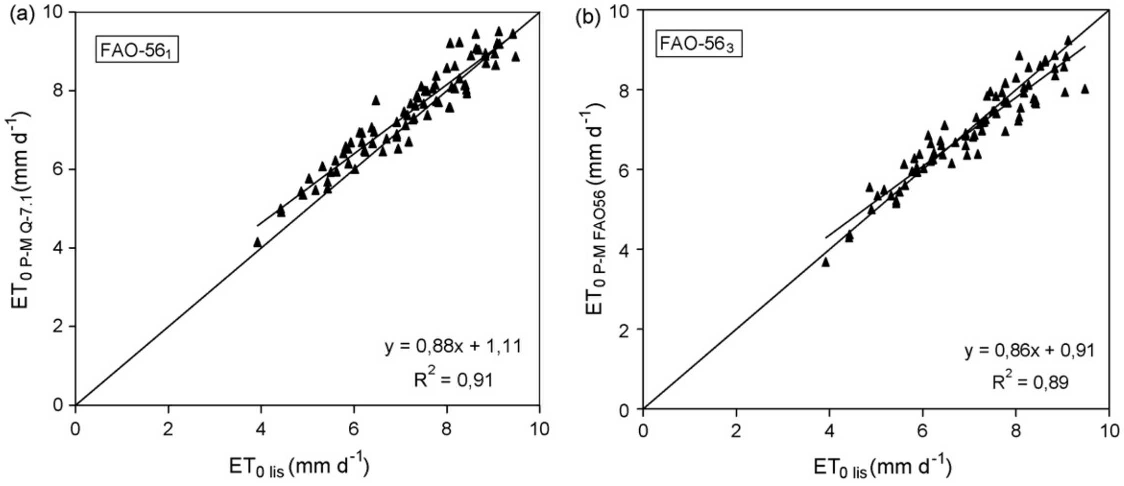

Fig. 3 – Comparison of lysimeter-measured (ET_{0Lis}) and estimated FAO56 daily ET_0 on a daily basis using measured and estimated R_n and G for 1999–2001 data set. R_n was measured using Q-7.1 net radiometer (a) and estimated according to the FAO-56 procedure (b).

(G_{est}) systematically overestimated the measurements (G_{meas}) when G was lower than approximately 40 W m^{-2} and underestimated it when G was greater than 40 W m^{-2} (Fig. 2). In these months, G_{est} was limited by the maximum R_n value (690 W m^{-2} approximately) and underestimation at high G was around 33%. From October to April, the accuracy of the estimations was higher and maximum underestimation reached 5% approximately (Fig. 2). Therefore, a simple linear regression through the origin does not describe precisely the relationship between R_n and G, especially for nighttime hours, and using a constant G/R_n relationship (0.1 and 0.5 for daytime and nighttime, respectively) produces significant differences between the measured and estimated G values (Berengena and Gavilán, 2005). This ratio varies during the day due to hysteresis problems caused apparently by soil surface wetness and thermal gradients and do not consider the impact of changing plant canopy height (Payero et al., 2005). The use of these constant relationships may introduce appreciable bias in ET_0 estimations when it is calculated on an hourly basis, according to Irmak et al. (2005). However, it is noted that the FAO-56 ET_0 definition is for 0.12 m height so that measurement of G should be restrained to within a relatively narrow range around 0.12 m. The 'gap' between 0 and the large grouping of negative G was caused by the relatively rapid transition of R_n to a nearly constant, negative value during nighttime.

