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Daily forecasting of reference and strawberry crop evapotranspiration in greenhouses in a Mediterranean climate based on solar radiation estimates

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ABSTRACT

This paper presents a method for carrying out daily forecasting of strawberry crop evapotranspiration (ET_c), using forecasted greenhouse reference evapotranspiration values ($ET_{o\ green}$) and crop coefficients. $ET_{o\ green}$ was estimated using two methods, the first based on incoming solar radiation and the second using the Makkink FAO-24 equation. In both cases, $ET_{o\ green}$ was estimated using daily meteorological variables forecasted by the Spanish Meteorology National Agency (AEMET) and then comparing it with the result obtained using measured meteorological data under greenhouse conditions. In addition, values of estimated ET_c using measured and forecasted meteorological data were also compared. Lastly, these values were compared with ET_c measurements using drainage lysimeters. Incoming solar radiation was estimated from forecasted temperatures and sky cloudiness conditions. Forecasted outdoor and indoor incoming solar radiation values were more accurate using the method based on temperatures. Small differences and high correlations were observed when comparing forecasted and weather measured $ET_{o\ green}$ and ET_c. With respect to forecasted $ET_{o\ green}$, the errors were smaller when incoming solar radiation was estimated from forecasted temperature data, especially when using the Makkink equation, with underestimations below 3%. Therefore, these results suggest that the latter method is best suited to the task. Also, the use of forecasted ET_c, especially from Makkink FAO24 equation, provided more accurate estimates when compared with lysimeter-measured values.

1. Introduction

Spain is the world's third largest producer of strawberries. According to estimates by the Department of Agriculture, Fisheries and Rural Development of the Government of Andalusia, an area of 7500 ha was dedicated to strawberry cultivation in the province of Huelva in the 2013/2014 season (Consejería de Agricultura y Pesca, 2012). The strawberry generates high economic value goods and employment, however, the fact that it is cultivated in the vicinity of the Doñana National Park, the most important protected wetland in Europe, requires the reconciliation of environmental conservation and productive activity. Consequently, finding ways to reduce agricultural water use are of considerable interest.

Strawberry crops in Spain are irrigated solely by drip irrigation but the irrigation efficiency for this crop is unknown. Despite the widespread use of this method of irrigation in this crop, there is still uncertainty about the precise amount of water needed to maximize strawberry crop production. Strawberry farmers schedule their irrigations based on past experience, observation of weather conditions and visual plant indicators of stress. As the lateral drip irrigation pipe is placed under the plastic mulch, the water applied from the drip pipelines is not visible to field managers. Therefore, over-irrigation easily occurs when managers believe they have to water the entire field area, including the row middles. Furthermore, for the time being, water in this area is a relatively inexpensive input and is often managed carelessly.

Most of the research on strawberry irrigation has been carried out in California and Florida (USA), where open-field cultivation is the standard strawberry production method (Clark et al., 1996; Grattan et al., 1998; Hanson and Bendixen, 2004; Trout and Gartung, 2004). However, in many of the winter and early spring production areas outside the USA, strawberries are grown under

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clear plastic tunnels (Childers, 2003; Hancock, 1999). Almost all strawberries are grown in tunnels in Spain.

Efficient water use requires an efficient and uniform irrigation system and correct scheduling of water applications. The FAO methodology based on reference evapotranspiration (ET_o) and crop coefficient (K_c) has been used worldwide to determine crop water requirements (ET_c) under open-field conditions. This methodology can also be applied to greenhouse crops (Bonachela et al., 2006). In addition, K_c values have been determined for the main greenhouse crops cultivated on the southeast Spanish Mediterranean coast (Orgaz et al., 2005). A standardized method for estimating outdoor ET_o was defined in the FAO-56 Irrigation and Drainage Paper (Allen et al., 1998). However, there is no standardized method for greenhouse crops. The most comprehensive comparison of methods for estimating greenhouse ET_o was performed by Fernández et al. (2010) on the southeastern Mediterranean coast. In this work Penman, radiation and evaporimetric tank methods, in their version FAO24, and Penman–Monteith FAO56 and Hargreaves equations were evaluated. In addition, an equation based only on incoming solar radiation was proposed to estimate $ET_{o\ green}$. The latter method requires only greenhouse transmissivity (τ) and measurements or estimations of incoming solar radiation. It is, therefore, the most practical way to determine greenhouse ET_o. Also, its accuracy is similar to that of the Makkink FAO24 and Penman–Monteith FAO56 methods.

The water-holding capacity and available water of most sandy soils around the Doñana National Park are low in comparison to other soils with higher silt and clay fractions. In sandy soils, lateral movement of water is limited to 15–30 cm from a drip or point source emitter (Clark et al., 1993) and rapid vertical movement of water can occur (Clark and Smajstrla, 1983). Therefore, these soils need real-time irrigation scheduling and pulse drip irrigation. Accordingly, a daily ET_c forecast would help save water.

Seasonal or monthly ET_o and crop water requirement forecasts, useful for mid- to long-term irrigation planning, can be produced using historical weather data, thanks to the periodicity of ET_o and crop coefficients. Irrigation advisory services provide excellent information on near-real-time ET_o but do not provide a daily ET_o forecast, which is useful for real-time irrigation scheduling, especially for high-frequency irrigation systems, shallow-rooted vegetation or sandy soils (Luo et al., 2014). Real time irrigation scheduling using weather data forecasts has proven appropriate to estimate ET_o and applications are reported for several crops (Gowing and Ejieji, 2001; Wilks and Wolfe, 1998; Cabelguenne et al., 1997). Also, public weather forecasts are now easier to access and to understand. Cai et al. (2007) compared weather forecasted ET_o estimations with the ET_o values computed with full data sets from synoptic stations and non-synoptic locations (Cai et al., 2009). More recently, Perera et al. (2014) quantify the performance of forecasted daily ET_o using numerical weather prediction outputs for different lead times and Luo et al. (2014) reported a short-term ET_o forecast based on data from daily temperature forecasts using the Hagreaves-Samani model.

Since 2011, the Andalusian Institute of Agricultural Research and Training (IFAPA in Spanish) has conducted studies on drip irrigation of strawberries in the vicinity of the Doñana National Park, southern Spain, in order to help strawberry growers to irrigate efficiently. These studies have included measurement of ET_c and estimation of K_c, determination of irrigation efficiency and calculation of water productivity (Gavilán et al., 2014). For these studies, two meteorological stations were installed outside and inside the strawberry greenhouses to monitor meteorological variables and to estimate outdoor and greenhouse ET_o

The objectives of this study were: (1) to estimate greenhouse reference evapotranspiration ($ET_{o\ green}$) and strawberry crop evapotranspiration (ET_c) using daily meteorological forecasts from the Spanish Meteorology National Agency (AEMET); (2) to compare these estimations with those obtained from meteorological measurements and lysimeter data.

2. Material and methods

2.1. Experimental site

The studies were carried out in Almonte (Huelva) on a commercial strawberry (*Fragaria x ananassa*) farm. The farm is near the village of El Rocío, in the vicinity of the Doñana National Park (longitude 6° 31′ 39" West, latitude 37° 05′ 13" North, altitude 24 m above mean sea level). The mean annual rainfall is 467 mm and average annual mean, maximum and minimum temperatures are 17.4, 24.5 and 11.0 °C, respectively. The soil of the study area is classified as sandy (USDA classification), with 90% sand and 10% clay.

Two experiments were conducted in order to measure strawberry consumptive water use, irrigation efficiency and water and land productivity using different amounts of water applied. In the first growing season, the transplant was performed on October 9th 2012 with a planting density of 71,888 plants per ha. The experiment finished on June 6th 2013. In the second season, the transplant was performed on October 10th 2013 with a planting density of 62,000 plants per ha and the experiment finished on May 15th 2014. For both experiments, the greenhouses were set up on November 10th 2012 and November 11th 2013. The berries were planted in trapezoidal beds measuring 0.60 m at the base, 0.50 m at the top, with a height of 0.50 m, and 1.1 and 1.2 m apart for the first and second growing season, respectively. There were six and five beds at each tunnel for the first and second growing season, respectively. Two rows of plants were placed along the bed with a drip irrigation tape in the center installed during bed construction. The tape used was able to apply 5 $l\,m^{-1}\,h^{-1}$ flow rate at a pressure of 0.55 MPa.

