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Crop evapotranspiration-based irrigation management during the growing season in the arid region of northwestern China

Xuexiang Chang · Wenzhi Zhao · Fanjiang Zeng

Abstract In arid northwestern China, water shortages have triggered recent regulations affecting irrigation water use in desert–oasis agricultural systems. In order to determine the actual water demand of various crops and to develop standards for the rational use of water resources, we analyzed meteorological data from the Fukang desert ecosystem observation and experiment station (FKD), the Cele desert–grassland ecosystem observation and research station (CLD), and the Linze Inland River Basin Comprehensive Research Station (LZD), which all belong to the Chinese Ecosystem Research Network. We researched crop evapotranspiration (E_{Tc}) using the water balance method, the FAO-56 Penman–Monteith method, the Priestley–Taylor method, and the Hargreaves method, during the growing seasons of 2005 through 2009. Results indicate substantial differences in E_{Tc}, depending on the method used. At the CLD, the E_{Tc} from the soil water balance, FAO-56 Penman–Monteith, Priestley–Taylor, and Hargreaves methods were 1150.3 ± 380.8, 783.7 ± 33.6, 1018.3 ± 22.1, and 611.2 ± 23.3 mm, respectively; at the FKD, the corresponding results were 861.0 ± 67.0, 834.2 ± 83.9, 1453.5 ± 47.1, and 1061.0 ± 38.2 mm, respectively; and at the LZD, 823.4 ± 110.4, 726.0 ± 0.4, 722.3 ± 29.4, and 1208.6 ± 79.1 mm, respectively. The FAO-56 Penman–Monteith method provided a fairly good estimation of E_{Tc} compared with the Priestley–Taylor and Hargreaves methods.

Keywords Agricultural system · Water balance · Penman–Monteith · Priestley–Taylor · Hargreaves · Desert–oasis

X. Chang · W. Zhao
Linze Inland River Basin Research Station, Chinese Ecosystem Research Network, Linze, China

X. Chang · W. Zhao
Key Laboratory of Ecohydrology of Inland River Basin, Cold & Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

F. Zeng
Cele Desert-Grassland Ecosystem Observation and Research Station, Chinese Ecosystem Research Network, Cele, China

F. Zeng
Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, China

X. Chang (✉)
Cold & Arid Regions Environmental And Engineering Research Institute, Chinese Academy of Sciences, No. 260, Dong-Gang West Road, Lanzhou 730000, People's Republic of China
e-mail: chxx@ns.lzb.ac.cn

Introduction

In northwest China, annual rainfall averages less than 200 mm (excluding areas in the mountains) and is less than 50 mm in places (Cheng et al. 1999). Furthermore, evaporation from water surfaces is often more than 2000 mm per year (Cheng et al. 1999), so that high temperature, high irradiation, a dry atmospheric environment, and deserts are common in this region, which account for about 28 % of the land area of China (Fu et al. 2010). Tributaries from the mountains (e.g., Qilian

Shan, Tian Shan, Kunlun Shan), though, feed large rivers, supporting the formation of many oases. In these oases of arid northwestern China, agriculture depends completely on irrigation, and agricultural irrigation accounts for 70–86 % of total water use. Furthermore, over 75 % of China's grain production comes from such irrigated land (Jia 2000; Cheng et al. 2004; Chang et al. 2006; Xiong et al. 2010; Zhao et al. 2010).

With increasing pressure on water resources from competing users, water shortages have highlighted the importance of water resources for agricultural production in arid regions (Payero et al. 2008). In northwestern China, this awareness has triggered recent regulations affecting irrigation water use: for example, installation of water meters on pumping stations, moratoriums on drilling new wells, and severe limitations on groundwater pumping to fixed multi-year water allocations. Under these conditions, it is necessary to carefully determine the water use and requirements of all crops. Research on crop evapotranspiration is helpful for understanding the water balance of the desert oases' agricultural land ecosystem in this region, and research results can be used to determine the actual water demand of various crops and to develop standards for the rational use of water resources (Dinpashoh 2006; Zhang et al. 2010), to protect and maintain the oases. Furthermore, to develop more efficient and sustainable water management techniques for arable regions and to better predict potential crop production, it is necessary to evaluate crop evapotranspiration (E_{Tc}).

Recently, many researchers have concentrated on crop water requirements in arid regions (Abdelhadi et al. 2000; Ali et al. 2000; de Azevedo et al. 2003; Jia and Luo 2006; Shen et al. 2013; Jiang et al. 2014). However, E_{Tc} is still ambiguous because the upper limit of E_T depends on vegetation type as well as soil water and climatic conditions (Burman and Pochop 1994). E_{Tc} has been estimated by many methods, such as the Penman–Monteith, the Bowen ratio-energy balance, the Eddy covariance, the aerodynamic method, the remote sensing method, the hydrological model, the soil water budget, and the crop coefficient approach (Ghamarnia et al. 2014; Karim et al. 2013; Araya et al. 2011; Descheemaeker et al. 2011; Amer et al. 2009; Frank 2003; Hunt et al. 2002; Domingo et al. 2001; Allen 2000; Kang et al. 2000; Bjerkholt and Myhr 1996; Vogt and Jaeger 1990; Idso et al. 1975); these methods range from complex energy balance equations (Allen et al. 1989) to simpler equations that require limited

meteorological data (Hargreaves and Samani 1985). Differences in E_T are significant among these methods (Shuttleworth 1991). The Penman–Monteith method has been successfully recommended by the FAO to calculate E_{To} under a number of different conditions (Bormann et al. 1999; Abdelhadi et al. 2000; Kang et al. 2003; Goyal 2004; Descheemaeker et al. 2011) and has shown higher accuracy and wider suitability compared with the Priestley–Taylor, Hargreaves, Penman, Blaney–Criddle, and other methods (Beyazgül et al. 2000; Kashyap and Panda 2001; Droogers and Allen 2002; Rivas and Caselles 2004). However, the climate data required in the Penman–Monteith method are not always available, especially in developing regions. Therefore, it is necessary to select the most appropriate and feasible method of estimating E_T in the arid regions of northwest China. Hence, we selected long-term dynamic monitoring scientific data at three desert–oasis agricultural comprehensive monitor fields in the arid regions of northwest China.

Our aim in the research reported here was to evaluate various equations to calculate evapotranspiration under arid climatic conditions; evapotranspiration variation is likely attributable to differences in soil, crop characteristics, and management practices, in northwest China. This research was an attempt to develop useful recommendations for rational and strategic water management for agricultural irrigation. In addition, assessments of ecosystem services were conducted, to provide science-based ecological information for sustainable agricultural ecosystem management.

Methods

Study area

This study was carried out during the period from 2005 to 2009 at a desert–oasis agricultural comprehensive monitor field in the Fukang desert ecosystem observation and experiment station (FKD), the Cele desert–grassland ecosystem observation and research station (CLD), and the Linze Inland River Basin Comprehensive Research Station (LZD). These stations all belong to the Chinese Ecosystem Research Network (CERN).

