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Evaluation of FAO Penman–Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada

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ABSTRACT

Grass reference evapotranspiration (*ETo*) is an important agrometeorological parameter for climatological and hydrological studies, as well as for irrigation planning and management. There are several methods to estimate *ETo*, but their performance in different environments is diverse, since all of them have some empirical background. The FAO Penman–Monteith (FAO PM) method has been considered as a universal standard to estimate *ETo* for more than a decade. This method considers many parameters related to the evapotranspiration process; net radiation (*Rn*), air temperature (*T*), vapor pressure deficit (Δe), and wind speed (*U*); and has presented very good results when compared to data from lysimeters populated with short grass or alfalfa. In some conditions, the use of the FAO PM method is restricted by the lack of input variables. In these cases, when data are missing, the option is to calculate *ETo* by the FAO PM method using estimated input variables, as recommended by FAO Irrigation and Drainage Paper 56. Based on that, the objective of this study was to evaluate the performance of the FAO PM method to estimate *ETo* when *Rn*, Δe, and *U* data are missing, in Southern Ontario, Canada. Other alternative methods were also tested for the region: Priestley–Taylor, Hargreaves, and Thornthwaite. Data from 12 locations across Southern Ontario, Canada, were used to compare *ETo* estimated by the FAO PM method with a complete data set and with missing data. The alternative *ETo* equations were also tested and calibrated for each location. When relative humidity (*RH*) and *U* data were missing, the FAO PM method was still a very good option for estimating *ETo* for Southern Ontario, with *RMSE* smaller than 0.53 mm day^{-1}. For these cases, *U* data were replaced by the normal values for the region and Δe was estimated from temperature data. The Priestley–Taylor method was also a good option for estimating *ETo* when *U* and Δe data were missing, mainly when calibrated locally (*RMSE* = 0.40 mm day^{-1}). When *Rn* was missing, the FAO PM method was not good enough for estimating *ETo*, with *RMSE* increasing to 0.79 mm day^{-1}. When only *T* data were available, adjusted Hargreaves and modified Thornthwaite methods were better options to estimate *ETo* than the FAO PM method, since *RMSE*s from these methods, respectively 0.79 and 0.83 mm day^{-1}, were significantly smaller than that obtained by FAO PM (*RMSE* = 1.12 mm day^{-1}).

1. Introduction

Evapotranspiration (*ET*) is the simultaneous process of transfer of water to the atmosphere by transpiration and evaporation in a soil–plant system (Rosenberg et al., 1983; Allen et al., 1998; Mavi and Tupper, 2004). In an agricultural field, when the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and the canopy completely covers the soil, transpiration becomes the main process of water loss. *ET* is an important parameter for climatological and hydrological studies, as well as for irrigation planning and management.

According to Allen et al. (1998), the main meteorological parameters affecting evapotranspiration are solar radiation, air temperature, vapor pressure deficit and wind speed. The crop type, variety, development stage, and plant density also affect crop evapotranspiration, since differences in resistance to transpiration, crop height, canopy roughness, reflection, ground cover and crop rooting characteristics result in distinct *ET* levels for different crops under the same meteorological and soil conditions.

As *ET* is influenced by several factors, its study, in a more comprehensive way, was made possible by the definition of some boundary conditions in terms of available weather data, which was done in 1948 by both Thornthwaite and Penman when defining

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their potential evapotranspiration (*ETP*), which is the rate of water loss from a vegetated surface when plants have unlimited soil water availability. Since then, the concept of *ETP* has been widely accepted. Recently the grass reference evapotranspiration (*ETo*) has become more popular than *ETP*. *ETo* expresses the evaporative demand of the atmosphere independent of crop type, crop development and management practices. As water is abundantly available at the grass reference evapotranspiring surface, soil moisture does not affect *ETo*. The only factors affecting *ETo* are weather variables. Consequently, *ETo* is a climatic parameter and can be computed from meteorological data.

There are several methods to estimate *ETo*, but their performances in different environments vary, since all of them have some empirical background. After Allen et al. (1998), the FAO Penman–Monteith method (FAO PM) is recommended as the sole method for determining *ETo*, even considering that in special weather conditions it can lead to errors as high as 30% (Widmoser, 2009).

The FAO PM has been selected as the standard method for estimating *ETo* because it closely approximates short grass and alfalfa *ETo* at the locations evaluated (Allen et al., 1989; Allen and Pruitt, 1991; Pereira et al., 2002; López-Urrea et al., 2006; Xing et al., 2008), is physically based, and explicitly incorporates both physiological and aerodynamic parameters. However, in some cases, the use of the FAO PM method is restricted by the lack of input variables. Concerned about that, Allen et al. (1998) suggested procedures for estimating missing climatic parameters, like net radiation, vapor pressure deficit and wind speed. Such procedures have required evaluation in different countries and climates to test their feasibility, as done by Stöckle et al. (2004) for five locations in the Netherlands, Spain, Philippines, USA, and Syria, by Popova et al. (2006) for Bulgaria, and by Jabloun and Sahli (2008) for Tunisia.

In a similar way, the objective of this study was to evaluate the performance of the FAO PM method to estimate *ETo* with missing data in Southern Ontario, Canada, as well as to test alternative methods to determine this variable.

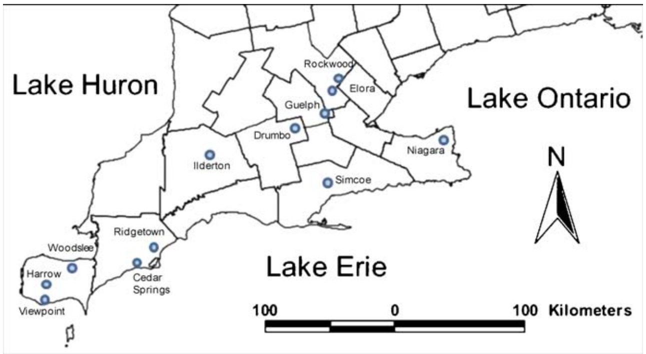

Fig. 1. Geographical location of the weather stations used in this study, in Southern Ontario, Canada. The black circles indicate the weathers stations considered.

2. Material and methods

2.1. Research sites and operating dates

This study used meteorological data from 12 locations in Southern Ontario, Canada, where *Environment Canada* and *Weather Innovations Incorporated* have full weather stations operating and collecting incoming solar radiation, air temperature and relative humidity at 2 m, and wind speed at 10 m. Fig. 1 and Table 1 present respectively the geographical position of the locations evaluated, and their coordinates and period of data.

The study was conducted from April to October, the period that covers the growing season of the main crops in Southern Ontario. This period of time is characterized by a variety of weather conditions, allowing wide variability of data for testing the methods studied (Table 2). All days with negative average temperatures during the evaluated period, which is relatively common during early May and late September in this region, were not considered in the analysis, since one of the *ETo* methods assessed (Thornthwaite) is not adjusted for this condition.

Table 1
Locations and their respective coordinates and number of years evaluated.

Location	Code	Latitude N	Longitude W	Altitude (m)	Period
Cedar Springs	CSP	42°15′	82°05′	205	2007
Drumbo	DRU	43°16′	80°35′	310	2003–2004
Elora	ELO	43°41′	80°26′	402	2002–2003
Guelph	GUE	43°33′	80°13′	320	2002–2003
Harrow	HAR	42°12′	82°55′	190	2001–2004
Ilderton	ILD	43°05′	81°20′	289	2003–2007
Niagara College	NIA	43°09′	79°10′	180	2003–2004
Ridgetown	RID	42°26′	81°53′	212	2000–2003
Rockwood	ROC	43°39′	80°12′	355	2005–2007
Simcoe	SIM	42°51′	80°16′	215	2002–2006
View Point	VPT	41°59′	82°55′	185	2005–2007
Woodslee	WOO	42°12′	82°72′	185	2003–2007

Table 2
Average and standard deviation of input weather variables at each assessed location, in Southern Ontario, Canada.