Both trials were arranged as a randomized complete block design with three treatments with different irrigation volumes replicated four times. The first treatment (T1) was set up to apply the crop water requirements, based on $ET_{o\ green}$ and estimated crop coefficients, using an irrigation efficiency of 85%. T2 and T3 applied 25% and 50% more water than T1, respectively. The experimental unit was a complete parabolic tunnel $70 \times 6.6\,m^2$ and 3 m high, and the trial consisted of 12 tunnels (Gavilán et al., 2014). The tunnels were covered with 0.15 mm-thick thermal polyethylene plastic film. Irrigation scheduling based on crop water requirements was applied each day to replace ET_c and maintain non-limiting soil water content. ET_c was calculated by the well-known FAO56 method (Allen et al., 1998):

$$ET_c = ET_{o\ \ green} \times K_c \tag{1}$$

where $ET_{o\,green}$ was estimated inside the greenhouse, as proposed by Fernández et al. (2010). For this, we used meteorological forecasts from the Spanish Meteorology National Agency (AEMET) and meteorological data measured inside the tunnels. K_c was estimated as function of crop coverage recommended by Hanson and Bendixen (2004) and Trout and Gartung (2004) for the first and second season, respectively.

2.2. Forecasting meteorological variables

For estimating forecasted $ET_{o\,green}$, meteorological forecast provided by AEMET (http://www.aemet.es) was used. It provides sky cloudiness conditions, rainfall probability, maximum and minimum temperatures and relative humidity of the air and wind speed and direction.

Forecasted greenhouse temperature and relative humidity data were estimated from the correlations between outdoor and indoor values of both variables measured during two previous growing

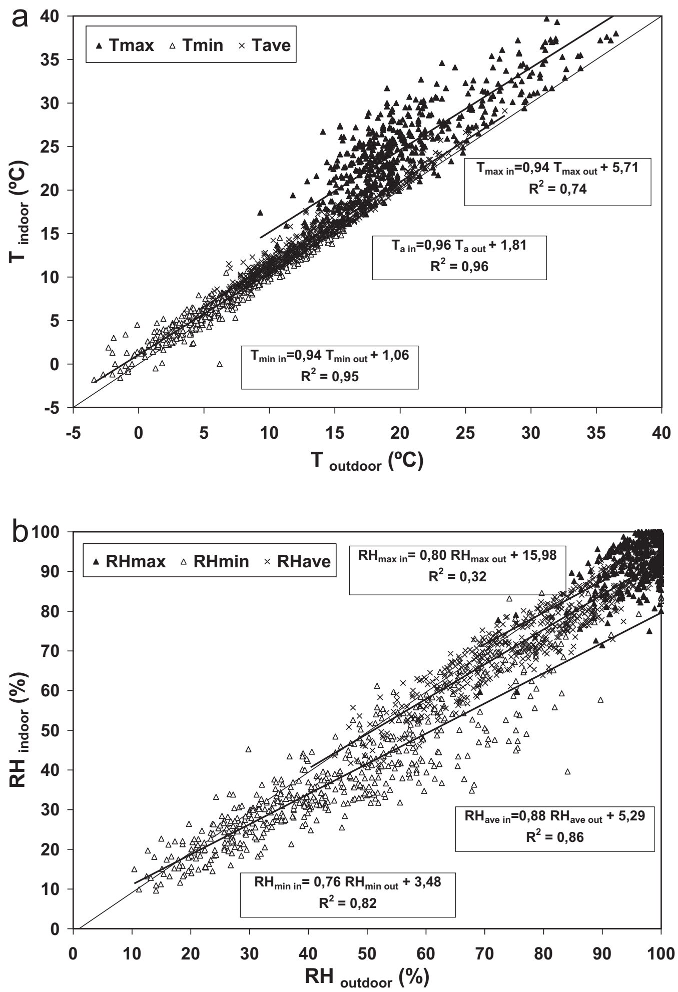

Fig. 1. (a) Comparison between daily maximum, minimum and average air temperatures measured outdoor and under greenhouse. (b) Comparison between daily maximum, minimum and average relative humidity of the air measured outdoor and under greenhouse. Also shown is the 1:1 line.

season (Fig. 1a and 1b). Therefore, greenhouse temperature and relative humidity of the air can be forecasted using the outdoor variables forecasted by the AEMET.

Outdoor incoming solar radiation was forecasted using two procedures. In the first case (temperature method), it was estimated from outdoor forecasted temperatures using a simple mechanistic model developed by Hargreaves and Samani, (1982). They proposed that R_s is proportional to the square root of the difference between daily maximum and daily minimum air temperature (daily air temperature range, $\Delta T = T_{max} - T_{min}$) and, therefore, that R_s could be estimated according to the Eq. (2):

$$R_s = K_r \times (T_{max} - T_{min})^{0.5} R_a \tag{2}$$

where R_s is the outdoor incoming solar radiation ($\mathrm{MJ\,m^{-2}\,d^{-1}}$); T_{max} and T_{min} are the forecasted outdoor daily maximum and minimum air temperatures (°C), respectively; R_a is the extraterrestrial radiation ($\mathrm{MJ\,m^{-2}\,d^{-1}}$), estimated for each day of the year on the basis of latitude and the solar constant (Allen et al., 1998); and K_r is an empirical coefficient (unitless). Hargreaves (1994) recommended using K_r values of 0.16 and 0.19 for inland and coastal locations, respectively. In this work, a calibrated coefficient (K_r) for this location was used, taken from Estévez et al. (2012):

$$Kr = 0.0008\Delta T^2 - 0.0279\Delta T + 0.4017 \tag{3}$$

where ΔT is the historical average daily temperature range. According this equation, K_r value used in this work was 0.18.

In the second procedure (cloudiness method), incoming solar radiation under clear-sky conditions (R_{so}) was estimated according Allen et al. (1998) using the Eq. (4):

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

where z is the location elevation (m)

This value was used as actual incoming solar radiation ($R_s = R_{so}$) when clear-sky conditions were forecasted by the AEMET. On the contrary, incoming solar radiation was estimated using forecasted temperatures according to the first procedure (Eq. (1)). In all cases the R_{so} value was used as the upper limit in the estimation of incoming solar radiation.

Forecast of indoor solar radiation (R_{sgreen}) was subsequently estimated as the product of outdoor forecasted incoming solar radiation (R_s) by average transmissivity (Eq. (5)):

$$R_{sgreen} = R_s \times \tau \tag{5}$$

where, R_s is the incoming solar radiation outside the greenhouse ($\mathrm{mm\,d^{-1}}$) and τ is the plastic transmissivity. τ depends of the material used for coverage, as well as the age and dirtiness of the plastic. Measurements of outdoor and inside solar radiation, using two meteorological stations, were done during the 2011/2012 growing season. It was estimated that an average value of 0.75 for τ would be suitable for this type of greenhouses (Fig. 2).

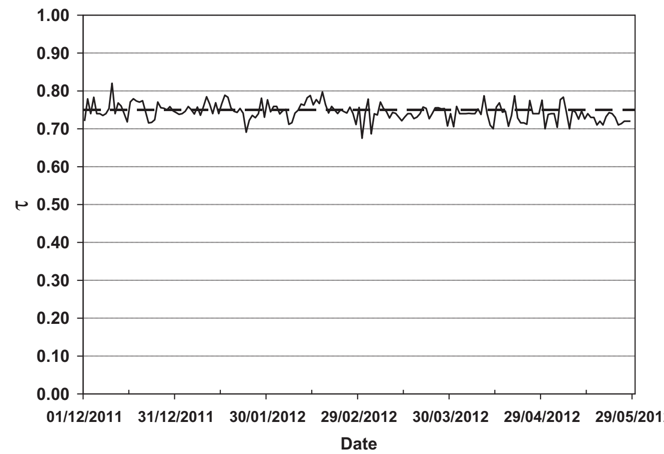

Fig. 2. Seasonal trend of transmissivity (τ) estimated from measured of outdoor and greenhouse incoming solar radiation during the 2011/2012 growing season.