The FKD (44° 17.4′ N, 87° 55.8′ E and alt. 1319 m) is located in the Fukang City of Xinjiang Uygur Autonomous Region (Fig. 1). The annual mean temperature is 6.6 °C, the maximum temperature is 42.6 °C, and the
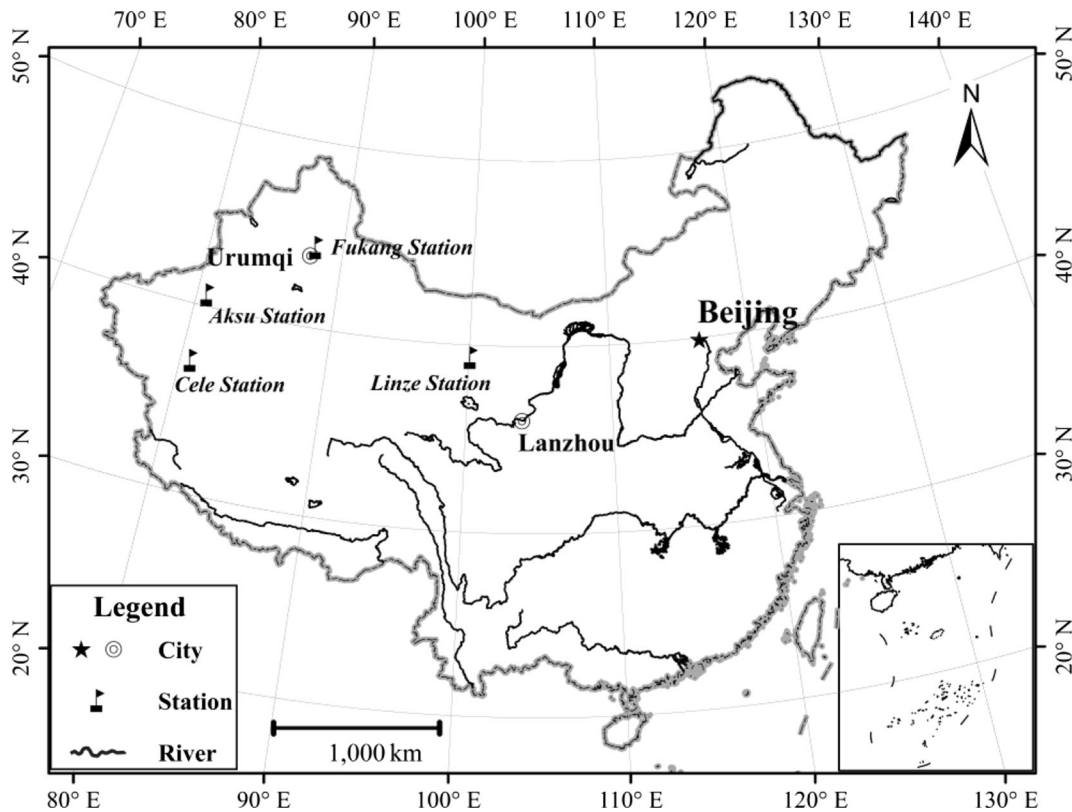
Fig. 1 Map of the research station locations in China

minimum temperature is −41.6 °C. The annual mean precipitation is 164.0 mm and the mean annual open water evaporation is 2000 mm. The frost-free period is about 174 days. The soil is sandy loam, and its field water capacity, total porosity, and soil bulk density are 19.9 %, 43.3 %, and 1503 kg m^{-3}, respectively. The CLD (37° 0.95′ N, 80° 43.75′ E and alt. 1319 m) is located in the Cele County in the Xinjiang Uygur Autonomous Region (Fig. 1). The annual mean temperature is 11.9 °C, the maximum temperature is 41.9 °C, and the minimum temperature is −23.9 °C. The mean annual precipitation is 35.1 mm and evaporation from water surfaces is 2596.3 mm. The frost-free period is about 196 days. The soil is aeolian sandy, and its field water capacity, total porosity, and soil bulk density are 19.6 %, 55.6 %, and 1174 kg m^{-3}, respectively. The LZD (100° 07′ E, 39° 21′ N and alt. 1374 m) is located in the Linze County, Gansu Province (Fig. 1). The mean annual precipitation is 116.8 mm, the mean annual open water evaporation is 2390 mm, the mean annual air temperature is 7.6 °C, the mean maximum and the mean minimum temperatures are 39.1 and −27 °C, respectively, and the frost-free period is about 165 days. The soil is

sandy, and its field water capacity, total porosity and soil bulk density are 11.4 %, 42.1 % and 1536 kg m^{-3}, respectively (Table 1).

These stations are fully representative of the surrounding irrigated land in arid northwestern China. In this region, cotton, corn, and wheat are the major irrigated crops. According to local reports, cotton is planted in the desert–oasis agricultural comprehensive monitor fields in the FKD and CLD, and corn is grown in rotation with wheat in the desert–oasis agricultural comprehensive monitor field in the LZD. The area of the desert–oasis agricultural comprehensive monitor field is 2332 m^2, with flood irrigation.

Meteorology, soil moisture, and irrigation

During the study, climatic data—including short-wave incoming radiation, air temperature, relative humidity, wind speed, and precipitation—were obtained from the automated meteorological station MILOS520 and were provided by the Chinese Ecosystem Research Network based on a norm. Short-wave radiation, air temperature, relative humidity, and wind speed were measured every

Table 1 Physical characteristics of the soil at the desert–oasis agricultural comprehensive monitor fields

Location	Depth (cm)	Bulk density (kg m^{-3})	Saturated water content (%)	Field water capacity (%)	Wilting moisture (%)	Total porosity (%)
LZD	0–10	1383	27.1	11.9	4.2	42.5
	10–20	1593	28.9	8.8	2.3	37.4
	20–40	1607	28.5	8.7	2.2	47.4
	40–60	1578	26.7	5.1	5.1	40.4
	80–100	1517	30.8	22.6	14.2	42.7
	Average	1536	28.4	11.4	5.6	42.1
CLD	0–10	1190	37.6	20.0	3.7	54.8
	10–20	1040	47.0	21.0	4.5	60.8
	20–40	1250	36.6	18.7	2.6	52.8
	40–60	1310	35.6	16.7	2.5	50.7
	80–100	1080	42.9	21.4	4.3	58.8
	Average	1174	39.9	19.6	3.5	55.6
FKD	0–10	1449	33.8	20.3	11.3	45.3
	10–20	1604	30.0	19.7	11.6	39.5
	20–40	1550	26.0	18.6	11.2	41.5
	40–60	1433	25.5	19.7	11.8	45.9
	80–100	1480	31.8	21.5	12.3	44.2
	Average	1503	29.4	19.9	11.6	43.3

5 min and stored in a datalogger as mean values for 30-min periods, and the precipitation was recorded as a cumulative value every day. The global short-wave radiation and net radiation were measured in the open with two pyranometers (CM11 and QMN101, Kipp & Zonen, Delft, Netherlands) and air temperature and humidity with Rotronic sensors (HMP45A & HMP45D, Helsinki, Finland), all at 2-m height above the ground surface. Wind speed was measured at a height of 10 m with a Rotronic sensor (wav151, Vaisala, Helsinki, Finland). CM7B shielding is a glass dome, which was cleaned frequently, and the dessicator inspected. The thermometer screen was plastic and the ventilation gap 20 mm. There was no vegetation at the weather station and the station itself was not irrigated. The precipitation was manually recorded at 0800 hours and 2000 hours local time from meteorological stations at FKD, CLD, and LZD (sometimes it was read immediately after the cessation of rain).