Location	*Tmax* (°C)	*Tmin* (°C)	*RH* (%)	*SR* (MJ m^{-2} day^{-1})	U_2 (m s^{-1})
Cedar Springs	22.7 (±4.5)	14.1 (±5.0)	80.0 (±10.4)	15.5 (±6.4)	2.0 (±1.2)
Drumbo	21.1 (±6.5)	9.0 (±5.7)	78.9 (±9.6)	15.0 (±6.9)	1.5 (±0.7)
Elora	18.9 (±8.2)	8.4 (±6.9)	80.6 (±10.5)	16.9 (±8.6)	2.7 (±1.1)
Guelph	19.1 (±8.1)	6.7 (±6.7)	76.3 (±10.6)	17.1 (±7.9)	2.1 (±0.9)
Harrow	21.1 (±6.4)	11.4 (±6.1)	72.5 (±10.3)	16.9 (±7.2)	2.2 (±1.1)
Ilderton	21.9 (±6.8)	10.0 (±5.8)	82.8 (±10.9)	18.0 (±7.8)	2.2 (±1.0)
Niagara College	20.0 (±6.7)	9.9 (±6.0)	81.3 (±18.5)	17.1 (±8.2)	1.9 (±1.2)
Ridgetown	21.7 (±7.0)	10.2 (±6.6)	76.7 (±9.1)	18.1 (±7.8)	2.5 (±1.0)
Rockwood	21.2 (±7.4)	9.1 (±6.1)	73.7 (±13.1)	15.5 (±6.9)	2.4 (±0.8)
Simcoe	20.7 (±7.2)	10.4 (±6.4)	76.9 (±12.0)	17.3 (±7.8)	2.2 (±0.7)
View Point	21.0 (±6.5)	12.4 (±6.3)	76.9 (± 9.9)	14.5 (±6.3)	1.7 (±1.2)
Woodslee	22.5 (±6.9)	11.6 (±6.2)	77.6 (±11.6)	18.2 (±7.5)	2.6 (±1.1)

2.2. ETo methods

The following methods have been chosen for this research because of their wide acceptance for estimating *ETo* in many regions:

(a) *FAO-56 Penman–Monteith* (*FAO PM*)—This method is considered as a standard, and the most precise method to estimate *ETo*. It is expressed as (Allen et al., 1998):

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma(900/(T+273))U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

where *ETo* is the grass reference evapotranspiration (mm day^{-1}); Δ is the slope of the saturated vapor pressure curve (kPa °C^{-1}); *Rn* is the net radiation (MJ m^{-2} day^{-1}); *G* is the soil heat flux density (MJ m^{-2} day^{-1}), considered as null for daily estimates; *T* is the daily mean air temperature (°C) at 2 m, based on the average of maximum and minimum temperatures; U_2 is the average wind speed at 2-m height (m s^{-1}); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); $(e_s - e_a)$ is the saturation vapor pressure deficit (Δe, kPa) at temperature *T*; and γ is the psychrometric constant (0.0677 kPa °C^{-1}).

The following equations were recommended by Allen et al. (1998) to estimate *Rn*:

$$Rn = Rns - Rnl \tag{2}$$

$$Rns = 0.77SR \tag{3}$$

$$Rnl = \left[\sigma\left(\frac{Tmax_K^4 + Tmin_K^4}{2}\right)(0.34 - 0.14\sqrt{e_a})\left(1.35\frac{SR}{SRo} - 0.35\right)\right] \tag{4}$$

$$SRo = 0.75Ra \tag{5}$$

where *Rns* is the net shortwave radiation (MJ m^{-2} day^{-1}); *Rnl* is the net longwave radiation (MJ m^{-2} day^{-1}); *SR* is the incoming solar radiation (MJ m^{-2} day^{-1}); σ is the Stefan–Boltzmann constant (4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1}); $Tmax_K$ is the maximum temperature (K); $Tmin_K$ is the minimum temperature (K); *SR*/*SRo* is ratio between the incoming solar radiation and the clear sky solar radiation (MJ m^{-2} day^{-1}), which is less or equal to 1; and *Ra* is the extraterrestrial solar radiation (MJ m^{-2} day^{-1}). The other parameters of Eq. (1) were determined as follows:

$$\Delta = \frac{4098[0.6108\exp(17.27T/(T+237.3))]}{(T+237.3)^2} \tag{6}$$

$$e_s = \frac{[0.6108\exp((17.27Tmax_c)/(Tmax_c+237.3))] + [0.6108\exp((17.27\,Tmin_c)/(Tmin_c+237.3))]}{2} \tag{7}$$

$$e_a = \frac{RH}{100}e_s \tag{8}$$

where $Tmax_c$ is the maximum temperature (°C); $Tmin_c$ is the minimum temperature (°C); and *RH* is the mean daily relative humidity, calculated from maximum and minimum values.

To convert wind speed data obtained at 10 m to the standard height of 2 m, a logarithmic wind speed profile, for measurements above a short grass surface, was used:

$$U_2 = U_z\left[\frac{4.87}{\ln(67.8z - 5.42)}\right] \tag{9}$$

where *z* is the height of the wind speed measurement (=10 m).

(b) *Priestley–Taylor* (*PT*)—The PT equation is a simplification of the original Penman method, where the aerodynamic term is replaced by an empirical coefficient, known as the Priestley–Taylor parameter (Priestley and Taylor, 1972). The method is expressed by:

$$ETo = 1.26\frac{\Delta}{\Delta + \gamma}\left(\frac{Rn - G}{\lambda}\right) \tag{10}$$

where λ is the latent heat of vaporization (2.45 MJ kg^{-1}). In fact, the PT parameter varies with different vegetation types, soil moisture conditions, and strength of advection (Priestley and Taylor, 1972; Stannard, 1993; Suleiman and Hoogenboom, 2007), and should be calibrated for different environmental conditions.

(c) *Hargreaves* (*HA*)—The Hargreaves method (Hargreaves and Samani, 1985) estimates *ETo* using only the maximum and minimum temperatures, and is expressed by:

$$ETo = C_oRa'(Tmax_c - Tmin_c)^{0.5}(T + 17.8) \tag{11}$$

where *Ra*′ is the extraterrestrial solar radiation, in mm per day; and C_o the conversion parameter (=0.0023). For this study, C_o was also locally calibrated.

(d) *Thornthwaite* (*TH*)—This is the Thornthwaite's original method (Thornthwaite, 1948), which uses average temperature for a given day or period (*T*), climatological normal annual temperature (*Ta*) and photoperiod (maximum number of sunshine hours, *N*) as inputs. Using *T*, in °C, the *ETo* is calculated by the following equations:

$$ETp = 16\left(\frac{10T}{I}\right)^a \quad \text{for } 0\,°\text{C} \le T < 26.5\,°\text{C} \tag{12}$$

$$ETp = -415.85 + 32.24T - 0.43T^2 \quad \text{for } T \ge 26.5\,°\text{C} \tag{13}$$

where *ETp* is the standard 30-day evapotranspiration (mm 30 days^{-1}), considering *N* = 12 h; and *I* and *a* are thermal indices, calculated by:

$$I = 12(0.2\,Ta)^{1.514} \tag{14}$$

$$a = 0.4924 + 1.79 \times 10^{-2}I - 7.71 \times 10^{-5}I^2 + 6.75 \times 10^{-7}I^3 \tag{15}$$

Finally, *ETo*, in mm day^{-1}, is calculated by the following expression:

$$ETo = \frac{ETp}{30}\frac{N}{12} \tag{16}$$

(e) *Thornthwaite with effective temperature* (TH_{Tef})—The original Thornthwaite method was adapted by Camargo et al. (1999) to adjust to arid and very humid conditions. For that, the average temperature (*T*) was replaced by the effective temperature (*Tef*), given by:

$$Tef = \beta(3Tmax_c - Tmin_c) \tag{17}$$

where β is named the Camargo parameter (=0.36). For this study, β was also locally calibrated.