2.3. Meteorological measurements

Measured meteorological data from two meteorological stations, belonging to the Meteorological Information Network of Andalusia (Gavilán et al., 2008), were used in the study. The outdoor station was equipped with sensors for measuring temperature and relative humidity of the air (HMP45C probe, Vaisala), incoming solar radiation (pyranometer CM3, Kipp and Zonen) and wind speed and direction (Young wind monitor), controlled by a datalogger CR10X (Campbell Scientific). A similar automatic weather station was installed inside the greenhouse, but in this last case wind speed and direction were not measured.

2.4. Reference evapotranspiration estimations

$ET_{o\ green}$ was estimated using measured meteorological data inside the greenhouse and compared with those estimated from the forecasted meteorological data.

For this study, two methods for estimating $ET_{o\ green}$ were used. The first (radiation method) was based only on incoming solar radiation (Fernández et al., 2010):

$$\text{If DOY} < 220\, ET_{ogreen} = (0288 + 0.0019 \times \text{DOY}) \times R_{sgreen} \quad (6)$$

$$\text{If DOY} > 220\, ET_{ogreen} = (1.339 - 0.00288 \times \text{DOY}) \times R_{sgreen} \quad (7)$$

where DOY is the day of year and R_{sgreen} is the daily incoming solar radiation inside the tunnels (mm d^{-1}) (Eq. (5)).

The second one used the Makkink FAO24 equation (Doorenbos and Pruitt, 1977):

$$ET_{o\ \ green} = b \times \left(\frac{\Delta}{\Delta + \gamma}\right) Rs_{green} - 0.3 \quad (8)$$

where b is the adjustment factor calculated according to Allen and Pruitt (1991), from daily data of indoor relative humidity of the air; Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}), estimated using indoor air temperature; γ is the psychrometric constant (kPa °C^{-1}) and R_{sgreen} is the incoming solar radiation inside the greenhouse (mm d^{-1}).

2.5. Crop evapotranspiration measurements

The most accurate method for measuring ET_c is by using weighing lysimeters, which have long been used to measure evapotranspiration (Wright, 1982), although they are expensive and non-portable. However, drainage lysimeters are a less expensive method for measuring evapotranspiration. Thus, ET_c was measured using drainage lysimeters installed in each treatment. These lysimeters were made of polyester reinforced with fiberglass, and with the dimensions 1.40m × 0.62 m × 0.40 m. The lysimeters were buried with their upper edge at ground level and then the strawberry beds were rebuilt over them. In each lysimeter, 11 plants were planted the same distance apart as the plants in the rest of the bed. Readings of the drainage lysimeters were taken daily in order to obtain ET_c based on a water balance method, which requires data on the volume of water applied to each lysimeter and soil moisture measurements. The average of ET_c from the three treatments was used as reference. The amount of water applied in each of the treatments was measured using flowmeters. In addition, flowmeters were installed at the beginning of the drip lines in the beds where the lysimeters were installed, in order to measure the amount of water applied to the lysimeters. The soil moisture was measured using ECH2O (Decagon Devices) and EasyAG (Sentek Technologies) probes, with five sensors at each location. During the 2011/2012 season both types of probes were locally calibrated by gravimetric methods. The soil moisture values were used to estimate the storage soil moisture in order to estimate ET_c.

2.6. Statistical analysis

Forecasted and estimated from meteorological measurement values of $ET_{0\ green}$ and ET_c were compared by using simple error analysis and linear regression. Comparison between forecasted and lysimeter measured ET_c was also made. The following parameters were calculated (Willmott, 1982): mean bias and absolute errors (MBE and MAE, respectively), root mean square error (RMSE), relative error (RE), and the Ratio between both average values.

$$\text{MAE} = \frac{\Sigma_{i=1}^{n} |(y_i - x_i)|}{n} \quad (9)$$

$$\text{MBE} = \frac{\Sigma_{i=1}^{n} (y_i - x_i)}{n} \quad (10)$$

$$\text{RMSE} = \sqrt{\frac{\Sigma_{i=1}^{n} (Y_i - X_i)^2}{n}} \quad (11)$$

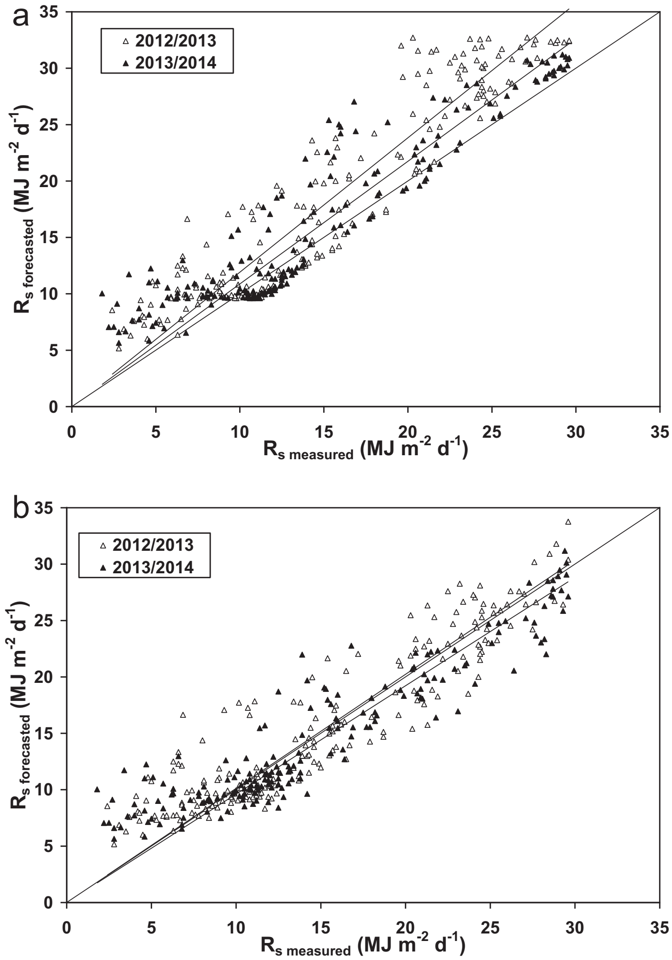

Fig. 3. (a) Comparison between forecasted and measured incoming solar radiation using the cloudiness method. Also shown is the 1:1 line. (b) Comparison between forecasted and measured incoming solar radiation using the temperature method.

$$\text{RE} = \frac{\text{RMSE}}{X_{\text{ave}}} \times 100 \quad (12)$$

$$\text{Ratio} = \frac{y_{\text{ave}}}{x_{\text{ave}}} \quad (13)$$

where n is the number of available days; y_i is the forecasted value, x_i is the estimated from meteorological measurement value or lysimeter measurement; and x_{ave} and y_{ave} are the averages of both values, respectively.

3. Results and discussion

3.1. Forecasting incoming and greenhouse solar radiation

The average daily integral of outdoor incoming solar radiation ranged between 1.8 MJ m^{-2} d^{-1} in winter and 29.6 MJ m^{-2} d^{-1} in spring (Fig. 3). Tables 1 and 2 show the values of statistical parameters used to evaluate the performance of the outdoor (R_s) and greenhouse daily incoming solar radiation (R_{sgreen}), respectively. They were obtained by comparison of measurements and estimations using forecasted meteorological data. The parameters shown are RMSE, MAE, MBE, RE and Ratio, calculated as defined above. In addition, the coefficient of determination R^2 corresponding to the best-fit line from ordinary linear regression of estimates was included. Both methods for forecasting R_s worked rather well, with correlations and relative errors similar to those obtained when measured data are used for estimating incoming solar radiation.