The volumetric soil moisture content (S, m^3 m^{-3}) was monitored using L520 neutron probes (Jiangsuruidi, Nanjing, China). To obtain these measurements, we installed monitoring sites at three locations in the desert–oasis agricultural comprehensive monitor field; at each location, an aluminum access tube (internal diameter 40 mm) was installed to facilitate insertion of the probe. Soil water content between depths of 0.1 and 1.5 m was measured at intervals of 0.1 m using a neutron moisture probe. Soil water moisture was measured once every 5 days and additional measurements were made before and after irrigation and after every rainfall.

The irrigation quantity was measured with a water meter (Shandongweifang Tec. Co., Shandong, China).

Crop evapotranspiration

Crop evapotranspiration (E_{Tc}) was evaluated with two computing methods; these equations are as follows.

Water balance method

E_{Tcp} was determined by the water balance method as proposed by Jensen (1973):

$$E_{Tcp} = I + P \pm \Delta S - D_p - S_R \tag{1}$$

Where I is the applied irrigation water (cm), P is the precipitation (cm), ΔS is the difference change in soil

water content for the given period (cm), D_p is the deep percolation below the root zone for the given period, and S_R (cm) is the surface runoff, which was assumed to be zero in all cases. This assumption is justified since runoff was prevented by the levees around the basin irrigation.

The change in soil water storage (ΔS) is positive when water is added to the root zone; otherwise, it is negative:

$$\Delta S = W(t+1) - W(t) \tag{2}$$

The water storage W in the root zone was derived from the soil moisture values (θ_i), per layer. At moment t, the storage across the depth (δ_{zi}) of the 15 layers ($i = 1, 2, 3,... 15$) can be computed as

$$W(t) = \delta_{Z1}\theta_1 + \delta_{Z2}\theta_2 + \cdots + \delta_{Z15}\theta_{15} \tag{3}$$

We defined deep drainage as the downward movement of soil water below the rooting depth of the plants. In theory, the maximum soil water storage capacity of a given volume of soil equals its saturated water storage capacity. Thus, deep drainage was estimated as follows:

$$D_d = (I + P) - W_{SWS} \tag{4}$$

$$w_{sws} = \sum_{i=1}^{k} \left(S_{si}\rho_s / \rho_w \right) H_i \tag{5}$$

where W_{sws} is the saturated water storage, S_{si} is the saturated water capacity of the ith soil layer, and k is the number of soil layers. If $D_d > 0$, D_d, this indicates a downward movement of soil water after irrigation or rain.

Reference evapotranspiration

E_{Tc} is calculated by multiplying the reference crop evapotranspiration by a crop coefficient (Allen et al. 1998):

$$E_{Tc} = K_c E_{To} \tag{6}$$

where K_c is the crop coefficient and E_{To} is the reference evapotranspiration (mm day^{-1}).

This research work evaluated three E_{To} computing methods, using grass as a reference crop. These equations are as follows.

Hargreaves The Hargreaves equation is expressed as follows (Hargreaves and Samani 1985; Allen et al. 1998):

$$E_{To} = 0.0023(T + 17.8)(T_{max} - T_{min})^{0.5} R_a \tag{7}$$

where E_{To} is the reference evapotranspiration (mm day^{-1}), T is the daily mean air temperature (°C), T_{max} is the daily maximum air temperature (°C), T_{min} is the daily minimum air temperature (°C), and R_a is the extraterrestrial radiation (mm day^{-1}).

The following empirical simplifications were used to estimate R_a using the latitude and the day of the year, as mentioned by Allen et al. (1998):

$$R_a = \frac{37.6 \times d_r(\omega_s \sin(\varphi_l)\sin(\delta) + \cos(\varphi_l)\sin(\omega_s))}{\lambda} \tag{8}$$

$$\delta = 0.4093 \times \sin\left(\frac{2\pi(284 + J)}{365}\right) \tag{9}$$

$$d_r = 1 + 0.033 \times \cos\left(\frac{2\pi J}{365}\right) \tag{10}$$

$$\omega_s = \cos(\tan(\varphi_l)\tan(\delta)) \tag{11}$$

where d_r is the relative distance from the earth to the sun, J is the Julian day, ω_s is the sunset hour angle (rad), ϕ_l is the latitude (rad), δ is the declination of the sun (rad), and λ is the latent heat of vaporization ($\lambda \approx 2.54$).

FAO-56 Penman–Monteith The FAO-56 Penman–Monteith equation is expressed as follows (Allen et al. 1998):

$$E_{To} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{12}$$

where E_{To} is the reference evapotranspiration (mm day^{-1}), Δ the slope vapor pressure curve (kPa °C^{-1}), R_n the net radiation at the crop surface (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T the daily mean air temperature at 2-m height (°C), U_2 the wind speed at 2-m height (m s^{-1}), e_s the pressure deficit (kPa), and g the psychrometric constant (kPa °C^{-1}).

$$\Delta = \frac{4098\left[0.6108\exp\left(\dfrac{17.27T}{T + 237.3}\right)\right]}{(T + 237.3)^2} \tag{13}$$

G was calculated based on the premise that soil temperature follows air temperature (Allen et al. 1998):

$$G = c_s \frac{T_i + T_{i-1}}{\Delta t} \tag{14}$$

where c_s is the soil heat capacity (MJ m^{-3} °C^{-1}), T_i is the air temperature at time i (°C), T_{i-1} is the air temperature at time $i-1$ (°C), Δt is the length of the time interval (day), and Δz is the effective soil depth (m).

For the calculation of E_{To}, wind speed measured at 2 m above the surface is required. To adjust the wind speed data obtained at 10-m height to the standard height of 2 m, a logarithmic wind speed profile may be used (Allen et al. 1998):

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{15}$$

Where u_2 is the wind speed at 2 m above ground surface (m s^{-1}), u_z is the measured wind speed at z m above the ground surface (m s^{-1}), and z is the height of measurement above the ground surface (m).

Priestley–Taylor The Priestley–Taylor method for estimating evaporation under no- or low-advective conditions is described as follows (Priestley and Taylor 1972; Sumner and Jacobs 2005):

$$E_{To} = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G_n) \tag{16}$$

Where α is an empirically determined dimensionless correction. A value of $\alpha = 1.26$ was used for the Priestley–Taylor coefficient.

Error analysis

The E_{Tc} values computed through the various methods were compared using a simple regression analysis (Box et al. 1989) and a series of statistics proposed by Willmott (1982). Error was calculated as

$$\text{RMSE} = \left[N^{-1}\sum_{i=1}^{N}(P_i - O_i)^2\right]^{0.5} \tag{17}$$

$$\text{RE} = \frac{\text{RMSE}}{O} \times 100\% \tag{18}$$

where RMSE is the root mean square error (mm day^{-1}), N the number of observations, P_i the estimated E_{Tc} values (mm day^{-1}), O_i the E_{Tc} values measured (mm day^{-1}), and $\bar{O}$ the mean value of the E_{Tc} values measured (mm day^{-1}).