3.2. *Comparison between daily ET_0 on a daily basis and lysimeter measurements*

Table 3 shows the results of the comparison between daily ET_0 measured by lysimeter and estimated by FAO-56 and ASCE Penman–Monteith, using measured and estimated R_n and G, for 1999–2001 data set. The relationships were good in all cases when calculations were made on a daily basis, with r^2 and RMSE ranging from 0.89 to 0.91 and from 0.43 to 0.47 mm day^{-1}, respectively. The average ratio of measured to estimated values and MBE ranged from 0.98 to 1.04 and from −0.07 to 0.26 mm day^{-1}, respectively. When R_n was measured by Q-7.1 ($FAO56_1$) a small overestimation occurred (4% on the average), the method being more accurate for high evaporative demand (Fig. 3). When R_n was measured by NR-Lite ($FAO56_2$), underestimation was only 2% on the average, although a tiny tendency to underestimate occurred for high ET_0 values. Finally, when R_n was estimated ($FAO56_3$), the performance of the method improved, because underestimation decreased up to 1% and RMSE value was the lowest (0.43 mm day^{-1}), although again a little tendency to underestimate appeared for high ET_0 values. RE was smaller than 7% in all cases. These results are comparable with those reported by Jensen et al. (1990) and Allen et al. (1989) (0.41 mm day^{-1}), both in arid conditions, and compare advantageously with results like 0.70 mm day^{-1} obtained at Davis, California, by Hargreaves and Allen (2003), and 0.77 reported by Jensen et al. (1990) with

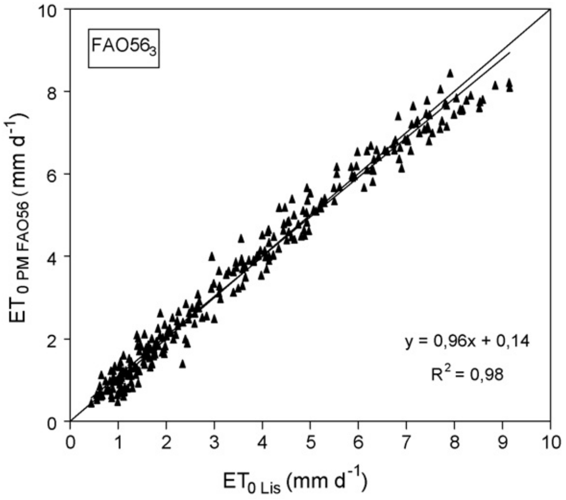

Fig. 4 – Comparison of lysimeter-measured (ET_{0Lis}) and estimated FAO56 daily ET_0 on a daily basis using estimated R_n and G for 2004 data set.

Table 4 – Summary of statistics from comparison between estimated Penman–Monteith daily ET_0 ($ET_{0\ est}$) and measured lysimeter ET_0 ($ET_{0\ meas}$) for 2004 data set

Method	N	$\overline{ET_{0\,meas}}$ (mm day^{-1})	$\overline{ET_{0\,est}}/\overline{ET_{0\,meas}}$	a (mm day^{-1})	b	r^2	RMSE (mm day^{-1})	MBE (mm day^{-1})	RE (%)
FAO56$_2$	266	3.6	0.99	0.18	0.94	0.98	0.34	−0.05	9.3
FAO56$_3$	266	3.6	1.00	0.14	0.96	0.98	0.35	0.00	9.6
FAO56$_5$	266	3.6	0.95	0.11	0.92	0.99	0.35	−0.17	9.8
FAO56$_6$	266	3.6	0.95	0.20	0.90	0.99	0.39	−0.17	10.6
ASCE$_2$	266	3.6	1.00	0.21	0.94	0.99	0.28	0.00	7.8
ASCE$_3$	266	3.6	1.00	0.28	0.92	0.99	0.31	−0.01	8.5

Measured ET_0 was taken as the independent variable. N: number of observations; a: intercept; b: regression coefficient; r^2: coefficient of determination; RMSE: root mean square error; MBE: mean bias error; RE; relative error. *Note*: See footnotes in Table 3.

data from three locations. In this study, measurement of R_n did not improve ET_0 estimations on a daily basis, under semiarid conditions and during the irrigation season; rather the opposite, the ET_0 estimate was more accurate when R_n was estimated.