Table 1
Ratio, determination coefficient (R^2), root mean square error (RMSE), relative error (RE), mean absolute error (MAE) and mean bias error (MBE) from the comparison of forecasted and measured incoming solar radiation using the cloudiness and temperature methods.

Season	R_s forecasted ($MJ\,m^{-2}\,d^{-1}$)	R_s measured ($MJ\,m^{-2}\,d^{-1}$)	Ratio	R^2	RMSE ($MJ\,m^{-2}\,d^{-1}$)	RE (%)	MAE ($MJ\,m^{-2}\,d^{-1}$)	MBE ($MJ\,m^{-2}\,d^{-1}$)
				Cloudiness				
2012/2013	18.1	15.0	1.2	0.87	4.7	31.2	3.6	3.0
2013/2014	16.4	14.6	1.1	0.84	3.3	22.7	2.4	1.8
				Temperature				
2012/2013	15.6	15.0	1.0	0.82	2.9	19.6	2.4	0.5
2013/2014	14.6	14.6	1.0	0.82	2.8	19.1	2.1	0.1

Table 2
Ratio, determination coefficient (R^2), root mean square error (RMSE), relative error (RE), mean absolute error (MAE) and mean bias error (MBE) from the comparison of forecasted and measured greenhouse solar radiation using the cloudiness and temperature methods.

Season	R_{sgreen} forecasted ($MJ\,m^{-2}\,d^{-1}$)	R_{sgreen} measured ($MJ\,m^{-2}\,d^{-1}$)	Ratio	R^2	RMSE ($MJ\,m^{-2}\,d^{-1}$)	RE (%)	MAE ($MJ\,m^{-2}\,d^{-1}$)	MBE ($MJ\,m^{-2}\,d^{-1}$)
			Cloudiness					
2012/2013	13.5	12.2	1.1	0.89	2.7	21.9	2.0	1.3
2013/2014	11.8	10.4	1.2	0.85	2.4	23.1	1.8	1.4
			Temperature					
2012/2013	11.7	12.2	1.0	0.81	2.6	21.1	2.0	−0.5
2013/2014	10.5	10.4	1.0	0.79	2.1	20.6	1.6	0.2

However, forecasted R_s was more accurate when the temperature method was used, as most forecasted data are closely distributed around the 1:1 line (Fig. 3b). In this case values of RMSE were equal to 2.9 and 2.8 $MJ\,m^{-2}\,d^{-1}$ for the 2012/13 and 2013/14 growing seasons, respectively. On the contrary, these values were equal to 4.7 and 3.3 $MJ\,m^{-2}\,d^{-1}$ when the cloudiness method was used. Relative errors (expressed as RMSE in%) ranged from 19.1%, for the temperature method to 31.2% for the cloudiness model. When outdoor solar radiation was estimated using the cloudiness method the errors were higher for the first growing season. This difference was due to high errors in the clear-sky forecast during the 2012/2013 growing season (Fig. 4a and b). For 2012/2013 growing season AEMET forecasted numerous days with clear-sky conditions. However, when estimated radiation values were compared with measurements an overestimation of solar radiation was detected for these days (Fig. 4a).

The values of RMSE using the temperature method were quite similar to those reported by Estévez et al. (2012) using the Hargreaves-Samani method when the adjusted value of K_r (Eq. (2)) was used, although they used measured values of air temperature for the estimation. These authors evaluated in Southern Spain estimations of outdoor incoming solar radiation using several models (Hargreaves and Samani, 1982; Annandale et al., 2002; Mahmood and Hubbard, 2002; Allen, 1995; Samani, 2000; Bristow and Campbell, 1984). Average relative errors for coastal locations ranged from 19.6% for Bristow-Campbell model to 36% for Mahmood-Hubbard model. Therefore, in many cases, relative errors were higher than those found in our work. For Hargreaves-Samani model, the RMSE values reported by Mahmood and Hubbard (2002) and Hunt et al. (1998) were also slightly higher than those found in this work. Perera el al. (2014) evaluated forecasts of ET_o and other meteorological variables in Australia. RMSD and R^2 obtained of the comparison between measured and forecasted R_s in their work ranged from 2.8 and 7.4 $MJ\,m^{-2}\,d^{-1}$, for different lead times. Therefore, it can be concluded that accuracy of R_s estimations based on forecasted temperatures was similar to those based on measurements of temperatures using different models.

There was a tiny bias when the temperature method was used for forecasting incoming solar radiation (MBE ranging from 0.1 to 0.5 $MJ\,m^{-2}\,d^{-1}$) (Fig. 3b). However, a significant positive bias occurred when the cloudiness method was used (maximum value of MBE was equal to 3.0 $MJ\,m^{-2}\,d^{-1}$) and forecasted values were overestimated 20% and 12% during the first and second growing season, respectively, (Fig. 3a). By contrary, the temperature method produces overestimations smaller than 4% (Table 1). There-

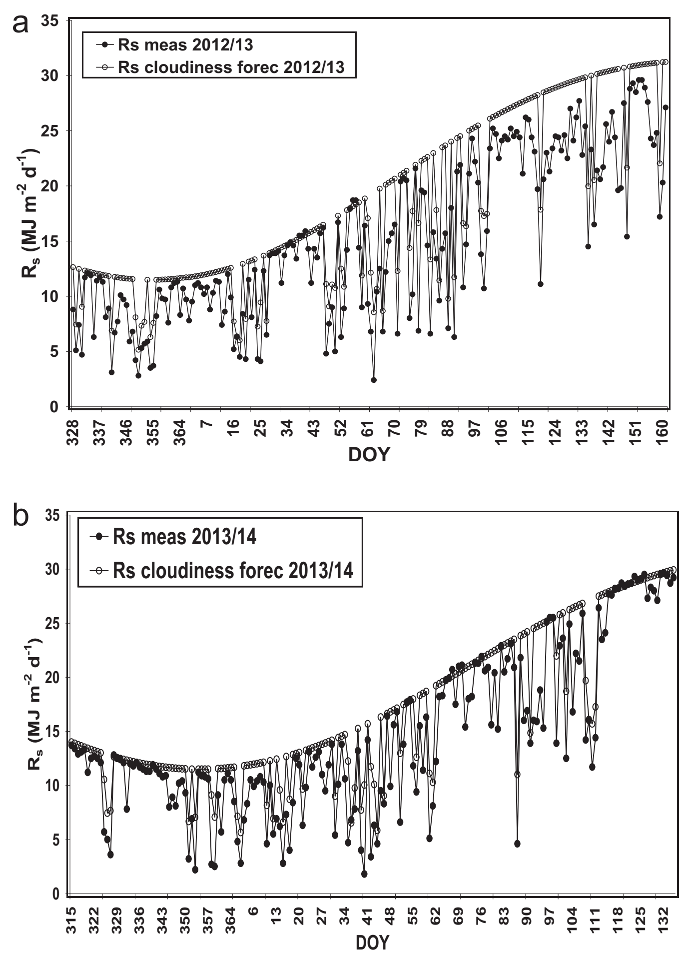

Fig. 4. (a) Seasonal trend of measured outdoor solar radiation and forecasted based on cloudiness method during 2012/2013 growing season. (b) Seasonal trend of measured outdoor solar radiation and forecasted based on cloudiness method during 2013/2014 growing season.