Results

Inter-annual and seasonal variation in environmental conditions

The inter-annual and seasonal variations in weather parameters from 2005 to 2009 are summarized in Table 2. During the growing seasons of 2005–2009, the monthly mean air temperature was lowest in April; it was between 11.3 ± 4.8 and 14.0 ± 3.8 °C at the LZD, between 15.8 ± 3.3 and 19.5 ± 4.5 °C at the CLD, and between 11.5 ± 5.1 and 15.2 ± 2.8 °C at the FKD. The monthly mean air temperature reached its maximum in July; it was between 23.1 ± 2.4 and 25.7 ± 3.6 °C at the LZD, between 25.0 ± 2.6 and 26.5 ± 2.3 °C at the CLD, and between 25.7 ± 2.3 and 27.3 ± 3.0 °C at the FKD. The minimum values of monthly mean relative humidity at the LZD, CLD, and FKD were 24.5 ± 12.8 % in April 2006, 20.1 ± 7.2 % in April 2005, and 34.6 ± 10.1 % in June 2006, respectively, and the corresponding maximum values of monthly mean relative humidity were 69.5 ± 6.2 % in October 2007, 43.8 ± 14.1 % in September 2007, and 56.7 ± 9.4 % in October 2007, respectively. Most of the wind occurred in April, May, and June; the monthly average wind speed had a maximum value of 2.5 ± 0.8 m s^{-1} at the LZD, 2.5 ± 1.0 m s^{-1} at the CLD, and 2.3 ± 0.7 m s^{-1} at the FKD. During the growing season, the precipitation was between 86.8 and 107.2 mm at the LZD—73.6 to 90.8 % of normal for the period; at the CLD, it was between 15.0 and 56.4 mm—42.7 to 160.7 % of normal for the period; at the FKD, between 87.0 and 206.2 mm—53.1 to 121.1 % of normal for the period.

Crop evapotranspiration

The daily values of E_{Tc} were estimated by the water balance method (E_{Tw}) and meteorological methods, including FAO-56 Penman–Monteith (E_{TPM}), Priestley–Taylor (E_{TPT}), and Hargreaves (E_{TH}).

At the CLD, the maximum E_{Tw} was 265 ± 80 mm, in July, and the minimum was 37 ± 12 mm, in October; at

Table 2 Mean monthly weather variables for the growing seasons for the period 2005 to 2009 (mean ± SD)

Location	Month	Mean air temperature (°C)					Relative humidity (%)				
		2005	2006	2007	2008	2009	2005	2006	2007	2008	2009
LZD	Apr	12.3 ± 4.6	11.9 ± 5.3	12.0 ± 6.5	11.3 ± 4.8	14.0 ± 3.8	32.0 ± 11.8	24.5 ± 12.8	37.3 ± 17.7	25.9 ± 11.2	20.3 ± 7.2
	May	19.5 ± 2.8	17.3 ± 4.3	18.7 ± 3.1	18.9 ± 2.9	17.3 ± 3.1	38.6 ± 13.3	35.3 ± 16.5	30.3 ± 10.5	23.3 ± 6.6	32.8 ± 13.7
	Jun	24.5 ± 2.8	22.7 ± 2.6	22.2 ± 3.3	22.7 ± 2.4	22.4 ± 2.6	39.0 ± 10.8	31.1 ± 10.2	38.6 ± 16.8	31.3 ± 10.8	32.8 ± 8.5
	Jul	25.7 ± 3.6	23.3 ± 2.5	23.1 ± 2.4	24.2 ± 2.8	24.3 ± 2.7	48.8 ± 12.4	51.9 ± 16.2	51.4 ± 14.0	43.2 ± 16.4	42.2 ± 12.9
	Aug	22.6 ± 3.8	22.9 ± 3.0	23.1 ± 2.5	21.4 ± 3.0	22.1 ± 1.9	57.0 ± 16.5	50.5 ± 14.5	50.1 ± 13.5	42.7 ± 11.9	48.9 ± 11.5
	Sep	18.7 ± 3.1	17.2 ± 2.5	16.3 ± 2.9	17.4 ± 3.3	16.6 ± 3.2	52.6 ± 11.0	44.5 ± 17.1	55.1 ± 12.3	50.0 ± 20.3	63.5 ± 18.0
	Oct[a]	12.6 ± 1.2	13.1 ± 1.6	10. ± 3.5	13.8 ± 2.6	14.1 ± 1.2	49.1 ± 7.9	42.7 ± 2.3	69.5 ± 6.2	63.8 ± 12.2	40.9 ± 8.6
CLD	Apr	17.1 ± 5.3	16.7 ± 5.8	19.5 ± 4.5	15.8 ± 3.3	18.3 ± 2.6	20.1 ± 7.2	22.9 ± 13.5	16.5 ± 4.9	22.5 ± 9.0	22.2 ± 10.1
	May	20.8 ± 3.3	23.2 ± 3.3	23.3 ± 2.4	22.9 ± 2.6	20.9 ± 2.3	27.7 ± 11.3	27.5 ± 9.3	20.4 ± 8.0	29.0 ± 19.0	24.6 ± 6.7
	Jun	25.6 ± 2.2	24.1 ± 2.9	25.5 ± 4.0	26.8 ± 2.1	25.2 ± 2.4	32.9 ± 9.4	32.6 ± 8.9	33.1 ± 14.5	29.4 ± 8.8	29.0 ± 7.8
	Jul	25.0 ± 2.6	25.9 ± 2.9	26.5 ± 2.3	25.9 ± 2.7	26.0 ± 2.4	44.0 ± 10.5	40.5 ± 12.0	33.3 ± 10.4	40.9 ± 13.6	32.5 ± 6.1
	Aug	23.6 ± 1.7	26.7 ± 2.2	25.8 ± 2.3	25.5 ± 2.1	25.4 ± 2.0	44.9 ± 7.6	35.7 ± 6.3	35.6 ± 9.1	31.8 ± 4.7	34.3 ± 6.2
	Sep	21.5 ± 1.9	20.7 ± 2.0	19.9 ± 3.0	20.7 ± 2.5	20.2 ± 2.1	38.0 ± 7.5	35.6 ± 6.8	43.8 ± 14.1	36.1 ± 10.2	51.1 ± 13.7
	Oct[a]	12.2 ± 3.9	15.3 ± 2.6	11.2 ± 2.2	13.1 ± 4.6	12.8 ± 3.6	38.3 ± 7.7	34.6 ± 4.4	37.8 ± 9.5	35.8 ± 7.8	40.0 ± 7.9
FKD	Apr	12.7 ± 6.2	13.1 ± 5.5	15.2 ± 2.8	11.5 ± 5.1	14.4 ± 2.7	44.7 ± 15.2	43.1 ± 13.8	44.1 ± 13.9	42.9 ± 17.0	50.1 ± 13.5
	May	20.1 ± 3.1	18.7 ± 5.5	18.0 ± 3.6	21.9 ± 5.1	18.1 ± 3.4	36.5 ± 11.5	38.9 ± 16.0	52.1 ± 13.8	33.1 ± 11.1	46.6 ± 12.2
	Jun	24.8 ± 3.6	25.5 ± 3.0	24.7 ± 3.0	25.9 ± 2.7	23.6 ± 3.3	37.4 ± 13.7	34.6 ± 10.1	37.5 ± 10.3	35.1 ± 9.3	44.0 ± 11.1
	Jul	27.3 ± 3.0	26.0 ± 2.7	25.9 ± 3.0	26.4 ± 2.5	25.7 ± 2.3	39.2 ± 9.6	43.2 ± 9.7	51.1 ± 14.3	43.3 ± 13.6	41.9 ± 8.7
	Aug	23.0 ± 3.4	24.6 ± 3.3	23.1 ± 3.1	23.9 ± 3.8	23.8 ± 2.7	54.7 ± 14.3	39.2 ± 9.7	54.5 ± 9.5	45.0 ± 10.7	41.7 ± 7.1
	Sep	19.3 ± 3.4	17.7 ± 2.6	18.5 ± 4.7	17.5 ± 4.8	17.9 ± 3.4	41.3 ± 8.3	39.5 ± 14.4	49.4 ± 13.7	45.1 ± 9.9	51.3 ± 12.4
	Oct[a]	14.0 ± 2.0	13.0 ± 3.3	9.5 ± 2.6	15.6 ± 1.6	15.5 ± 2.5	40.0 ± 10.1	52.3 ± 14.0	56.7 ± 9.4	54.6 ± 9.7	49.4 ± 8.8