To study the performance of the method during the whole year, 266 daily lysimeter data from 2004 were analysed, using measured G and R_n by NR-Lite and estimated by FAO-56 procedures. R_n measurements by Q-7.1 were not available this year. Again, there were in both cases good correlations between measured and estimated values, with r^2 higher than 0.98 (Table 4). The slopes were higher than 0.94 and the intercepts were smaller than 0.18 mm day^{-1}. Statistics indicate that there was no difference between both methods. Using measured R_n and G (FAO56$_2$), RMSE and RE were 0.34 mm day^{-1} and 9.3%, respectively, whereas when they were estimated these figures were 0.35 mm day^{-1} and 9.6%, respectively. There was no over or underestimation on average when R_n and G were estimated and the underestimation was only 1% when they were measured. In both

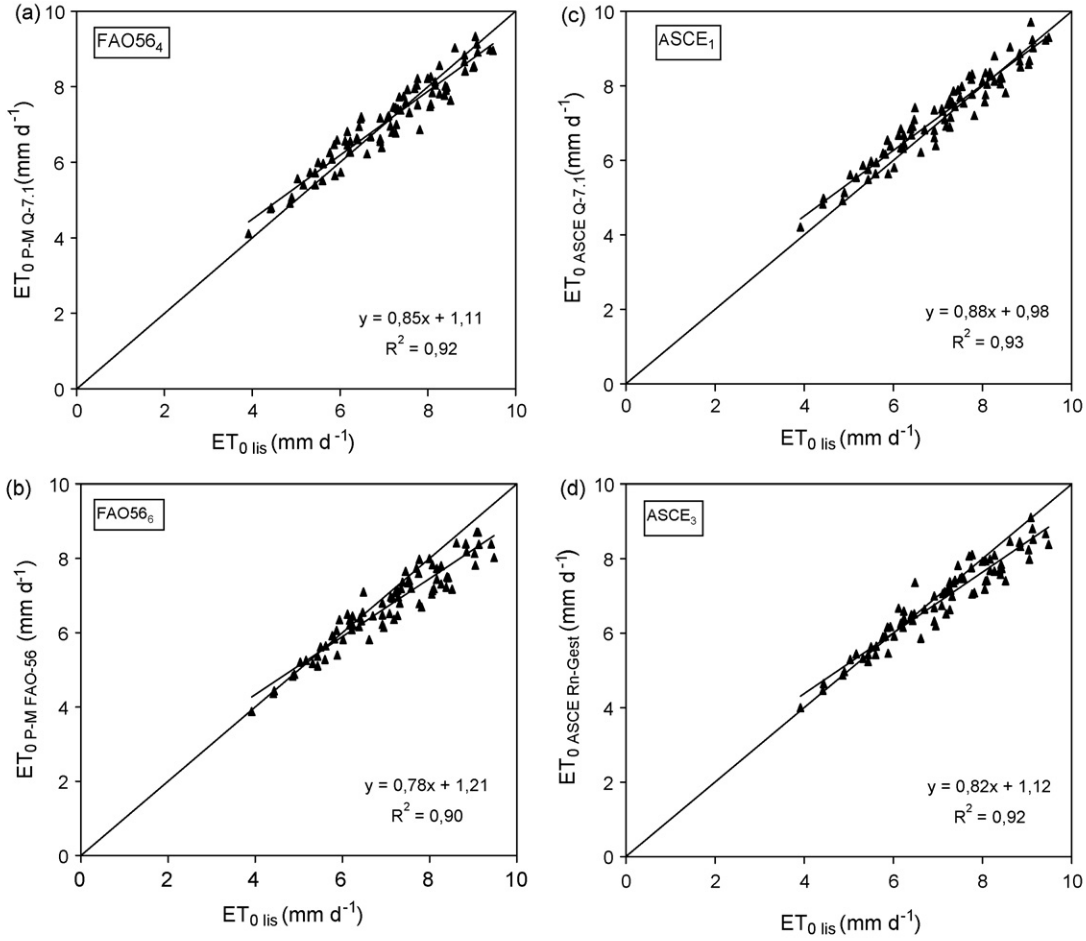

Fig. 5 – Comparison of lysimeter-measured (ET_{0Lis}) and estimated FAO56 (a and b) and ASCE (c and d) daily ET_0 on an hourly basis using measured and estimated R_n and G for 1999–2001 data set. R_n was measured using Q-7.1 net radiometer (a and c) and estimated according to the FAO-56 (b and d).