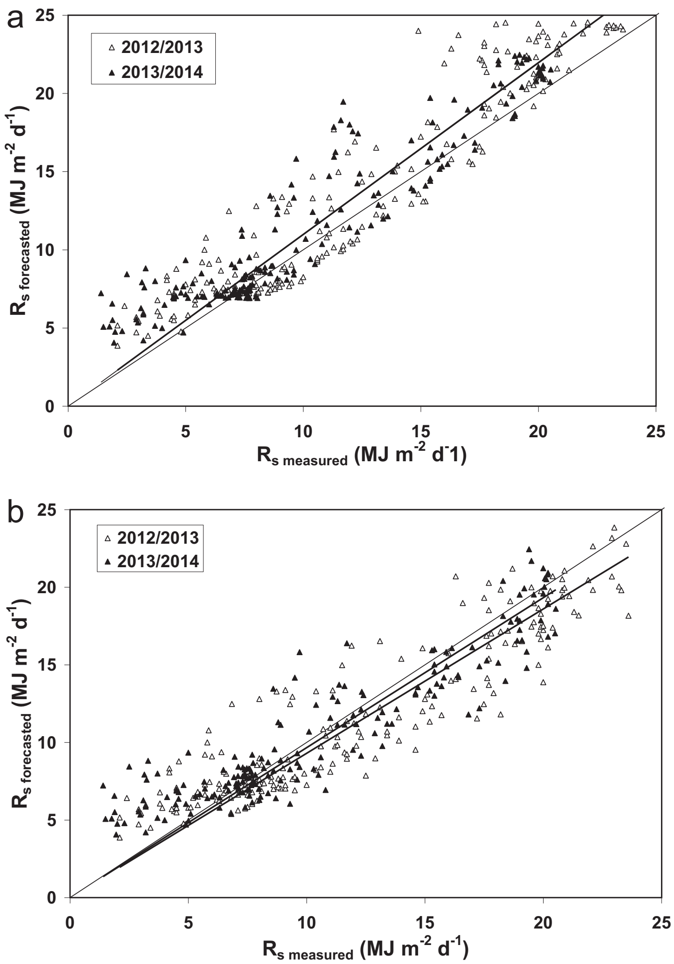

Fig. 5. (a) Comparison between forecasted and measured greenhouse solar radiation using the cloudiness method. (b) Comparison between forecasted and measured greenhouse solar radiation using the temperature method. Also shown is the 1:1 line.

fore, it can be concluded that temperature-based method was more appropriate in the forecasting of incoming solar radiation. The MBE reported by Estévez et al. (2012) for coastal locations in the cited work ranged from −0.20 ± 1.29 (average ± standard deviation) for the Hargreaves–Samani model to −5.17 ± 1.59 for the Mahmood and Hubbard. Therefore, the bias was higher than those found in this work in the majority of cases.

The average daily integral of measured greenhouse solar radiation ranged between 1.4 MJ m^{-2} d^{-1} in winter and 23.6 MJ m^{-2} d^{-1} in spring (Fig. 5). This range of R_{sgreen} was smaller than that measured by Fernández et al. (2010) under a plastic greenhouse in a Mediterranean climate due to their growing season included summer. The mean value of measured greenhouse radiation transmission was 76%, very close to that used for the estimations of greenhouse solar radiation in this work (τ = 0.75). This radiation transmission value was higher than that measured by Fernández et al. (2010) under non-whitened greenhouse (60.8%). In terms of RMSD, differences in accuracy of R_{sgreen} forecasting were both smaller when the two methods were used, only a tiny difference was found (Table 2). Values of RE ranged from 21.9 to 23.1% when de cloudiness method was used and from 20.6 to 21.1% when incoming solar radiation was estimated using the method based on the forecasting of temperatures. However, as in the case of forecasting outdoor solar radiation, the method based on cloudiness produced higher bias (maximum value of MBE was equal to 1.4 MJ m^{-2} d^{-1}) and forecasted values were overestimated 11% and 13% during the

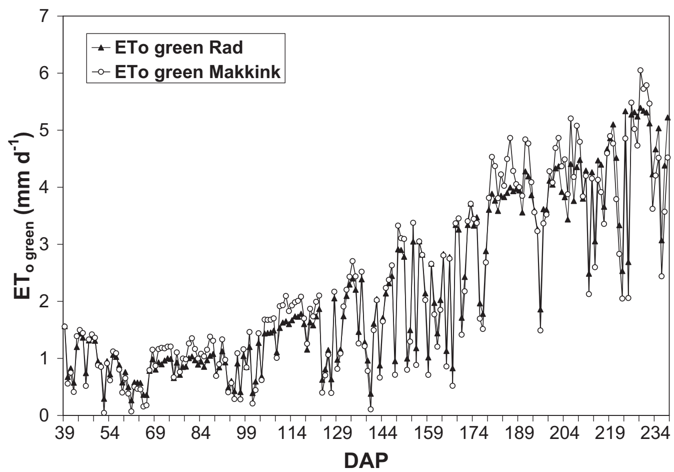

Fig. 6. Seasonal trend of daily greenhouse reference evapotranspiration, from measured data, using the Makkink FAO24 and the radiation methods during 2012/2013 growing season.

first and second growing season, respectively (Fig. 5a). By contrary, the temperature method produces a bias smaller than 5% and MBE ranged from −0.5 to 0.2 MJ m^{-2} d^{-1} (Fig. 5b). Therefore, this last method was also more appropriate in the forecasting of R_{sgreen}. These differences should have an effect on the forecast of $ET_{o\ green}$ as discussed below.

3.2. Comparison of estimated greenhouse ET_o using forecasted and measured meteorological data

Fig. 6 shows the seasonal evolution of estimated daily values of $ET_{o\ green}$, using measured meteorological data, during the first growing season (2012/13). The daily $ET_{o\ green}$ data ranged from values slightly lower than 0.5 mm d^{-1} in December–January up to values slightly higher than 5.5 mm d^{-1} at the beginning of June. Average daily $ET_{o\ green}$ from measured meteorological data was 2.2 mm d^{-1}. During the second season, these values ranged from 0.5 to 5.4 mm d^{-1}, with an average value of 1.9 mm d^{-1}. The higher average value of $ET_{o\ green}$ obtained during the first growing season was due to the higher length of this season. The ranges of $ET_{o\ green}$ were higher than those measured by Fernández et al. (2010) under a plastic greenhouse for a perennial grass crop in a Mediterranean climate, but they were lower than outdoor ET_o values estimated using Penman–Monteith FAO-56 from weather measured data (Estévez et al., 2009) and lysimeter measurements in areas with a similar climate (Berengena and Gavilán, 2005). The plastic greenhouse reduced incoming solar radiation inside the tunnels by 24% on average and also reduced wind speed. This means that the value for greenhouse reduction of solar radiation was lesser than that reported by Fernández et al. (2010) under non-whitened greenhouses (39%) due to they used 0.2 mm-thick thermal polyethylene. Outdoor ET_o values during the same season, estimated using the Penman–Monteith FAO-56 equation (Allen et al., 1998), from measured meteorological data in an outdoor weather station located near the tunnels, ranged from approximately 1 mm d^{-1} in winter up to approximately 6.5 mm d^{-1} in June, with an average value of 2.4 mm d^{-1} (data not shown). Therefore, greenhouse ET_o was approximately 21% lower than equivalent outdoor values, mainly as a result of the reduced solar radiation and wind speed inside the tunnels. These differences were also smaller than those reported by Möller and Assouline (2007) for a screenhouse in Israel, calculated from measured meteorological data following FAO56 methodology. The main reason for this difference was the significant reduction in solar radiation inside the screenhouse (56% less than open field con-

Table 3
Ratio, determination coefficient (R^2), root mean square error (RMSE), relative error (RE), mean absolute error (MAE) and mean bias error (MBE) from the comparison between daily greenhouse reference evapotranspiration, using measured meteorological data ($ET_{o\ greenmeas}$) and forecasted ($ET_{o\ greenforec}$), and the radiation and the Makkink FAO24 methods.