Mean wind speed (m s^{-1})

2005	2006	2007	2008	2009
2.3 ± 1.8	2.5 ± 0.8	2.4 ± 0.7	2.1 ± 0.7	2.3 ± 0.7
2.5 ± 1.2	2.2 ± 0.8	2.2 ± 0.8	2.0 ± 0.7	2.1 ± 0.8
2.2 ± 1.6	2.0 ± 0.7	2.0 ± 0.4	2.1 ± 0.3	1.9 ± 0.5
1.9 ± 1.6	2.0 ± 0.6	1.8 ± 0.5	1.7 ± 0.4	1.8 ± 0.8
1.3 ± 1.1	1.5 ± 0.5	1.7 ± 0.7	1.9 ± 0.7	1.8 ± 0.4
1.5 ± 1.2	1.7 ± 0.5	1.7 ± 0.5	1.7 ± 0.6	1.5 ± 0.6
0.8 ± 0.7	1.4 ± 0.5	1.5 ± 0.4	1.5 ± 0.4	1.5 ± 0.5
1.9 ± 1.0	1.9 ± 1.2	1.7 ± 0.6	1.9 ± 0.8	2.0 ± 0.9
2.2 ± 0.9	2.1 ± 1.0	1.9 ± 0.9	1.9 ± 0.8	2.0 ± 0.8
2.5 ± 0.8	2.5 ± 1.0	2.0 ± 0.8	2.1 ± 0.9	2.2 ± 0.9

Precipitation (mm)

2005	2006	2007	2008	2009
1.6	1.0	25.4	1.8	0.0
6.0	22.0	9.8	3.2	3.4
11.2	0.6	18.0	3.6	4.0
13.8	55.4	54.6	37.2	7.2
58.8	21.8	10.6	9.6	25.2
9.6	6.4	28.1	25.4	47.0
3.0	0.0	9.2	9.4	0.0
14.6	1.6	2.0	0.0	2.2
8.6	0.2	9.3	17.6	0.0
5.8	2.0	7.1	5.4	3.1

Table 2 (continued)

| Mean wind speed (m s^{-1})					Precipitation (mm)				
2005	2006	2007	2008	2009	2005	2006	2007	2008	2009
2.0 ± 1.2	1.8 ± 0.9	2.1 ± 1.2	1.8 ± 0.7	2.0 ± 0.7	15.8	11.0	3.5	9.0	0.0
2.1 ± 1.0	1.7 ± 0.9	1.9 ± 0.9	1.6 ± 0.9	1.6 ± 0.5	8.2	0.2	0.6	2.6	0.0
1.8 ± 0.5	1.7 ± 0.8	1.8 ± 1.0	1.7 ± 0.8	1.7 ± 0.7	3.4	0.0	18.0	0.0	35.6
1.4 ± 0.4	1.5 ± 0.3	1.5 ± 0.6	1.4 ± 0.6	1.3 ± 0.3	0.0	0.0	0.0	0.0	8.3
2.3 ± 0.7	2.2 ± 0.6	2.3 ± 0.7	2.1 ± 0.6	2.1 ± 0.6	22.8	13.8	25.6	26.8	35.6
2.1 ± 0.7	2.4 ± 0.5	2.0 ± 0.6	1.9 ± 0.8	2.0 ± 0.4	7.6	22.2	43.6	6.8	35.2
2.2 ± 0.6	2.2 ± 0.7	2.0 ± 0.6	2.1 ± 0.5	1.9 ± 0.5	16.8	7.4	8.8	7.2	13.6
1.8 ± 0.5	1.8 ± 0.5	2.0 ± 0.7	1.7 ± 0.5	1.7 ± 0.4	7.6	29.8	60.0	22.2	12.0
1.8 ± 0.5	1.8 ± 0.5	1.6 ± 0.5	1.7 ± 0.5	1.6 ± 0.4	54.8	7.2	38.8	14.2	4.2
1.7 ± 0.5	1.9 ± 0.6	1.5 ± 0.6	2.0 ± 1.96	1.7 ± 0.5	1.0	2.6	16.6	3.6	8.6
1.8 ± 0.5	1.7 ± 0.6	1.5 ± 0.5	1.4 ± 0.6	1.2 ± 0.4	4.4	15.6	12.8	6.2	6.4

[a] The first 10 days of Oct
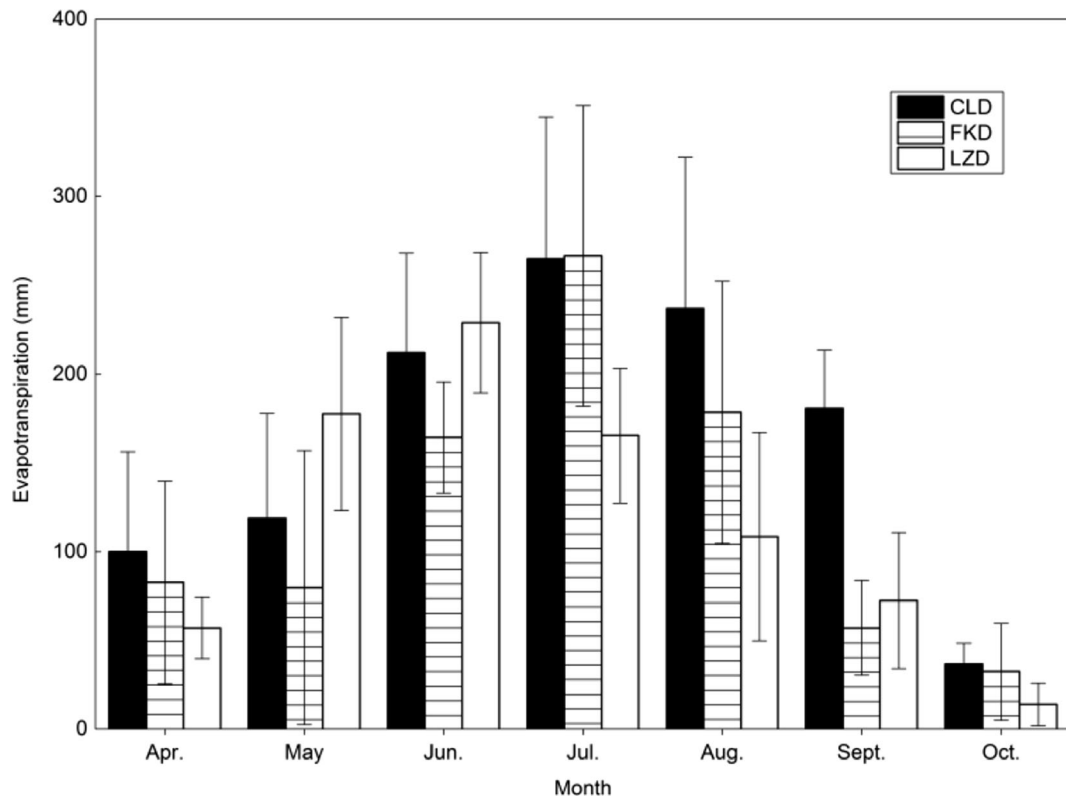
Fig. 2 Monthly evapotranspiration measured with the water balance method. Measurements were taken during the growing seasons for the period 2005 to 2009. The *bars* represent the standard deviation about the mean

the FKD, it was between 37 ± 12 and 265 ± 80 mm; the range of E_{Tw} was 14 ± 12 to 229 ± 40 mm (Fig. 2).