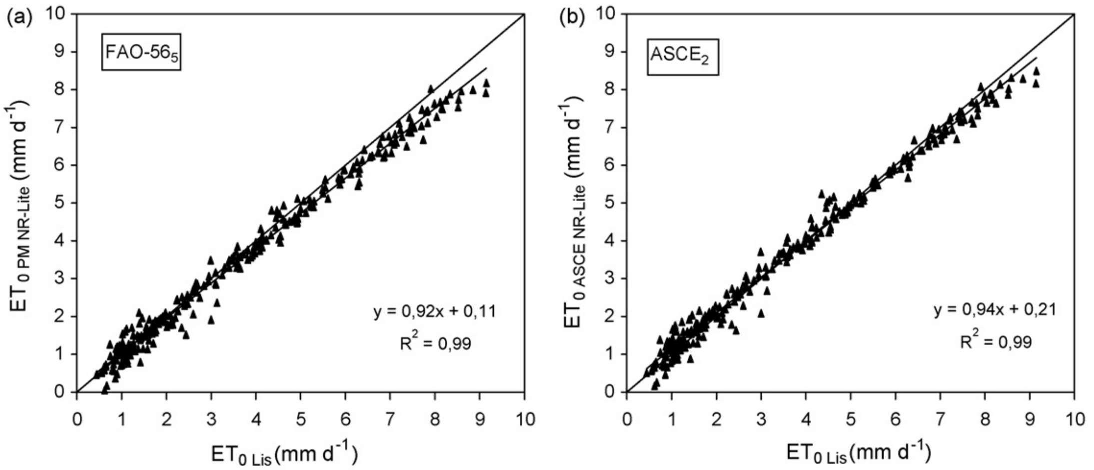

Fig. 6 – Comparison of lysimeter-measured (ET_{0Lis}) and estimated FAO56 (a) and ASCE (b) daily ET_0 computed on an hourly basis using measured R_n and G for 2004 data set. R_n was measured using NR-Lite net radiometer.

cases, the method showed a little tendency to underestimate for high evaporative demand (Fig. 4). Again, there was no gain in accuracy when R_n and G were measured.

3.3. *Comparison between daily ET_0 from hourly estimates and lysimeter measurements*

When applying the PM FAO-56 method for hourly time steps, only one value for r_s is considered (70 s m^{-1}) for both diurnal and night hours. However, for the ASCE-PM equation and for the PM FAO-56 method as amended by Allen et al. (2005), daily ET_0 estimations were calculated from hourly values computed with r_s = 50 s m^{-1} for diurnal hours ($R_n > 0$) and 200 s m^{-1} for night hours. In both cases, R_n and G were measured and estimated. Using the PM FAO56 version for 1999–2001 data set, with measured R_n by Q-7.1 (FAO56$_4$), the method performed rather well relative to the lysimeter measurements, with RMSE and MBE amounting to 0.39 and 0.02 mm day^{-1}, respectively (Table 3). When R_n was measured by the NR-Lite (FAO56$_5$) and estimated (FAO56$_6$), RMSE increased up to 0.57 and 0.56 mm day^{-1}, respectively, with an underestimation of 5% in both cases (Fig. 5). However, when ASCE version was used, better results with respect to FAO-56 version were obtained in all cases. When R_n was measured by Q-7.1 (ASCE$_1$), RMSE was the lowest (0.38 mm day^{-1}), although a tiny overestimation occurred (2% on the average), the method being more accurate for high evaporative demand (Fig. 5). When R_n was measured by NR-Lite (ASCE$_2$) or estimated (ASCE$_3$), the method underestimated lysimeter ET_0 up to 3–4% on the average, with RMSE values of 0.46 and 0.45 mm day^{-1}, respectively. In both cases, underestimations were greater for high evaporative demand. In conclusion, measurement of R_n by Q-7.1 provided improved ET_0 estimates relative to the lysimeter when both ASCE and FAO56 versions were used. When R_n was measured by NR-Lite or estimated by FAO-56 procedure, similar results were obtained.