Season	Method	$ET_{o\ greenmeas}$ (mm d^{-1}) (mm)	$ET_{o\ greenforec}$ (mm d^{-1}) (mm)	Ratio	R^2	RMSE (mm d^{-1})	RE (%)	MAE (mm d^{-1})	MBE (mm d^{-1})
2012/2013				Cloudiness					
	Radiation	2.2 (442)	2.5 (495)	1.12	0.93	0.56	25.5	0.4	0.3
	Makkink FAO24	2.2 (448)	2.4 (489)	1.09	0.93	0.53	23.8	0.4	0.2
				Temperature					
	Radiation	2.2 (442)	2.1 (427)	0.97	0.89	0.50	18.0	0.5	−0.1
	Makkink FAO24	2.2 (448)	2.2 (437)	0.98	0.86	0.57	23.2	0.5	−0.1
2013/2014				Cloudiness					
	Radiation	1.9 (334)	2.2 (371)	1.11	0.95	0.39	21.5	0.2	0.2
	Makkink FAO24	2.1 (355)	2.2 (380)	1.07	0.92	0.45	23.6	0.3	0.1
				Temperature					
	Radiation	1.9 (334)	2.0 (343)	1.03	0.91	0.36	20.0	0.3	0.1
	Makkink FAO24	2.1 (355)	2.1 (349)	0.98	0.87	0.51	26.6	0.4	0.0

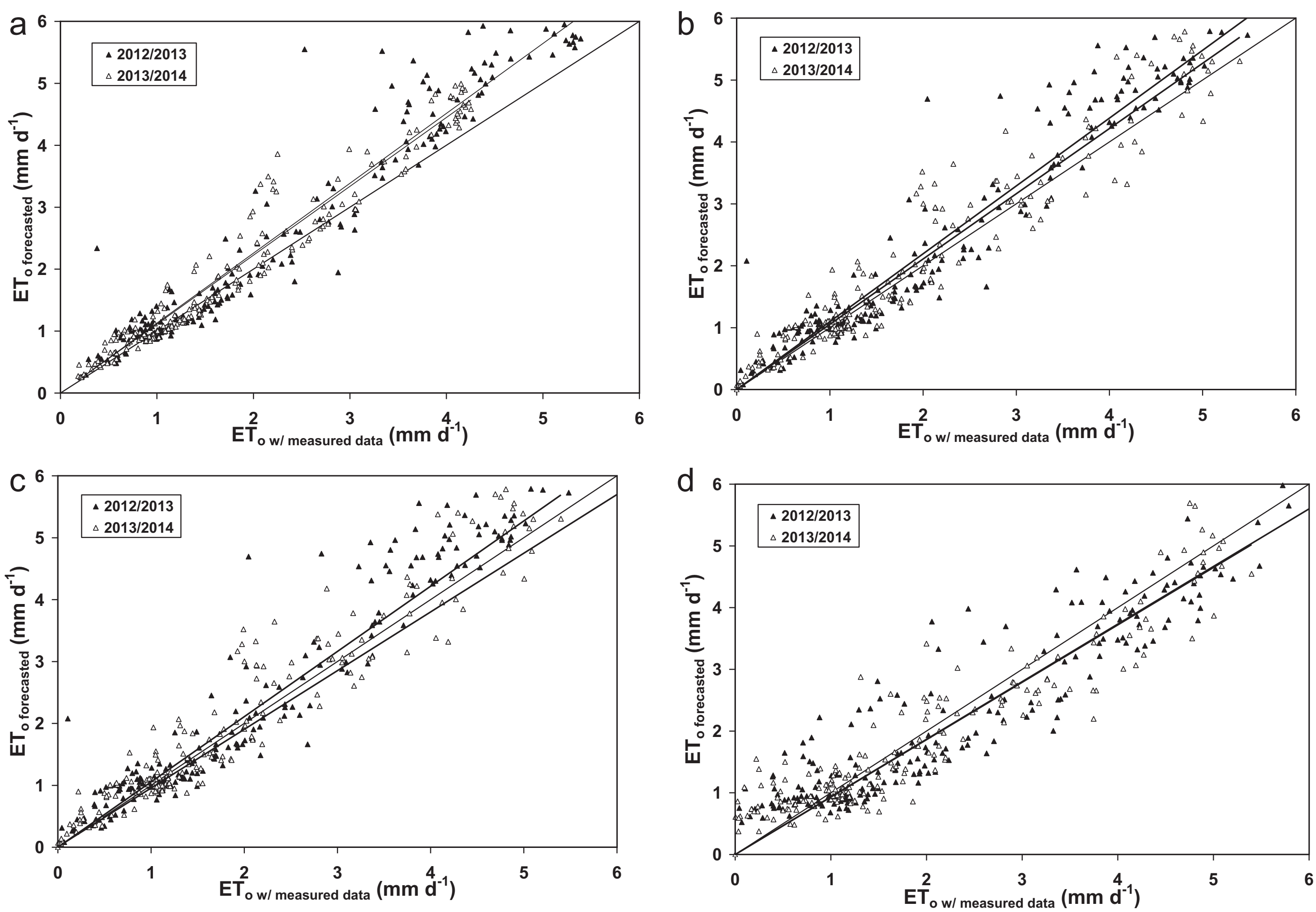

Fig. 7. (a) Comparison between daily greenhouse reference evapotranspiration using the radiation method from measured data and forecasted solar radiation estimated using the cloudiness method. (b) Comparison between daily greenhouse reference evapotranspiration using the Makkink FAO24 equation from measured data and forecasted solar radiation estimated using the cloudiness method. (c) Comparison between daily greenhouse reference evapotranspiration using the radiation method from measured data and forecasted solar radiation estimated using the temperature method. (d) Comparison between daily greenhouse reference evapotranspiration using the Makkink FAO24 equation from measured data and forecasted solar radiation estimated using the temperature method. Also shown is the 1:1 line.

ditions, over the season), that produces a reduction of 38% in daily ET_o, while the lower wind speeds inside contributed to a smaller extent (Fernández et al., 2010).

Table 3 shows the values of several parameters used to evaluate the performance of the daily estimated $ET_{o\ green}$, obtained by comparison, using forecasted and measured meteorological data. In both cases, $ET_{o\ green}$ was daily estimated using the radiation and the Makkink FAO-24 equations and outdoor solar radiation was forecasted using the methods based on cloudiness and temperature. In most cases, the correlations were very high, with all R^2 values above 0.86, and only ranging from 0.86 to 0.95. This narrow range is also reflected in the MBE (0.3 to −0.1 mm d^{-1}). The values of this parameter indicate that when the cloudiness method was used to estimate incoming solar radiation, overestimations of

Table 4
Ratio, determination coefficient (R^2), root mean square error (RMSE), relative error (RE), mean absolute error (MAE) and mean bias error (MBE) from the comparison of daily greenhouse reference evapotranspiration, using measured meteorological data, and the radiation ($ET_{o\ greenRad}$) and Makkink FAO24 ($ET_{o\ greenMakkink}$) methods.

Season	$ET_{o\ greenRad}$ (mm)	$ET_{o\ greenMakkink}$ (mm)	Ratio	R^2	RMSE ($mm\,d^{-1}$)	RE (%)	MAE ($mm\,d^{-1}$)	MBE ($mm\,d^{-1}$)
2012/2013	442	448	1.01	0.96	0.29	13.1	0.23	0.03
2013/2014	334	355	1.06	0.98	0.32	17.7	0.23	0.12

Table 5
Ratio, determination coefficient (R^2), root mean square error (RMSE), relative error (RE), mean absolute error (MAE) and mean bias error (MBE) from de comparison between daily crop strawberry evapotranspiration, using measured meteorological data ($ET_{c\ greenmeas}$) and forecasted ($ET_{c\ greenforec}$), and the radiation and the Makkink FAO24 methods.