Table 3 summarizes the inter-annual E_{Tc} variations measured by the water balance method and estimated by meteorological methods, from 2005 to 2009. In the 5-year period from 2005 to 2009, cotton was planted at the desert–oasis agricultural comprehensive monitor fields in the CLD and FKD; at the monitor field in the LZD, corn was grown in 2005, 2007, and 2009, while wheat was grown in 2006 and 2008. In the CLD, E_{Tw} was between 890 and 1337 mm, and the 5-year mean E_{Tw} was 1150 ± 381 mm. In the FKD, E_{Tw} was between 816 and 954 mm, and the 5-year mean E_{Tw} was 861 ± 67 mm. In the LZD, E_{Tw} was between 754 and 1019 mm, and the 5-year mean E_{Tw} was 823 ± 110 mm. E_{TPM} was between 718.6 and 802.8 mm, between 730.1 and 931.6 mm, and between 682.5 and 760.2 mm at the CLD, FKD and LZD, respectively; their 5-year mean E_{TPM} values were 783.7 ± 33.6, 834.2 ± 83.9, and 722.3 ± 29.4 mm, respectively. E_{TPT} was between 983.5 and 1026.0 mm, between 1429.5 and 1478.5 mm, and between 1075.7 and 1281.1 mm at
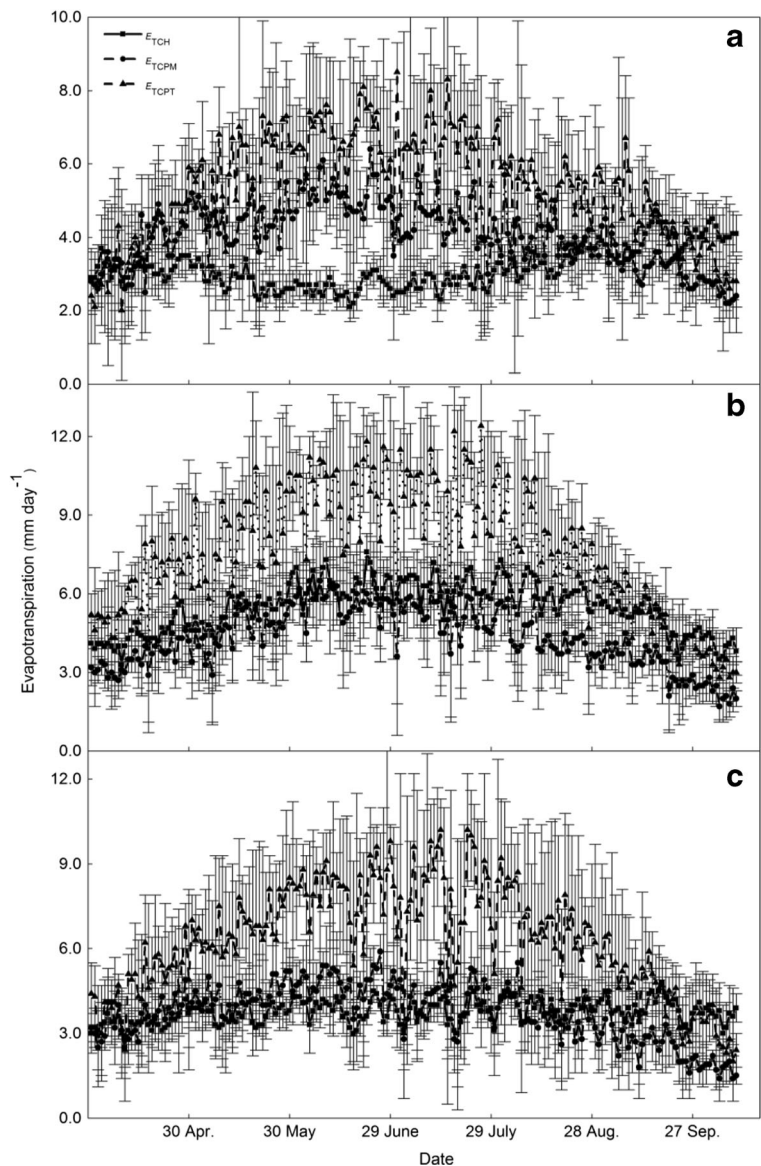
the CLD, FKD, and LZD, respectively; their 5-year mean E_{TPT} values were 1018.3 ± 22.1, 1453.5 ± 47.1, and 1208.6 ± 79.1 mm, respectively. E_{TH} was between 563.4 and 611.2 mm, between 993.0 and 1079.5 mm, and between 689.1 and 740.6 mm at the CLD, FKD, and LZD, respectively; their 5-year mean E_{TH} values were 611.2 ± 23.3, 1061.0 ± 38.2, and 726.0 ± 0.4 mm, respectively. Estimating these values using the three meteorological methods changed the daily mean of E_{Tc} greatly, but overall, E_{TPT} was the highest and E_{TH} the lowest.

Figure 3 shows the variations in the course of daily mean values of E_{Tc} estimated by the FAO-56 Penman–Monteith, Priestley–Taylor, and Hargreaves methods, at the LZD, CLD, and FKD during the growing seasons of the period 2005 to 2009 inclusive. Results were substantially different from those measured with the water balance method. As a whole, E_{Tc} was lower at the beginning of the growing season, increased sharply between April and May, reached its maximum value in June and July, and decreased at the end of the growing season. But E_{TH} exceeded both E_{TPM} and E_{TPT} at the

Table 3 Crop evapotranspiration measured by the water balance method and estimated by meteorological methods during the growing seasons for the period 2005 to 2009