2.3. Alternative methods for estimating missing weather data

The use of the FAO PM equation is only possible when a complete weather dataset is available. However, Allen et al. (1998) suggest that this method can also be used with limited climatic data, by estimating the missing data. These authors proposed the following procedures to estimate missing *Rn*, Δe and U_2 data:

(a) *Net solar radiation* (*Rn*)—In this case, *Rn* is estimated from Eqs. (2)–(5), with *SR* determined as a function of the air temperature (Allen et al., 1998):

$$SR = K_{Rs}\sqrt{Tmax_c - Tmin_c}Ra \tag{18}$$

where K_{Rs} is the solar radiation adjustment coefficient, ranging from 0.16, for continental conditions, to 0.19, for coastal conditions. For this study, $K_{Rs} = 0.16$ was adopted since the air masses that dominates in Southern Ontario have their origin over the continent.

(b) *Wind speed* (U_2)—Where no wind data are available, the procedure proposed by Allen et al. (1998) is to use average wind speed data observed in a nearby location within the same homogeneous region, preferably taking into consideration the seasonal variability of the wind. In fact, the effect of wind speed on the *ETo* estimates is relatively small, except for arid and windy areas (Popova et al., 2006). For this study, *Environment Canada* wind normal data (1971–2000), from April to October, available at "www.climate.weatheroffice.ec.gc.ca" were used to replace observed data, considering the closest weather station.

(c) *Vapor pressure deficit* (Δe)—Where air humidity data are missing, the vapor pressure deficit ($e_s - e_a$) can be estimated based on temperature data. Saturation vapor pressure is calculated by Eq. (7), whereas actual vapor pressure (e_a) is obtained by assuming that the dew point temperature (Td) is close to the daily minimum temperature ($Tmin_c$), which is usually observed early in the morning in reference weather stations (Allen et al., 1998). Then e_a, in kPa, is calculated by:

$$e_a = 0.6108\exp\left(\frac{17.27Tmin_c}{Tmin_c + 237.3}\right) \tag{19}$$

2.4. Data analysis

The results from *ETo* estimated by the FAO PM method with *Rn*, Δe and U_2 obtained with the procedures mentioned above (Section 2.3) were compared with *ETo* data computed with full datasets. The same kind of comparison was done between *ETo* estimated by alternative methods (PT, HA and TH) and the full-data FAO PM. Also, the alternative *ETo* methods were locally adjusted, through the calibration of their empirical parameters: Priestley–Taylor method (PT parameter); Hargreaves (C_o parameter); and Thornthwaite (Camargo parameter), and compared to the full-data FAO PM. The empirical calibration of the parameters of each method was performed by minimizing *ETo* errors between the calibrated methods and the full-data FAO PM method, approximating the slope of the regression analysis to one.

The performance of the methods for each location was determined by regression analyzes, always forcing the linear coefficient through the origin ($a = 0$). The slope (b) was used as a measure of accuracy, while coefficient of determination (R^2) was considered as a measure of precision. A perfect method should result in $b = 1$ and $R^2 = 1$. Following the suggestion of Jacovides and Kontoyiannis (1995) and Jabloun and Sahli (2008), the performance of the *ETo* estimates was also evaluated using root mean square error (*RMSE*) and mean bias error (*MBE*). *RMSE* and *MBE*, in mm day^{-1}, were calculated by the following equations:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ETo_{est} - ETo_{\text{FAO PM}})^2} \tag{20}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(ETo_{est} - ETo_{\text{FAO PM}}) \tag{21}$$

To compare the performance of the different *ETo* methods, the overall *RMSE* averages for all methods analyzed were determined and submitted to the *t*-test. The critical *t*-value ($p = 0.05$) for 22 degrees of freedom (12 × 2-2) was 2.07. The hypothesis that the mean *RMSE* values of different methods were different was accepted when *t*-value was greater than critical *t* (2.07).

3. Results

3.1. Estimating daily ETo by the Penman–Monteith method with missing data

Table 3 presents the slope and the coefficient of determination for all the relationships between *ETo* estimated by the FAO PM method with a full dataset, and by this method when wind speed (U), actual vapor pressure (e_a) and solar radiation (SR) were estimated, as described previously. When just wind speed data are missing ($-U$), the use of the normal data from a nearby weather station is a very good option for the FAO PM method, since not much error was introduced in the estimates. For all locations, the slope of the regression between *ETo* with full data and *ETo* estimated with normal wind speed remained between 0.98 and 1.02, and R^2 between 0.96 and 0.99. Figs. 2–4 also confirm such performance. *MBE* is very small, indicating that there is no tendency of over or underestimation, and *RMSE* is always below 0.3 mm day^{-1}.

When e_a (usually obtained from relative humidity) is missing, the agreement between *ETo* estimated with full data and with missing data is still acceptable, with the slopes between 1.01 and 1.12 and R^2 between 0.76 and 0.96 (Table 3). *MBE*s for all locations (Fig. 2) show that in such situation there is an *ETo* overestimation in the majority of the locations, with exceptions for Harrow and View Point. *RMSE* increased to the range between 0.3 and 1.0 mm day^{-1} (Figs. 3 and 4).

The *ETo* estimates done when *SR* is missing resulted in significant increase in the data dispersion, with R^2 decreasing into the range between 0.44 and 0.69. The accuracy of the *ETo*

Table 3

Slope (b) and coefficient of determination (R^2) for the relationship between daily *ETo* estimated by the Penman–Monteith method, considering all weather data and missing data: $-U$ = without wind speed; $-e_a$ = without actual vapor pressure; $-SR$ = without solar radiation.

Location	$-U$		$-e_a$		$-SR$		$-U, -e_a$		$-U, -SR$		$-SR, -e_a$		$-U, -e_a, -SR$	
	b	R^2	b	R^2	b	R^2	b	R^2	b	R^2	b	R^2	b	R^2
CSP	0.99	0.97	1.03	0.89	0.99	0.44	1.04	0.87	0.99	0.47	1.02	0.15	1.03	0.20
DRU	1.02	0.99	1.09	0.94	1.16	0.58	1.17	0.88	1.17	0.62	1.24	0.40	1.32	0.37
ELO	0.99	0.99	1.12	0.92	0.98	0.52	1.10	0.94	0.98	0.42	1.10	0.25	1.09	0.24
GUE	1.00	0.99	1.10	0.94	1.04	0.63	1.13	0.93	1.04	0.60	1.14	0.42	1.17	0.42
HAR	0.99	0.96	1.00	0.92	0.94	0.54	1.00	0.88	0.92	0.47	0.94	0.38	0.94	0.31
ILD	1.00	0.99	1.13	0.90	0.98	0.63	1.16	0.91	0.99	0.62	1.12	0.35	1.14	0.39
NIA	0.99	0.97	1.07	0.76	0.99	0.50	1.08	0.80	0.98	0.47	1.06	0.03	1.07	0.08
RID	0.98	0.99	1.08	0.92	0.97	0.64	1.07	0.91	0.95	0.56	1.05	0.38	1.03	0.34
ROC	1.02	0.98	1.05	0.92	1.13	0.62	1.10	0.90	1.15	0.63	1.18	0.37	1.22	0.39
SIM	0.99	0.99	1.05	0.94	0.95	0.66	1.05	0.93	0.94	0.63	1.00	0.43	1.00	0.43
VPT	1.02	0.98	1.01	0.96	0.95	0.61	1.05	0.92	0.98	0.61	0.96	0.49	1.01	0.47
WOO	0.98	0.99	1.08	0.90	0.97	0.69	1.05	0.90	0.95	0.63	1.04	0.40	1.02	0.39