Season	Method	$ET_{c\ greenmeas}$ ($mm\,d^{-1}$) (mm)	$ET_{c\ greenforec}$ ($mm\,d^{-1}$) (mm)	Ratio	R^2	RMSE ($mm\,d^{-1}$)	RE (%)	MAE ($mm\,d^{-1}$)	MBE ($mm\,d^{-1}$)
2012/2013				Cloudiness					
	Radiation	1.5 (300)	1.7 (337)	1.17	0.94	0.39	26.0	0.2	0.2
	Makkink FAO24	1.5 (304)	1.7 (333)	1.14	0.94	0.37	24.2	0.2	0.1
				Temperature					
	Radiation	1.5 (300)	1.5 (297)	0.99	0.92	0.30	19.8	0.3	0.0
	Makkink FAO24	1.5 (304)	1.4 (290)	0.95	0.91	0.33	21.8	0.3	−0.1
2013/2014				Cloudiness					
	Radiation	1.3 (234)	1.4 (262)	1.12	0.97	0.29	23.3	0.2	0.2
	Makkink FAO24	1.4 (252)	1.5 (271)	1.08	0.95	0.33	24.6	0.2	0.1
				Temperature					
	Radiation	1.3 (234)	1.3 (240)	1.02	0.95	0.25	20.2	0.2	0.1
	Makkink FAO24	1.4 (252)	1.3 (246)	0.98	0.92	0.36	26.3	0.3	0.0

$ET_{o\ green}$ were detected in both growing season (MBE ranged from 0.2 to 0.3 $mm\,d^{-1}$) (Fig. 7a and b). This overestimation was due to the overestimates of greenhouse solar radiation when this same method was used. However, when incoming solar radiation was estimated from forecasted temperature data, there was a very slight underestimation of $ET_{o\ green}$ (MBE = −0.1 $mm\,d^{-1}$) (Fig. 7c and d). Differences are also reflected in the average ratio. Average values of this parameter ranged from 0.97 to 1.12. Both methods for estimating $ET_{o\ green}$ were more accurate when the temperature-based solar radiation procedure was used, with resulting differences of only around 2–3%. However, using forecasted cloudiness to estimate solar radiation resulted in overestimations of $ET_{o\ green}$ higher than 10%. Relative errors between measured and forecasted greenhouse ET_o data ranged from 3.6 to 7.2%. Forecasting open air ET_o using Penman–Monteith FAO-56 equation, Perera et al. (2014) reported values of RMSD on average of 0.73 and 1.43 $mm\,d^{-1}$ for 1 and 9 day lead times, respectively. Therefore, RMSD approximately doubled as the lead time increased from 1 to 9 days. For one day lead time, R^2 ranged from 0.51 to 1.00. The values of RMSD were higher than those found in our study (ranging between 0.36 and 0.57 $mm\,d^{-1}$) due to the higher values of open air ET_o in Australia (up to 9 $mm\,d^{-1}$) with respect to those estimated under greenhouse. Xu et al. (2012) predicted open air daily ET_o in a humid region of China by the locally calibrated Hargreaves-Samani equation using weather forecast data. Values of RMSD reported in this study ranged from 0.70 to 1.33 $mm\,d^{-1}$. However, the errors were also high using Hargreaves–Samani equation as predictor due to this equation overestimates ET_o in humid regions of China (Xu et al., 2012). Finally, Cai et al. (2007) compared Penman–Monteith FAO56 ET_o from weather forecast with those computed with observed data for eight weather stations in China. In their work results of R^2 were above 0.91 and, except for one location, RMSD and RE were smaller than 0.35 $mm\,d^{-1}$ and 13%, respectively. They found good estimations in humid and semi-humid regions but ET_o was underestimated for stations located in arid zones, resulting on RMSD and RE above 0.87 $mm\,d^{-1}$ and 24%, respectively. Using also daily weather forecast from Penman–Monteith FAO-56 in a non-synoptic location, Cai et al. (2009) found RMSD of 0.77 $mm\,d^{-1}$ and relative errors ranging from 27 to 39%. Therefore, they concluded that using daily weather forecasts produces estimates for ET_o comparable with those computed with observed weather data, particularly when some weather variables are not observed.

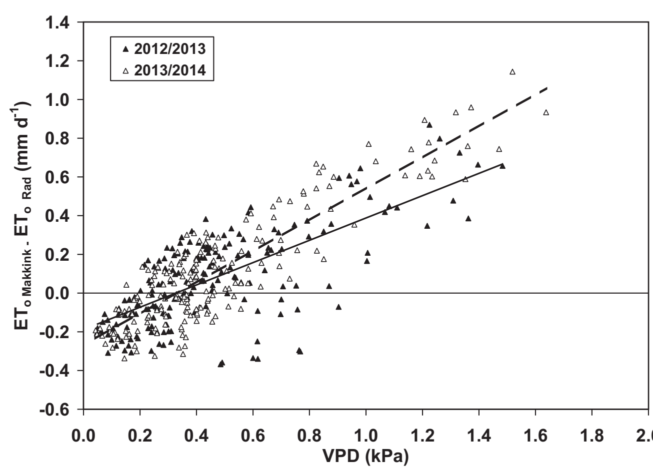

Fig. 8. Response of the difference between greenhouse reference evapotranspiration estimated using Makkink FAO24 ($ET_{o\ Makkink}$) and Radiation equation ($ET_{o\ Rad}$) to vapor pressure deficit (*VPD*). Solid and dashed lines correspond to 2012/13 and 2013/2014 growing season, respectively. Lines represent the best fit using linear regression.

It is interesting to compare the estimated greenhouse ET_o values using methods based on Makkink FAO24 and radiation equation. Using measured data, the Makkink FAO24 equation produced a slight underestimation, compared to the radiation equation, when vapor pressure deficit (VPD) was smaller than 0.2 kPa. The opposite was true when these values were greater than 0.5 kPa, in days with high air temperatures and low relative humidity of the air (Fig. 8). This difference in behavior of two equations can be attributed, at least in part, to the capacity of weighting $\Delta/(\Delta+\gamma)$ and b factors involved in the Eq. (8). They depend on temperature and relative humidity of the air, respectively, and they take into account the differences in vapor pressure deficit. Comparison of the two methods suggests that the Makkink FAO24 equation could result in an average overestimation of $ET_{o\ green}$ ranging between 1 and 6%, with respect to the equation based only on solar radiation, with relative differences ranging from 13.1 to 17.7% (Table 4).

Finally, to underscore that this work do not mean a validation of estimations methods of ET_o is necessary. Validation of the approaches proposed was made indirectly through the comparison of estimated values of crop evapotranspiration with those measured using lysimeters, as discussed below.

3.3. Comparison of strawberry ET_c using forecast, measurements and lysimeter data

Estimated daily ET_c from measured meteorological data during the first season ranged from values slightly lower than 0.2 mm d^{-1} in December–January up to values slightly higher than 4 mm d^{-1} at the beginning of June (data not shown). These values are similar to those estimated by Hanson and Bendixen (2004) for an irrigated strawberry crop at California. Average daily ET_c from weather measured data was 1.5 mm–d^{-1}. During the second season, these values ranged from 0.2 to 4.5 mm–d^{-1}, with an average value of 1.3 mm–d^{-1} (Table 5). The higher average value of ET_c obtained during the first growing season was due to the higher length of this.

Table 5 shows the values of parameters used to evaluate the performance of the estimated daily ET_c values, using measured and forecasted meteorological data. In both cases, daily ET_c was estimated using the radiation and the Makkink FAO-24 models. The correlations were also very high, with R^2 values always above 0.91 and only ranging from 0.91 to 0.97. This narrow range is also reflected in the MBE (−0.2 to 0.2 mm d^{-1}). Values of this parameter indicate that both methods overestimated ET_c when R_{sgreen} was estimated from the forecasted cloudiness method (Fig. 9a). However, when estimates of solar radiation from temperature method were used, the forecast data produced only a slight underestimation of ET_c (Fig. 9b). Relative errors between measured and forecasted data ranged from 19.8 to 26.3% and, as general rule, the errors were smaller when solar radiation was estimated from forecasted temperature data. Therefore, these results suggest that this latter method is preferable when forecast data are used. Differences are also reflected in the average ratio (Ratio), with average values ranging from 0.95 to 1.17. As a general rule, ET_c estimations were more accurate when the temperature-based solar radiation procedure was used, with the resulting underestimation only being around 2–5%. However, when solar radiation was estimated using the forecasted cloudiness, values were overestimated by up to 17%.