During 2004, similar behavior was observed using measured and estimated R_n and G. The best results were for the ASCE version (Fig. 6), which is equivalent to the amended PM FAO-56 method (Allen et al., 2005), with R_n and G measured (ASCE$_2$). In this case there was no over or underestimation on average (MBE = 0) and RMSE amounted to 0.28 mm day^{-1}

Table 5 – Summary of statistics from comparison between estimated Penman–Monteith hourly ET_0 ($ET_{0\ est}$) and measured lysimeter ET_0 ($ET_{0\ meas}$) for 1999–2001 data set

Method	N	$\overline{ET_{0\,meas}}$ (mm h^{-1})	$\overline{ET_{0\,est}}/\overline{ET_{0\,meas}}$	a (mm h^{-1})	b	r^2	RMSE (mm h^{-1})	MBE (mm h^{-1})	RE (%)
FAO56$_7$	1958	0.29	1.00	0.04	0.85	0.98	0.06	0.00	20.5
FAO56$_8$	1958	0.29	0.95	0.03	0.84	0.98	0.06	−0.02	22.0
FAO56$_9$	1958	0.29	0.95	0.02	0.87	0.98	0.06	−0.01	20.7
ASCE$_4$	1958	0.29	1.02	0.03	0.92	0.98	0.04	0.01	15.5
ASCE$_5$	1958	0.29	0.96	0.02	0.90	0.99	0.05	−0.01	16.3
ASCE$_6$	1958	0.29	0.97	0.01	0.93	0.98	0.05	−0.01	15.9

Measured ET_0 was taken as the independent variable. N: number of observations; a: intercept; b: regression coefficient; r^2: coefficient of determination; RMSE: root mean square error; MBE: mean bias error; RE; relative error. *Note*: FAO56$_7$, FAO56$_8$ and FAO56$_9$: estimated FAO-56 hourly ET_0, with R_n measured by Q-7.1, NR-Lite, and estimated, respectively; ASCE$_4$, ASCE$_5$, ASCE$_6$: estimated ASCE-PM hourly ET_0, with R_n measured by Q-7.1, NR-Lite and estimated, respectively. G was measured for FAO56$_7$, FAO56$_8$, ASCE$_4$ and ASCE$_5$, and estimated for FAO56$_9$ and ASCE$_6$.