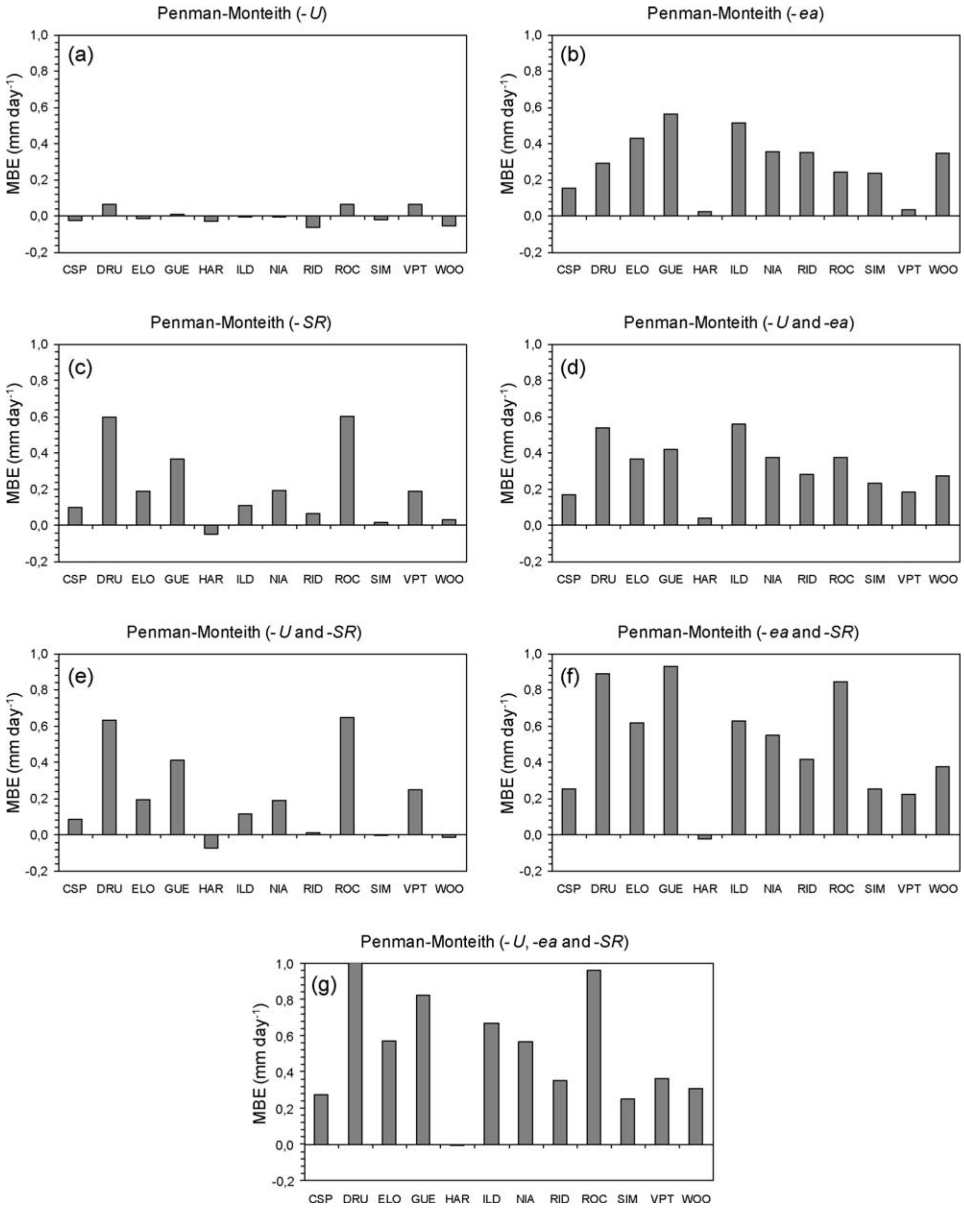

Fig. 2. Mean bias error (*MBE*) for *ETo* estimated by the Penman–Monteith method with missing data in different locations in Southern Ontario, Canada.

estimates remained high, with slopes between 0.94 and 1.16 (Table 3). The errors associated with this condition are presented in Fig. 2 for *MBE*, which shows an overestimation at the majority of the locations, and in Figs. 3 and 4, where *RMSE* values stay around 0.8 mm day^{-1}. For Harrow, where the *MBE* values heavily deviated from all other locations, the bias oscillated more between positive and negative values, resulting in a *MBE* close to zero. However, the *RMSE* had the same magnitude as observed at the other locations.

For conditions in which wind and humidity data are missing, the *ETo* estimates are very similar to those done when just e_a is estimated from minimum temperature. The slopes of the regressions between *ETo* estimated with the full dataset and with *U* and e_a data missing range between 1.00 and 1.17; whereas R^2 values varied from 0.80 to 0.94 (Table 3). The *MBE* values show a definite overestimation at all locations (Fig. 2), while *RMSE* values range from 0.42 to 0.66 mm day^{-1} (Figs. 3 and 4). For the situation in which *SR* and *U* data are missing, the *ETo* estimation errors are very similar to the situation when just *SR* data are missing (Table 3, Figs. 2–4). On the other hand, when *SR* and e_a data are missing or when just temperature data are available, the errors associated with *ETo* estimated by the FAO PM method increase considerably (Figs. 3 and 4), which resulted in the highest data dispersion observed, with R^2 ranging from 0.03 to 0.49 (Table 3).

MBE values show that there is a predominance of overestimations when e_a and *SR* data are missing and also when just temperature data are available (Fig. 2). The resulting errors of such overestimations, represented by *RMSE*, were always above 0.9 mm day^{-1}, reaching 1.4 mm day^{-1} in Drumbo (Figs. 3 and 4), which is a very high error for daily estimates.

The poor performance of FAO PM method to estimate *ETo* when solar radiation is missing ($-SR$) can be better understood by analyzing the relationship between observed and estimated *SR* data for Guelph, used as example to represent what happened in all the other locations (Fig. 5). The method recommended by Allen et al. (1998) to estimate *SR* proved not to be a good option for Ontario conditions, presenting high dispersion ($R^2 < 0.6$) and systematic overestimation for *SR* below 20 MJ m^{-2} day^{-1}.