Location	Method	Year										Average	
		2005		2006		2007		2008		2009			
		Total	Daily mean	Total	Daily mean	Total	Daily mean	Total	Daily mean	Total	Daily mean	Year	Daily
CLD	Hargreaves	563.4	3.1 ± 0.9	613.4	3.2 ± 0.8	612.8	3.2 ± 0.6	618.6	3.2 ± 0.7	616.1	3.2 ± 0.7	611.2 ± 23.3	3.2 ± 0.6
	FAO-56 Penman–Monteith	718.6	3.9 ± 1.6	802.8	4.2 ± 1.4	784.4	4.1 ± 1.4	773.4	4.0 ± 1.3	796.7	4.1 ± 1.3	783.7 ± 33.6	4.1 ± 0.9
	Priestley–Taylor	998.6	5.5 ± 2.4	1026.0	5.3 ± 2.2	983.3	5.1 ± 2.2	996.2	5.2 ± 2.2	1042.9	5.4 ± 1.8	1018.3 ± 22.1	5.3 ± 1.5
	Water balance method	1330.7	5.2	1336.8	5.2	955.0	3.7	1238.5	4.9	890.4	3.5	1150.3 ± 380.8	4.5 ± 0.8
FKD	Hargreaves	1057.6	5.5 ± 1.3	1077.1	5.6 ± 1.3	993.0	5.3 ± 1.3	1079.5	5.6 ± 1.4	1017.6	5.5 ± 1.2	1061.0 ± 38.2	5.5 ± 0.9
	FAO-56 Penman–Monteith	931.6	4.8 ± 1.7	863.1	4.5 ± 1.6	730.1	3.9 ± 1.5	818.8	4.2 ± 1.5	743.9	4.0 ± 1.3	834.2 ± 83.9	4.3 ± 1.1
	Priestley–Taylor	1457.0	7.5 ± 3.3	1478.5	7.7 ± 3.2	1358.0	7.3 ± 3.6	1429.5	7.4 ± 3.2	1403.1	7.6 ± 3.1	1453.5 ± 47.1	7.5 ± 2.4
	Water balance method	849.0	3.3	785.7	3.1	816.5	3.2	954.0	3.7	900.0	3.5	861.0 ± 67.0	3.4 ± 0.3
LZD	Hargreaves	748.7	3.9 ± 0.8	705.7	3.7 ± 0.8	689.1	3.6 ± 0.9	745.8	3.9 ± 0.8	740.6	3.8 ± 0.8	726.0 ± 0.4	3.8 ± 0.4
	FAO-56 Penman–Monteith	723.0	3.7 ± 1.6	737.7	3.8 ± 1.4	707.9	3.7 ± 1.4	760.2	3.9 ± 1.3	682.5	3.5 ± 1.3	722.3 ± 29.4	3.7 ± 1.0
	Priestley–Taylor	1282.1	6.6 ± 2.9	1208.2	6.3 ± 3.0	1229.0	6.4 ± 2.9	1248.1	6.5 ± 2.7	1075.7	5.6 ± 2.6	1208.6 ± 79.1	6.3 ± 1.9
	Water balance method	787.1	3.1	1019.0	4.0	754.3	3.0	791.2	3.1	765.5	3.0	823.4 ± 110.4	3.2 ± 0.4

Fig. 3 Mean daily evapotranspiration estimated by the FAO-56 Penman–Monteith (*line with filled circles*), Priestley–Taylor (*line with filled triangles*), and Hargreaves (*line with filled squares*) during growing seasons for the period 2005 to 2009 (**a** at the CLD, **b** at the FKD, **c** at the LZD). The *bars* represent the standard deviation about the mean

end of the growing season, while at CLD, E_{TH} was lower than E_{TPM} by 8.9 to 60.1 % and lower than E_{TPT} by 34.9 and 71.2 %, in June, July, and August. At the CLD, FKD, and LZD, the maximum values of E_{TPH} were 4.7, 7.6, and 4.8 mm day^{-1}, respectively; the minimum values 2.1, 3.3, and 2.5 mm day^{-1}, respectively; and the daily mean E_{TPH} 3.2 ± 0.6, 5.5 ± 0.9, and 3.8 ± 0.4 mm day^{-1}, respectively. E_{TPM} was between 2.2 and 6.4 mm day^{-1}, between 1.7 and 6.8 mm day^{-1}, and between 1.4 and 5.9 mm day^{-1}, at the CLD, FKD, and LZD, respectively; the daily mean E_{TPM} was 4.1 ± 0.9, 4.3 ± 1.1, and 3.7 ± 1.0 mm day^{-1}, respectively; E_{TPT}

was 2.0–8.0, 2.5–12.4, and 2.0–10.2 mm day^{-1}, respectively; and the daily mean E_{TPT} was 5.3 ± 1.5, 7.5 ± 1.4, and 6.3 ± 1.9 mm day^{-1}, respectively.

Statistical analysis

Because soil water content was measured every 5 days, the E_{Tc} for the soil water balance method was not obtained every day during the growing season. In a former study, the most accurate method for evaluating E_{To} in a semiarid climate was the FAO-56 Penman–Monteith (Gavilán and Berengena 2000;

López-Urrea et al. 2006). Therefore, the Penman–Monteith method was considered to be the standard in comparison with the other meteorological methods, for this type of environment. This comparison was conducted based on more than 900 observations carried out during the 5-year duration of the experimental work. At the CLD, the Hargreaves method gave an overestimation (approximately 39.1 %) compared to the FAO-56 Penman–Monteith method, with an RMSE of 1.6 mm day^{-1}; the Priestley–Taylor also gave a relatively high overestimation (approximately 68.2 %), with an RMSE of 2.8 mm day^{-1}. At the FKD, the Hargreaves method gave an overestimation (approximately 31.0 %) compared to the FAO-56 Penman–Monteith method, with an RMSE of 1.3 mm day^{-1}, and the Priestley–Taylor also gave a relatively high overestimation (approximately 68.2 %), with an RMSE of 3.5 mm day^{-1}. At the LZD, the Hargreaves method gave a slight overestimation (approximately 25.8 %) compared to the FAO-56 Penman–Monteith method, with an RMSE of 1.0 mm day^{-1}, and the Priestley–Taylor also gave a relatively high overestimation (approximately 74.7 %), with an RMSE of 2.8 mm day^{-1}.
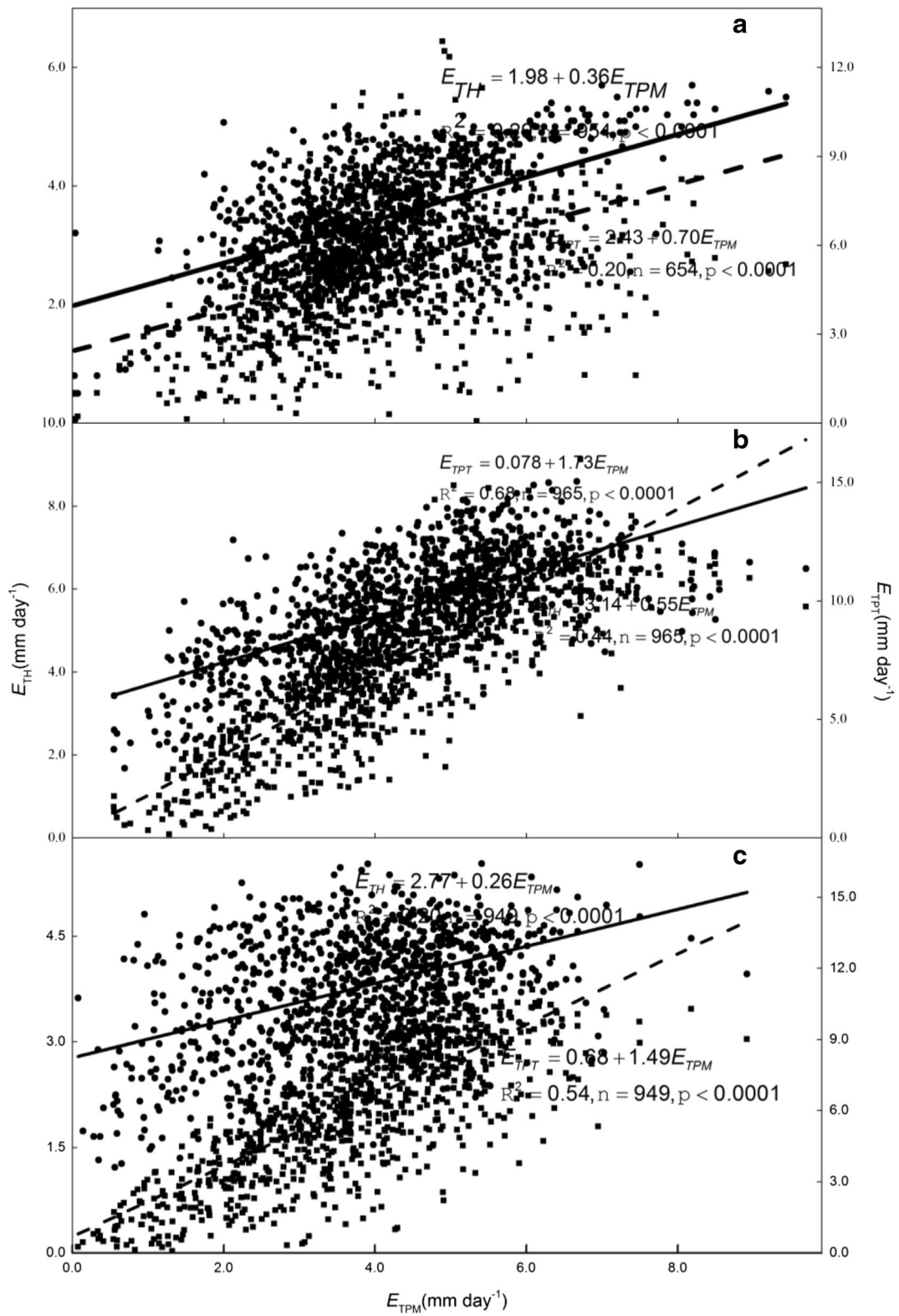
Figure 4 shows the relationships of the E_{TPM} and the E_{Tc} obtained using other meteorological methods at the CLD, FKD, and LZD. At these three stations, the relationships of E_{TPM} and E_{Tc} from the other meteorological methods were fitted with a simple linear regression (Fig. 4); these relations of E_{TPM} to E_{TPT} explained 20, 68, and 54 % of the variation of E_{TPT} at the CLD, FKD, and LZD, respectively, and the linear relations of E_{TPM} to E_{TH} explained 29, 44, and 20 % of the variation of E_{TH} at the CLD, FKD, and LZD, respectively.