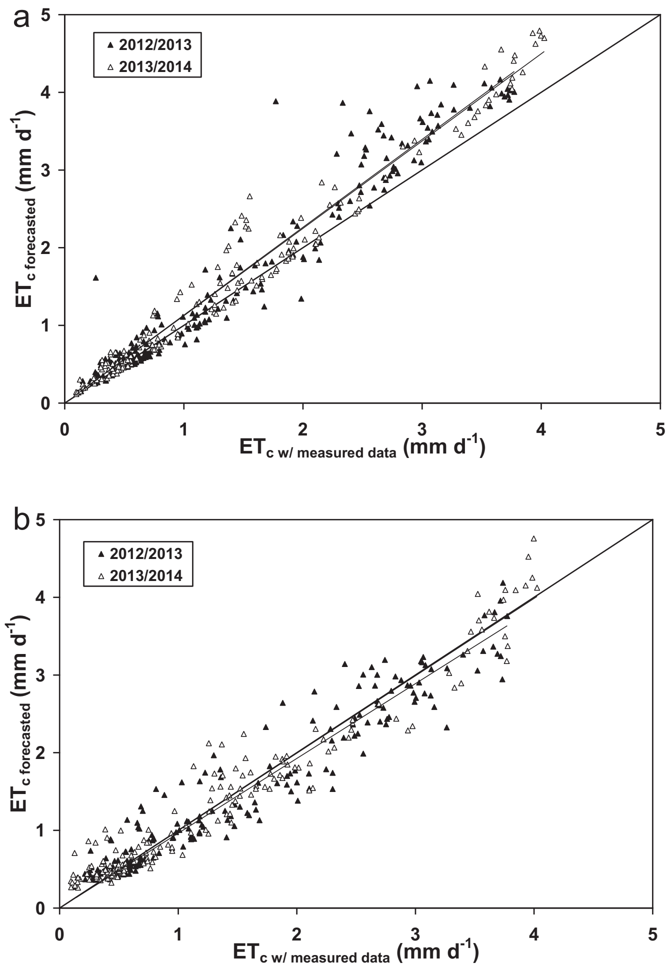

Fig. 9. (a) Comparison between daily crop evapotranspiration using the radiation method from measured data and forecasted solar radiation estimated using the cloudiness method. (b) Comparison between daily crop evapotranspiration using the radiation method from measured data and forecasted solar radiation estimated using the temperature method. Also shown is the 1:1 line.

Table 6
Ratio, determination coefficient (R^2), root mean square (RMSE), relative error (RE), mean absolute error (MAE) and mean bias error (MBE) from the comparison between 15-day estimated crop strawberry evapotranspiration (ET_c) and lysimeter evapotranspiration ($ET_{c\,lys}$), using measured and forecasted meteorological data.

Season		ET_c (mm d^{-1})	Ratio	RMSE (mm d^{-1})	RE (%)	MAE (mm d^{-1})	MBE (mm d^{-1})
2012/2013		Measured data					
$ET_{c\,Lys}$	Radiation	1.5 (300)	0.95	0.19	11.8	0.1	−0.1
1.6 mm d^{-1}	MakkinkFAO24	1.5 (304)	0.96	0,20	12.4	0.1	−0.1
(316 mmm)		Cloudiness					
	Radiation	1.7 (337)	1.07	0.18	11.7	0.1	0.1
	MakkinkFAO24	1.7 (333)	1.05	0,15	9.5	0.1	0.1
		Temperature					
	Radiation	1.5 (297)	0.94	0.18	11.7	0.1	−0.1
	MakkinkFAO24	1.4 (290)	0.92	0.24	15.5	0.2	−0.1
2013/2014		Measured data					
$ET_{c\,Lys}$	Radiation	1.3 (234)	0.93	0.29	21.5	0.2	−0.2
1.4 mm d^{-1}	MakkinkFAO24	1.4 (252)	1.00	0.19	14.0	0.2	−0.1
(253 mm)		Cloudiness					
	Radiation	1.4 (262)	1.04	0.17	12.4	0.2	0.0
	MakkinkFAO24	1.5 (271)	1.07	0.20	14.9	0.2	0.0
		Temperature					
	Radiation	1.3 (240)	0.95	0.24	17.5	0.2	−0.2
	MakkinkFAO24	1.3 (246)	0.98	0.15	11.2	0.2	−0.2

During the first season, seasonal ET_c values using the cloudiness forecast were 337 and 333 mm for radiation and Makkink FAO24 equations, respectively. When measured meteorological data were used, ET_c values were equal to 300 and 304 mm. Therefore, the use of weather forecast data led to ET_c values being overestimated by 17% for radiation method and by 14% for the Makkink FAO24 method. However, the estimation was more accurate when the estimates used forecasted temperature data, with differences lower than 5% (Table 5). During the 2013/2014 season, the results were similar, with estimates based on temperature forecast again being more accurate (underestimation lower than 2% versus overestimation higher than 8%). Estimated values of ET_c using measured and forecasted meteorological values were similar to that reported by Trout and Gartung (2004). They estimated a consumptive water use of 300 mm for a five-month growing season. Similar values were reported by Hanson and Bendixen (2004) with ET_c data from 310 to 396 mm. The higher value corresponded to an eight-month growing season.

The drainage lysimeters allowed the measurement of ET_c and the establishment of a baseline to evaluate the above methods. As a general rule, the estimations were more accurate when using measured meteorological data and the Makkink FAO24 method (Table 6). During the first and second growing seasons, seasonal measured lysimeter ET_c values were 316 and 253 mm, respectively. Clark et al. (1996) reported lysimeter measured values of open air strawberry ET_c ranging from 266 to 305 mm during a five-month growing season in Florida (USA), similar to those measured in this work.

During the first season, forecasted values of ET_c overestimated lysimeter values 6% on the average using solar radiation based on cloudiness and underestimated 7% using temperature based solar radiation. Underestimation reached 5% when measured data were used for ET_o estimations. During the second season, lysimeter ET_c was 7% higher than that estimated using the radiation method, and only 0.4% higher than that estimated using the Makkink FAO24 equation with measured meteorological data. ET_c was underestimated by less than 5% when using R_s based on temperature for forecasting ET_o. Therefore, in this growing season temperature-based estimation of ET_o, especially using Makkink FAO24 equation, provided more accurate estimates when compared with measured values. During the first season, the accuracy of all methods was similar, whether using measured or forecasted meteorological data (RMSE ranging from 0.15 to 0.24 mm d^{-1}). This first growing season was longer which resulted in higher seasonal ET_c, and all methods were less accurate when evaporative demand was higher.

4. Conclusions

The results of this study support the conclusion that the use of weather forecast data provided by the Spanish Meteorology National Agency (AEMET) would be a useful tool for real-time daily irrigation scheduling in crops growing on sandy soils under greenhouses. Analysis of comparisons between daily estimated values of $ET_{o\ green}$ calculated using measured and forecasted meteorological data correlated very well (R^2 between 0.86 and 0.95) and had low RMSD values (between 0.36 and 0.57 mm d^{-1}). The main differences occurred at the end of first growing season when solar radiation was estimated from the forecasted sky cloudiness. In this season AEMET forecasted clear-sky conditions but measurements of R_s do not reached potential solar radiation values. With respect to the forecasting of $ET_{o\ green}$, the errors were smaller when using estimated solar radiation from forecasted temperature data, especially when the $ET_{o\ green}$ was estimated using the Makkink equation, with underestimations below 3%. The results therefore suggest that this latter method is preferable. Agreement between daily estimated values of ET_c calculated using measured and forecasted data was also reasonable, with high correlations ($R^2 > 0.91$) and low relative errors (RE < 26%). Also, estimations of ET_c using measured or forecasted $ET_{o\ green}$, especially with the Makkink FAO24 equation, were quite accurate when compared with lysimeter-measured values, with RE < 21.5%.

Acknowledgments

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