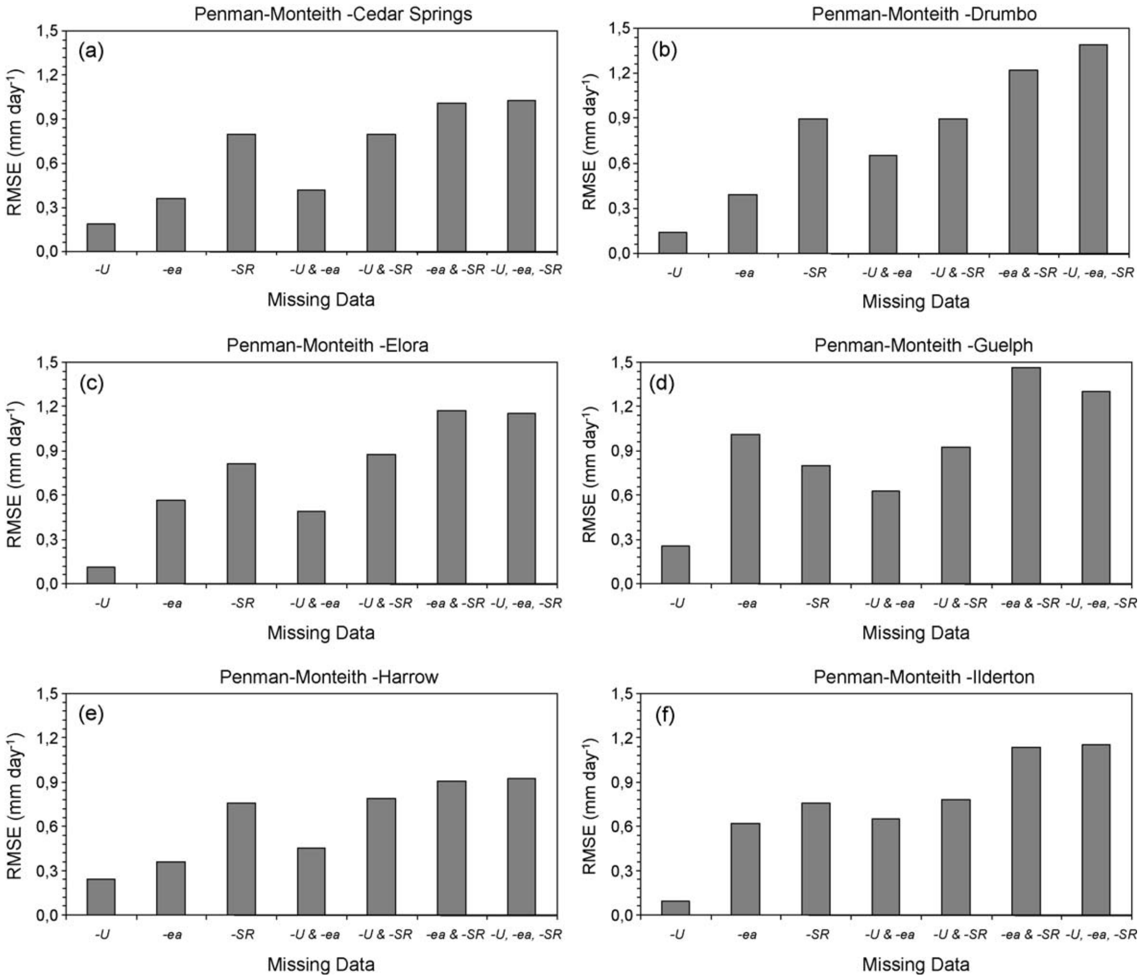

Fig. 3. Root mean square error (*RMSE*) for *ETo* estimated by the Penman–Monteith method with missing data, in Cedar Springs (a), Drumbo (b), Elora (c), Guelph (d), Harrow (e) and Ilderton (f), Southern Ontario, Canada.

3.2. Estimating daily ETo by alternative methods

When a weather station has just a limited dataset it is very common to estimate *ETo* by alternative methods. If the weather station has only temperature and solar radiation data, the best option seems to be the use of the Priestley–Taylor method, which is in fact a simplification of the original Penman method. The PT method considers the aerodynamic term of the Penman equation as a fraction of the radiation term, which was averaged for different conditions, resulting in a value of 0.26. Table 4 presents the results of the application of the PT method for Southern Ontario, when compared with the full-data FAO PM method. The *ETo* obtained with the original PT parameter (1.26) overestimated the FAO PM *ETo* in all locations, as can be seen by analyzing the slopes in Table 4, and the *MBE* in Fig. 6a. The *RMSE* when the original PT was used ranged between 0.4 and 0.9 mm day^{-1} (Fig. 6b). However, when the empirical parameter in this method (alpha) was adjusted for each location, with alpha decreasing from 1.26 to the range between 1.01 and 1.18, the results improved considerably, particularly the accuracy of the estimates (Table 4). For this case, slopes of the linear regressions decreased to 1.0, R^2 ranged from 0.82 to 0.96 (Table 4), *MBE* decreased to close to zero, and *RMSE* decreased to less than 0.6 mm day^{-1} (Fig. 6). As observed in the tables and figures mentioned above, the process of alpha calibration only changed the accuracy of the estimates, reducing bias; however, the precision, represented by R^2, remained the same.

The use of the adjusted PT method has some advantage over the use of the FAO PM method when *U* and e_a data are missing. While FAO PM method, using average *U* and e_a estimated with *Tmin*, presented *RMSE* values between 0.42 and 0.67 mm day^{-1}, the adjusted PT method had errors ranging from 0.25 to 0.60 mm day^{-1}. However, the complexity of the PT method calibration process must be considered in this case, since it is only possible where a complete dataset is available. On the other hand, the FAO PM method does not require such a process, giving results with enough accuracy and precision for daily *ETo* estimates.

The same kind of analysis was done using the Hargreaves method. Originally this method was developed for semi-arid environments, and because it is based only on temperature data, it is expected that this method overestimates *ETo* in a humid climate. Such overestimation was confirmed for Southern Ontario, where the original Hargreaves method overestimated *ETo* in all locations, as can be seen through the slopes of the regression analysis, between 1.06 in Harrow and 1.36 in Drumbo (Table 5). Such overestimation can also be seen by analyzing the MBE values (Fig. 7a). As this method is empirical and based only in temperature data, the precision of the estimates decreased, compared with methods tested above, with R^2 ranging from 0.46 to 0.71 (Table 5).

The errors associated with the original Hargreaves method, expressed by *RMSE*, were between 0.76 and 1.96 mm day^{-1} (Fig. 7b), which are very high for daily estimates and were similar to the errors between 0.92 and 1.40 mm day^{-1} obtained by the FAO PM method when *U*, e_a and *SR* data were missing (Figs. 3 and 4).

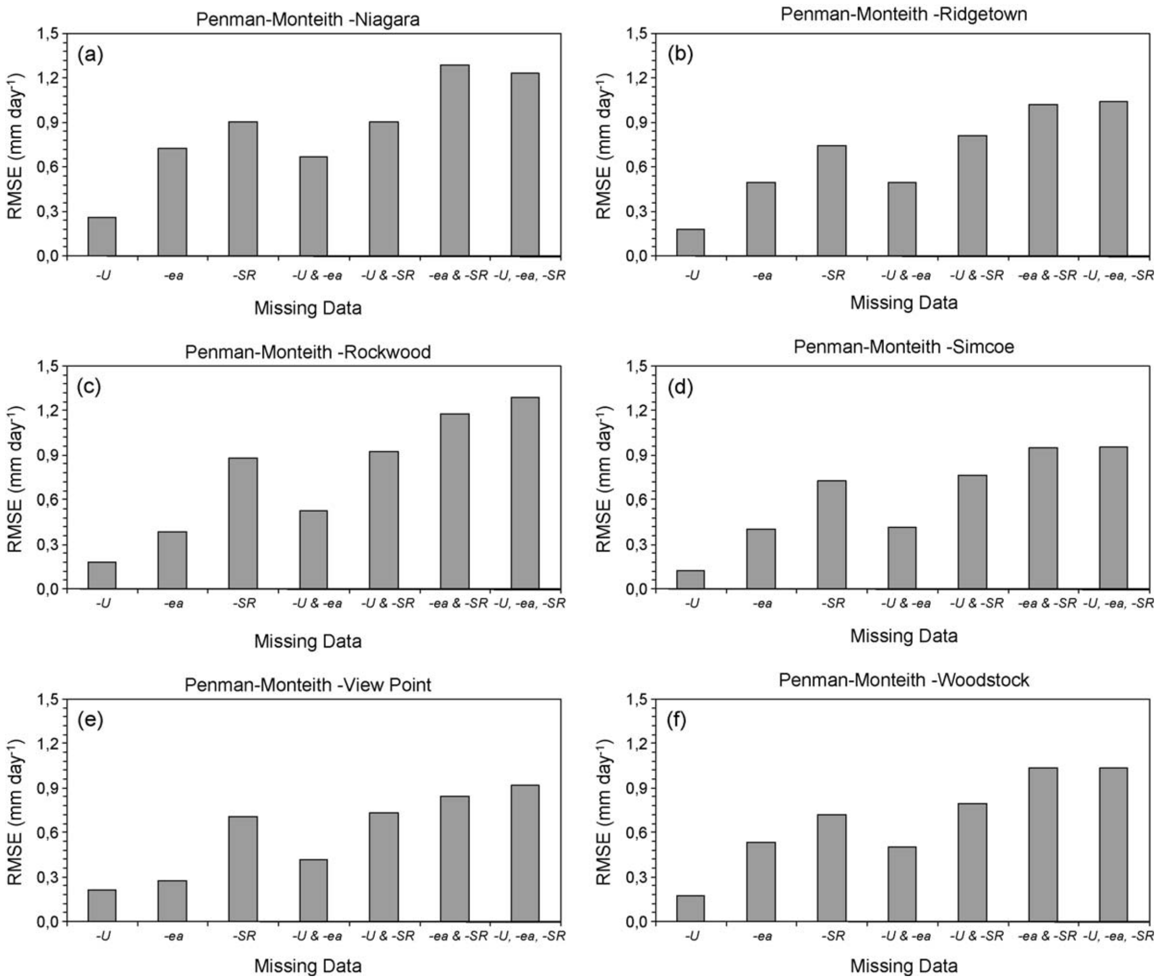

Fig. 4. Root mean square error (*RMSE*) for *ETo* estimated by the Penman–Monteith method with missing data in Niagara (a), Ridgetown (b), Rockwood (c), Simcoe (d), View Point (e), and Woodstock (f), Southern Ontario, Canada.