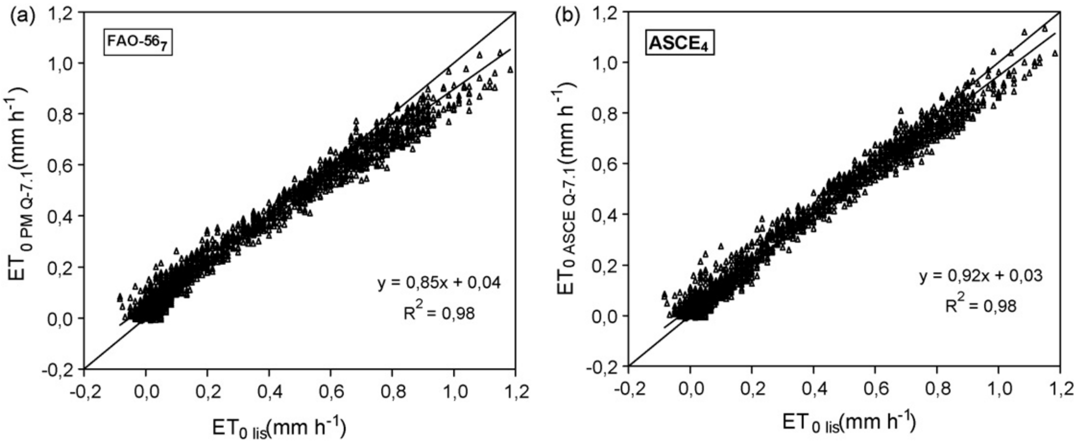

Fig. 7 – Comparison of lysimeter-measured (ET_{0Lis}) and estimated FAO56 (a) and ASCE (b) hourly ET_0 using measured R_n and G for 1999–2001 data set. R_n was measured using Q-7.1.

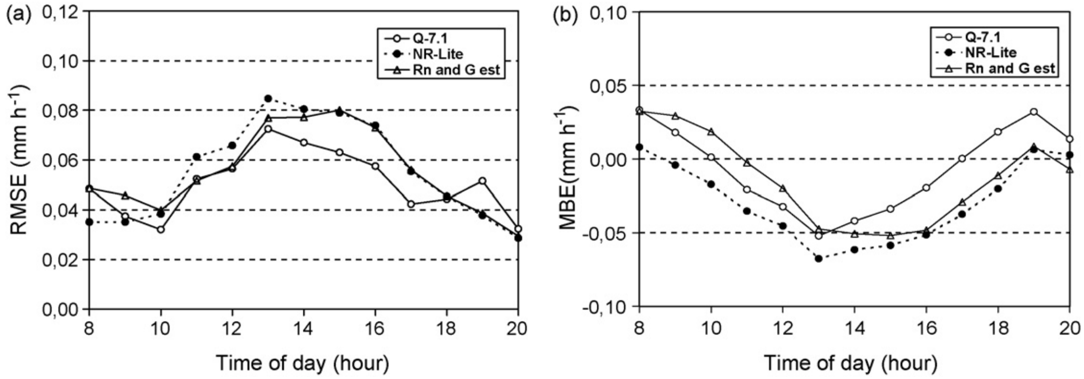

Fig. 8 – Diurnal trends of RMSE (a) and MBE (b) from comparison between measured and estimated hourly ET_0 (from standardized ASCE Penman–Monteith equation) for 1999–2001 data set using measured and estimated R_n and G.

(Table 4). When R_n and G were estimated ($ASCE_3$) the performance of the equation was also rather good (RMSE = 0.31 mm day^{-1}). The worst results were obtained when the FAO-56 version was used, where RMSE rose up to 0.39 mm day^{-1} when R_n and G were estimated ($FAO56_6$) and underestimation amounted to 5%. The difference in performance in favor of ASCE with respect to FAO-56 version can be attributed to the effect produced by the reduction of r_s from 70 to 50 s m^{-1} for daylight time in the first case.

3.4. *Comparisons between hourly ET_0 estimates and lysimeter measurements*

When the PM FAO-56 was used on hourly basis (r_s = 70 s m^{-1}), with R_n measured using Q-7.1 net radiometer ($FAO56_7$), no under or overestimation on average occurred (Table 5). Nevertheless, from 0 to 0.3 mm h^{-1} it tended to overestimate ET_0. Then, the method performed rather well over the 0.3–0.5 mm h^{-1} range, but tended to increasingly underestimate for larger values of ET_0 (Fig. 7). This behavior may be due to the use of a single value for r_s through the whole day, where lower values for r_s have been reported under conditions of high R_s (Price and Black, 1989; Allen et al., 1996). Several studies suggest that r_s for daytime should be lower than 70 s m^{-1} (Todorovic, 1999; Ventura et al., 1999; Lecina et al., 2003; Berengena and Gavilán, 2005; Irmak et al., 2005; Allen et al., 2005). When R_n was measured by NR-Lite ($FAO56_8$) or estimated ($FAO56_9$), the method underestimated by 5% on the average. In all cases, RMSE was equal to 0.06 mm h^{-1}.