Discussion

In the various approaches to estimating E_{Tc}, results were substantially different. In this study, E_{Tc} was estimated by the water balance method, FAO-56 Penman–Monteith, Priestley–Taylor, and Hargreaves, during the growing seasons of 2005–2009, in the desert–oasis agricultural comprehensive monitor fields at three stations in the Chinese Ecosystem Research Network. At the CLD, the daily mean values of E_{Tw}, E_{TH}, E_{TPM}, and E_{TPT} were 4.5 ± 0.8 ,

3.2 ± 0.6, 4.1 ± 0.9, and 5.3 ± 1.5 mm day^{-1}, respectively; at the FKD, the values were 3.4 ± 0.3, 5.5 ± 0.9, 4.3 ± 1.1, and 7.5 ± 1.4 mm day^{-1}, respectively; and at the LZD, 3.2 ± 0.4, 3.8 ± 0.4, 3.7 ± 1.0, and 6.3 ± 1.9 mm day^{-1}, respectively. Our results showed that the FAO-56 Penman–Monteith method provided fairly good estimations of E_{Tc} when compared with the soil water balance method. With the FAO-56 Penman–Monteith, the daily E_{TPM} and E_{Tw} at the CLD were respectively 4.1 ± 0.9 and 4.5 ± 0.8 mm day^{-1}; at the FKD, 4.3 ± 1.1 and 3.4 ± 0.3 mm day^{-1}; and at the LZD, 3.7 ± 1.0 and 3.2 ± 0.4 mm day^{-1} (Table 3). When using the FAO-56 Penman–Monteith method as the standard, the Hargreaves method gave about a 39.1 % overestimation and the Priestley–Taylor method about a 68.2 % overestimation at the CLD; the Hargreaves method gave about a 31.0 % overestimation and the Priestley–Taylor about a 68.2 % overestimation at the FKD; while the Hargreaves method gave about a 25.8 % overestimation and the Priestley–Taylor about a 74.7 % overestimation at the LZD. The results did not coincide with the results obtained by Jensen et al. (1990) or Li et al. (2003). Jensen et al. (1990) found that the Hargreaves method underestimated evapotranspiration by about 8 %, compared with the Penman–Monteith method, in an arid environment. Li et al. (2003) found that the Hargreaves method underestimated evapotranspiration by 7.5 % compared to the 56-PM method for wheat and by 3.4 % for maize, in Naiman, Inner Mongolia, China—a zone with a continental semiarid monsoon climate. In the semiarid region of Karnal, India, the Hargreaves method overestimated evapotranspiration by 3.4 % compared to the FAO-56 Penman–Monteith method. A similar conclusion was reported by Tyagi et al. (2000): the Hargreaves method, even using adjusted equations, overestimated evapotranspiration by 23.1 % compared to the Penman–Monteith method. These discrepancies imply that these methods' estimated E_{Tc} values were impacted by the specific climatic conditions in the

Fig. 4 Relationships of E_{TPM} and E_{Tc} using other meteorological ▶ methods (**a** at the CLD, **b** at the FKD, **c** at the LZD). The corresponding regression line and function relationship are shown in **a**, **b**, and **c**. The *bold line* is the regression line between E_{TH} and E_{TPM}, and the *dashed line* is regression line between E_{TPT} and E_{TPM}

$E_{TH} = 1.98 + 0.36E_{TPM}$

$R^2 = 0.20, n = 654, p < 0.0001$

$E_{PT} = 2.43 + 0.70E_{TPM}$

$R^2 = 0.20, n = 654, p < 0.0001$

a

$E_{TPT} = 0.078 + 1.73E_{TPM}$

$R^2 = 0.68, n = 965, p < 0.0001$

$E_{TH} = 3.14 + 0.55E_{TPM}$

$R^2 = 0.44, n = 965, p < 0.0001$

b

$E_{TH} = 2.77 + 0.26E_{TPM}$

$R^2 = 0.20, n = 949, p < 0.0001$

$E_{TPT} = 0.68 + 1.49E_{TPM}$

$R^2 = 0.54, n = 949, p < 0.0001$

c

E_{TH}(mm day^{-1})

E_{TPT}(mm day^{-1})

E_{TPM}(mm day^{-1})

different study areas. The attractiveness of the Hargreaves method, as compared with the Priestley–Taylor method, is its simplicity, reliability, minimal data requirements, and ease of computation. If we want to acquire greater accuracy for the value of E_{Tc}, however, the model must be adjusted based on the specific climatic conditions and seasons.

Conclusion

This study took four approaches to estimating E_{Tc} in a desert–oasis agricultural system in northwest China. Results were substantially different using different methods. E_{Tc} was between 611.2 ± 23.3 and 1150.3 ± 380.8 mm at the CLD site, between 834.2 ± 83.9 and 1453.5 ± 47.1 mm at the FKD, and between 722.3 ± 29.4 and 1208.6 ± 79.1 mm at the LZD. The FAO-56 Penman–Monteith method provided a fairly good estimation of E_{Tc} compared with the soil water balance method, and the Hargreaves and Priestley–Taylor methods were the alternative estimation methods for E_{Tc} when only air temperature and solar radiation data were available at the weather stations. If we want to acquire greater accuracy in the value of E_{Tc}, however, the model we use must be adjusted based on the conditions present at the selected location and time. For future studies, an adjusted model should be considered for estimating E_{Tc}.

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