However, when the Hargreaves method is locally calibrated by reducing C_o, there was a significant improvement in the accuracy of the estimates, with *MBE* decreasing to less than 0.3 mm day^{-1} and *RMSE* ranging from 0.59 to 0.87 mm day^{-1} (Fig. 7); however the precision of the estimates remained the same (Table 5).

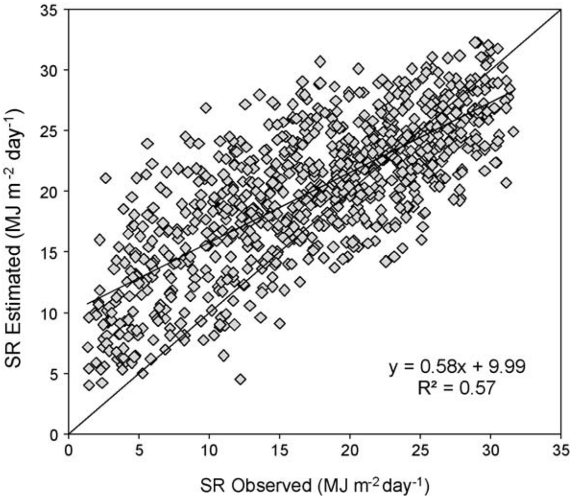

Fig. 5. Relationship between incoming solar radiation (*SR*) observed and estimated by the method recommended by Allen et al. (1998), in Guelph, Ontario, Canada, during the growing seasons of 2002 and 2003.

This process of calibration, as also mentioned for PT method, only is possible for locations where a complete dataset is available, to make the comparison between H and FAO PM methods feasible; however, this process improved the estimates, making results better than when using the FAO PM method with only temperature data. The advantage of this process is to provide a calibration parameter that could be used by other stations in the region that do not have full data.

Table 4
Slope (b) and coefficient of determination (R^2) for the relationship between daily *ETo* estimated by the Penman–Monteith and by the Priestley–Taylor (original and adjusted PT parameter) methods.

Location	Priestley–Taylor original alpha = 1.26		Priestley–Taylor adjusted		
	b	R^2	Alpha	b	R^2
CSP	1.13	0.87	1.12	1.00	0.87
DRU	1.15	0.96	1.10	1.00	0.96
ELO	1.18	0.95	1.07	1.00	0.95
GUE	1.15	0.90	1.13	1.00	0.90
HAR	1.06	0.88	1.18	1.00	0.88
ILD	1.25	0.96	1.01	1.00	0.96
NIA	1.17	0.82	1.07	1.00	0.82
RID	1.12	0.93	1.13	1.00	0.93
ROC	1.07	0.93	1.18	1.00	0.93
SIM	1.12	0.94	1.13	1.00	0.94
VPT	1.12	0.93	1.13	1.01	0.93
WOO	1.12	0.91	1.13	1.00	0.91

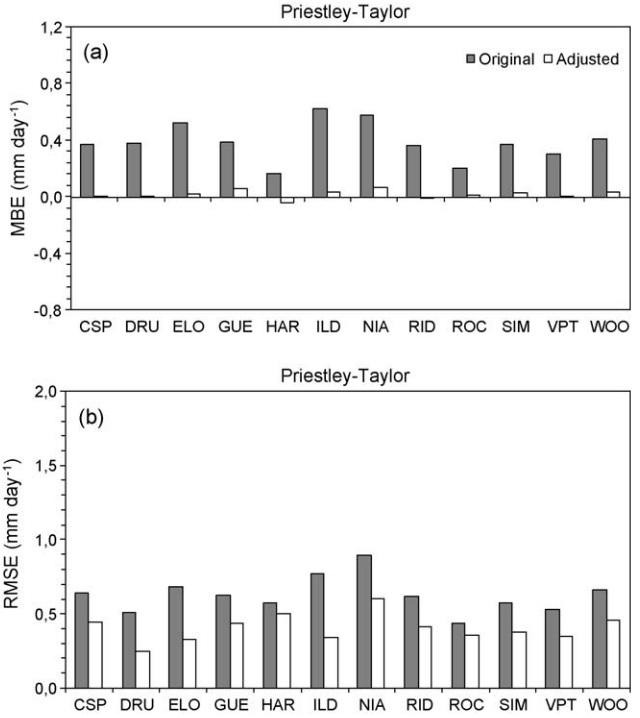

Fig. 6. Mean bias error (*MBE*) and root mean square error (*RMSE*) for *ETo* estimated by the Priestley–Taylor method with the original (=1.26) and adjusted alpha in different locations in Southern Ontario, Canada.

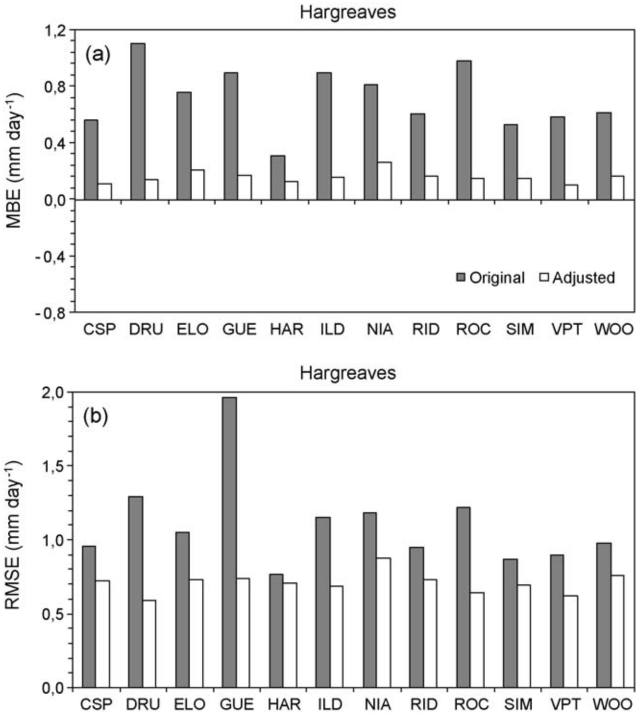

Fig. 7. Mean bias error (*MBE*) and root mean square error (*RMSE*) for *ETo* estimated by the Hargreaves method with the original (=0.0023) and adjusted C_o, in different locations in Southern Ontario, Canada.

When *ETo* was estimated by the original Thornthwaite method, the results showed that it underestimated *ETo* in relation to the FAO PM method at all locations, with the slopes of the linear regressions ranging from 0.75 to 0.97 and *MBE* varying between -0.64 and 0.08 (Table 6 and Fig. 8a). The precision of the estimates was the lowest among the tested methods, with R^2 varying between 0.11 and 0.53 (Table 6). The *RMSE* values associated with the TH method were always above 1 mm day^{-1} (Fig. 8b).

Considering the modification done by Camargo et al. (1999) in the Thornthwaite method, by introducing the concept of effective temperature (*Tef*), the accuracy and precision of the *ETo* estimates for Southern Ontario improved substantially. The slope of the linear regressions increased to 1.0, resulting in *MBE*s smaller than 0.2 mm day^{-1}, and the R^2 increased to the range between 0.38 and 0.68 (Table 6 and Fig. 8a). The *RMSE* values associated with this method were reduced, but still remained high, above 0.7 mm day^{-1} (Fig. 8b). These results prove that TH with *Tef* method is better than the FAO PM method to estimate *ETo* using just temperature data. However, it is not better than Hargreaves method, which also only uses temperature and presented smaller *RMSE* values.