When the ASCE-PM version was applied with measured R_n (by Q-7.1) and G ($ASCE_4$), the method performed rather well and RMSE reduced to 0.04 mm h^{-1}, overestimating by 2% on average (Table 5). When R_n was measured by NR-Lite ($ASCE_5$), RMSE increased to 0.05 mm h^{-1} and the method underestimated by 4% on the average. Finally, when both R_n and G were estimated ($ASCE_6$), the behavior was similar to $ASCE_5$, with RMSE and underestimation amounting to 0.05 mm h^{-1} and 3%, respectively. In all cases, the ASCE version tended to overestimate for low evaporative demand and underestimate for high ET_0 values, although less than the FAO56 version (Fig. 7). Therefore, the ASCE-PM equation (and amended PM FAO56) tended to provide more accurate values of hourly ET_0, even when using estimated values of R_n and G. Evolution of hourly RMSE along the day can be seen in Fig. 8. The smallest hourly errors occurred when R_n was measured by Q-7.1. During the morning (from 8 a.m. to 1 p.m.), hourly RMSE were similar when R_n was measured by Q-7.1 or estimated. During the afternoon (from 1 to 8 p.m.), hourly RMSE when R_n was estimated or measured by NR-Lite were similar. Behavior of hourly MBE follows a similar pattern (Fig. 8).

4. Conclusions

The Penman–Monteith equation for ET_0 calculation was evaluated against lysimeter measurements using the standardized FAO-56 and ASCE versions. In both cases hourly and daily computational steps, and measured and estimated values of R_n and G were applied. The results indicate that using measured or estimated values of R_n and G can have significant effect on the accuracy of the ET_0 estimations, especially when calculations were made on an hourly basis. The FAO-56 version on a daily basis performed very well under semiarid conditions during the irrigation season. Measurement of R_n and G did not improve ET_0 estimation using 24 h computation time steps. On the contrary, the method was more accurate when R_n and G were estimated. A small tendency to underestimate appeared for higher ET_0 values when R_n was measured by NR-Lite or estimated. Therefore, using estimated R_n and G appears to be dependable when calculations are made on a daily basis.

When daily ET_0 was estimated from hourly estimations, the results were different depending on the version used. The ASCE version was more accurate, especially when R_n was measured by Q-7.1 net radiometer. In this case, RMSE amounted to 0.38 and 0.28 mm day^{-1} during the irrigation season and the whole year, respectively. Different results were obtained when R_n was measured by NR-Lite or was estimated (RMSE = 0.45 mm day^{-1} during the irrigation season and 0.31 mm day^{-1} during the whole year). Therefore, we can conclude that measurement of R_n and G may only have potential to improve estimation when daily ET_0 is calculated from hourly estimations. The original PM FAO56 version was always a little less accurate than the ASCE version. We recognize that we used only one each of the Q7.1 and NR-Lite net radiometers, so that impacts of within-population variation and impact of specific sensor selection were not investigated. Selection of different individual sensors might have impacted our results and conclusions.

For hourly calculations, using a constant r_s (FAO56 version), the PM method underpredicted for high evaporative demand and vice versa and the RMSE increased up to 0.06 mm h^{-1}. The ASCE version performed better and RMSE decreased down to 0.04 mm h^{-1} when R_n was measured by Q-7.1 and G was also measured or when both parameters were estimated (RMSE = 0.05 mm h^{-1}). Therefore, ASCE version tend to provide quite accurate values of hourly ET_0, even using estimated values of R_n and G and even when a constant $r_s = 50$ s m^{-1} is used during all daytime periods.

As a final conclusion and recommendation, the methods proposed by FAO56 for estimating R_n and G tended to produce accurate estimates for daily and hourly ET_0 under our semiarid conditions and can be used with some degree of confidence for estimating ET_0. In addition, results suggest that the ASCE standardized equation on an hourly basis improved the accuracy of ET_0 estimation with respect to the original FAO56 version.

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