4. Discussion

The FAO PM method estimates *ETo* considering a full weather data set. This is normally the main restriction for its use in locations where weather data are limited (Pereira et al., 2002; Popova et al., 2006; Jabloun and Sahli, 2008). The situation occurs in Southern Ontario, where very few weather stations measure a full weather data set. For conditions where wind speed, relative humidity and solar radiation data are missing, there is no previous study assessing the performance of various methods to estimate *ETo* in this region of Canada.

Table 5
Slope (b) and coefficient of determination (R^2) for the relationship between daily *ETo* estimated by the Penman–Monteith method and by the Hargreaves method (original and adjusted).

Location	Hargreaves original (C_o = 0.0023)		Hargreaves Adjusted		
	b	R^2	C_o	b	R^2
CSP	1.15	0.53	0.00200	1.00	0.53
DRU	1.36	0.70	0.00170	1.00	0.70
ELO	1.19	0.65	0.00194	1.00	0.65
GUE	1.25	0.64	0.00185	1.00	0.64
HAR	1.06	0.64	0.00218	1.00	0.64
ILD	1.24	0.68	0.00220	1.00	0.68
NIA	1.18	0.46	0.00195	1.00	0.46
RID	1.13	0.68	0.00203	1.00	0.68
ROC	1.29	0.73	0.00180	1.01	0.73
SIM	1.12	0.71	0.00205	1.00	0.71
VPT	1.18	0.69	0.00196	1.00	0.69
WOO	1.13	0.66	0.00203	1.00	0.66

Table 6
Slope (b) and coefficient of determination (R^2) for the relationship between daily *ETo* estimated by the Penman–Monteith method and by the Thornthwaite method (original and adjusted).

Location	Thornthwaite original		Thornthwaite *Tef* adjusted		
	b	R^2	β	b	R^2
CSP	0.97	0.11	0.350	1.01	0.38
DRU	0.91	0.45	0.306	1.00	0.59
ELO	0.83	0.44	0.340	1.00	0.62
GUE	0.75	0.42	0.330	1.01	0.61
HAR	0.79	0.44	0.375	1.00	0.62
ILD	0.83	0.39	0.365	1.00	0.63
NIA	0.79	0.34	0.357	1.00	0.50
RID	0.79	0.53	0.355	1.01	0.68
ROC	0.88	0.46	0.315	1.01	0.66
SIM	0.83	0.46	0.355	1.01	0.68
VPT	0.95	0.45	0.350	1.00	0.62
WOO	0.81	0.43	0.355	1.00	0.63

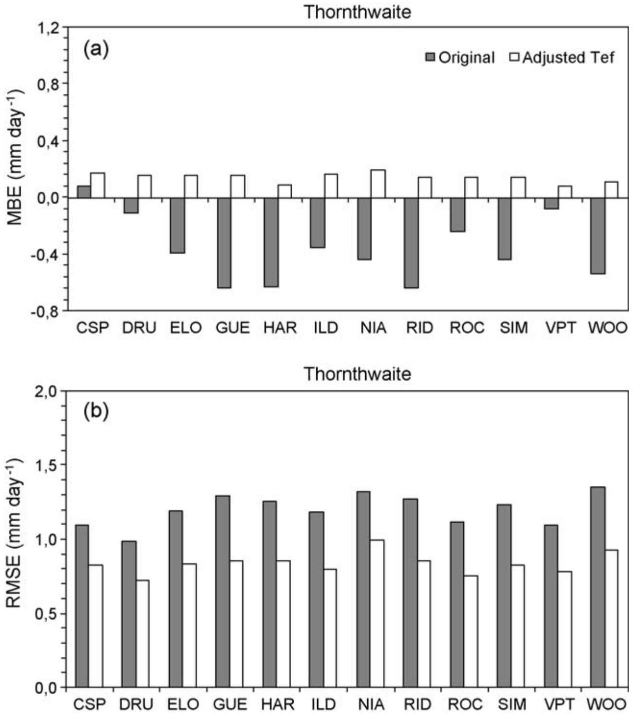

Fig. 8. Mean bias error (*MBE*) and root mean square error (*RMSE*) for *ETo* estimated by Thornthwaite method with the original procedures and with adjusted β parameter for effective temperature, in different locations in Southern Ontario, Canada.

A summary of the results obtained with our analysis, based on the average *RMSE*, including data from all locations (Table 7), shows that for the Southern Ontario, Canada, the method of FAO PM is among the best options to estimate *ETo* even when wind speed and relative humidity data are missing. In these cases, the estimates done by the FAO PM method resulted in the first and third smallest average errors, which agrees with the results obtained by Popova et al. (2006) and Jabloun and Sahli (2008).

When solar radiation data are not available, the estimation procedures for this variable using maximum and minimum temperatures (Allen et al., 1998) did not show good agreement with the FAO PM method for the assessed regions, with the average *RMSE* = 0.8 mm day^{-1}, seventh in the rank among the methods tested. This is very different from the results obtained by Popova et al. (2006) for Bulgaria and by Jabloun and Sahli (2008) for Tunisia, where the *RMSE* in similar tests remained small, respectively 0.3 and 0.4 mm day^{-1}. The errors for the FAO PM method in Southern Ontario are even higher when estimated *SR* is used together with estimated *U* and/or e_a data. In such cases, the *ETo* estimates presented errors that are ranked in 9th, 11th and 12th places, behind some simpler empirical methods. The highest errors observed in our study when using estimated *SR* may be due to the use of a non-calibrated K_{Rs} coefficient in Eq. (18). As suggested by Allen et al. (1998), the K_{Rs} value adopted for Southern Ontario was 0.16, recommended for continental conditions. However, even though located near the middle of the continent, the southern region of Ontario is situated between four lakes: Eire, Huron, Ontario and St. Clair (Fig. 1). Such a situation may influence the value of K_{Rs}, which must be investigated in further studies. For Tunisia, Jabloun and Sahli (2008) calibrated K_{Rs} for each location, which improved the *ETo* estimates by the FAO PM method.

Table 7
Average *RMSE* ranking for reference evapotranspiration estimated by the Penman–Monteith (FAO PM) method with missing data, and by the Priestley–Taylor (PT Original and PT Adjusted), Hargreaves (H Original and H Adjusted), and Thornthwaite (TH Original and TH with effective temperature, *Tef*) methods in Southern Ontario, Canada.

Rank #	Method and Condition	Average RMSE (mm day^{-1})[a]
1	FAO PM ($-U$)	0.182 a
2	PT Adjusted	0.402 b
3	FAO PM ($-e_a$)	0.512 b
4	FAO PM ($-U$ and $-e_a$)	0.530 bc
5	PT Original	0.624 c
6	H Adjusted	0.704 c
7	FAO PM ($-SR$)	0.793 d
8	TH *Tef*	0.830 d
9	FAO PM ($-U$ and $-SR$)	0.835 d
10	H Original	1.103 e
11	FAO PM ($-e_a$ and $-SR$)	1.105 e
12	FAO PM ($-U$, $-e_a$ and $-SR$)	1.121 e
13	TH Original	1.194 e

[a] The averages followed by the same letter are not statistically different by the *t*-test ($p = 0.05$).

For conditions when *U* and e_a data are missing, another good option to estimate *ETo* is the PT method. When the original PT method was used for Southern Ontario, it was ranked in 5th place with an average *RMSE* of 0.62 mm day^{-1}, similar to the results obtained by Suleiman and Hoogenboom (2007) for the state of Georgia, USA, from April through September. However, when this method was locally calibrated for Ontario the average error decreased to 0.4 mm day^{-1}, the second smallest error. Recalibration of the PT method has been done for different locations around the world, since the original alpha (=1.26) is based on comparisons with the initial Penman method, which normally overestimates *ETo* because it omits the canopy resistance that was added in the Penman–Monteith method (Allen et al., 1989; Suleiman and Hoogenboom, 2007). For the majority of conditions, alpha is smaller than 1.26, as also observed in our analysis, where alpha ranged from 1.01 to 1.18 (Table 4). Results from different parts of the world have shown that alpha depends on the climate of the region or season where the measurements were done (McAneney and Itier, 1996; Xiaoying and Erda, 2005). In humid climates alpha normally is smaller than 1.26; whereas in drier climates this parameter increases to more than 1.3 (Sentelhas et al., 2000; Medeiros et al., 2003).

When the weather stations only have temperature data available, which is very common on farms, the best way among the tested methods to estimate *ETo* in Southern Ontario is using the adjusted Hargreaves method. The same result was also observed in Tanzania by Igbadun et al. (2006) and in Iran by Fooladmand and Haghighat (2007). In our study, the adjusted Hargreaves method is ranked in 6th place, with an average *RMSE* = 0.7 mm day^{-1}. Other results are: Thornthwaite with *Tef* in 8th place (*RMSE* = 0.83 mm day^{-1}); original Hargreaves in 10th place (*RMSE* = 1.10 mm day^{-1}); FAO PM, with missing *U*, e_a and *SR* data, in 12th place (*RMSE* = 1.12 mm day^{-1}); and original Thornthwaite in the last position (*RMSE* = 1.19 mm day^{-1}) (Table 7).

Considering the *t*-test ($p = 0.05$), the *ETo* methods tested can be divided into five groups, with no statistical difference of *RMSE* among the methods in each group. In the first group, the FAO PM ($-U$) is isolated, representing the best option to estimate *ETo*, when no wind speed data are available. In the second group are: PT Adjusted, FAO PM ($-e_a$) and FAO PM ($-U$ and $-e_a$), where *RMSE* ranged from 0.40 to 0.53 mm day^{-1}. The third group is comprised of PT Original and Hargreaves Adjusted, with *RMSE* between 0.60 and 0.71 mm day^{-1}. The fourth group, with *RMSE* around 0.8 mm day^{-1}, include FAO PM ($-SR$), TH *Tef* and FAO PM ($-U$ and $-SR$). Finally, the methods H Original, FAO PM ($-e_a$ and $-SR$), FAO PM ($-U$, $-e_a$ and $-SR$) and TH Original are in the group with the worst performance to estimate *ETo*, with *RMSE*s above 1.1 mm day^{-1}.

5. Conclusions

Our comprehensive study has investigated 13 alternatives to estimate *ETo* in Southern Ontario, Canada, with different availabilities of weather data, in relation to the standard method of Penman–Monteith, parameterized in FAO Irrigation and Drainage Paper 56 (Allen et al., 1998). The results proved that the FAO PM method can be used to estimate daily *ETo* acceptably well in Southern Ontario when wind speed and/or relative humidity data are not available, with errors smaller than 0.6 mm day^{-1}. Using the estimation procedures recommended by the FAO 56 Paper to replace *U* and e_a missing data had little negative impact on *ETo* estimations, but the recommended methods to replace missing radiation data did not perform well for Southern Ontario. The Priestley–Taylor method was also a good alternative when *U* and e_a data were missing, with *RMSE* = 0.62 mm day^{-1}; however we recommend the use of this method only after local calibration, since the original method, with alpha = 1.26, overestimated daily *ETo* systematically in all locations, by 6–25%. When calibrated, performance of the PT method improved, with *RMSE* = 0.4 mm day^{-1}. The procedure of estimating solar radiation from air maximum and minimum temperature data was not accurate enough in Southern Ontario, resulting in poor *ETo* estimates by the FAO PM method (*RMSE* between 0.79 and 1.12 mm day^{-1}). When *SR*, *U* and e_a data were missing, Hargreaves method, adjusted locally, was more accurate (*RMSE* = 0.7 mm day^{-1}) to estimate *ETo* than Penman–Monteith (*RMSE* = 1.12 mm day^{-1}) or Thornthwaite (*RMSE* = 1.19 mm day^{-1}) methods. The advantage of having the temperature-based *ETo* methods calibrated for the region is to provide an option to estimate this variable even where the weather stations do not have full datasets.

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References

Allen, R.G., Jensen, M.E., Wright, J.L., Burman, R.D., 1989. Operational estimates of reference evapotranspiration. Agronomy Journal 81, 650–662.

Allen, R.G., Pruitt, W.O., 1991. FAO-24 reference evapotranspiration factors. Journal of Irrigation and Drainage Engineering 117, 758–773.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO, Rome, Italy (FAO Irrigation and Drainage Paper, No. 56. 300 p.).

Camargo, A.P., Marin, F.R., Sentelhas, P.C., Picini, A.G., 1999. Ajuste da equação de Thornthwaite para estimar a evapotranspiração potencial em climas áridos e superúmidos, com base na amplitude térmica. Revista Brasileira de Agrometeorologia 7, 251–257.

Fooladmand, H.R., Haghighat, M., 2007. Spatial and temporal calibration of Hargreaves equation for calculating monthly reference evapotranspiration based on Penman–Monteith method. Irrigation and Drainage 56, 439–449.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Applied Engineering Agriculture 1, 96–99.

Igbadun, H.E., Mahoo, H.F., Tarimo, A.K.P.R., Salim, B.A., 2006. Performance of two temperature-based reference evapotranspiration models in the Mkoji subcatchment, Tanzania. Agricultural Engineering International: The CIGR E-journal 8, 1–18.

Jabloun, M., Sahli, A., 2008. Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data: applications to Tunísia. Agricultural Water Management 95, 707–715.

Jacovides, C.P., Kontoyiannis, H., 1995. Statistical procedures for the evaluation of evapotranspiration computing models. Agricultural Water Management 27, 365–371.

López-Urrea, R., Martin de Santa Olalla, F., Fabeiro, C., Moratalla, A., 2006. Testing evapotranspiration equations using lysimeter observations in a semiarid climate. Agricultural Water Management 85, 15–26.

Mavi, H.S., Tupper, G.J., 2004. Agrometeorology—Principles and Applications of Climate Studies in Agriculture. Food Products Press, New York, p. 364.

McAneney, K.J., Itier, B., 1996. Operational limits to the Priestley–Taylor formula. Irrigation Science 17, 37–43.

Medeiros, A.T., Sentelhas, P.C., Lima, R.N., 2003. Estimativa da evapotranspiração de referência a partir da equação de Penman–Monteith, de medidas lisimétricas e de equações empíricas, em Paraipaba, CE. Engenharia Agrícola 23, 31–40.

Pereira, A.R., Sentelhas, P.C., Folegatti, M.V., Villa Nova, N.A., Maggiotto, S.R., Pereira, F.A.C., 2002. Substantiation of the daily FAO-56 reference evapotranspiration with data from automatic and conventional weather stations. Revista Brasileira de Agrometeorologia 10, 251–257.

Popova, Z., Kercheva, M., Pereira, L.S., 2006. Validation of the FAO methodology for computing *ETo* with limited data. Application to South Bulgaria. Irrigation and Drainage 55, 201–215.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat-flux and evaporation using large-scale parameters. Monthly Weather Review 100, 81–92.

Rosenberg, N.J., Blad, B.L., Verma, S.B., 1983. Microclimate—The Biological Environment, 2nd ed. Jon Wiley & Sons, New York, p. 495.

Sentelhas, P.C., Pereira, A.R., Folegatti, M.V., Pereira, F.A.C., Villa Nova, N.A., Maggiotto, S.R., 2000. Variação sazonal do parâmetro de Priestley–Taylor para estimativa diária da evapotranspiração de referência. Revista Brasileira de Agrometeorologia 8, 49–53.

Stannard, D.I., 1993. Comparison of Penman–Monteith. Shuttleworth–Wallace, and modified Priestley–Taylor evapotranspiration models for wildland vegetation in semiarid rangland. Water Resources Management 29, 1379–1392.

Stöckle, C.O., Kjelgaard, J., Bellochi, G., 2004. Evaluation of estimates weather data for calculating Penman–Monteith reference crop evapotranspiration. Irrigation Science 23, 39–46.

Suleiman, A.A., Hoogenboom, G., 2007. Comparison of Priestley–Taylor and FAO-56 Penman–Monteith for daily reference evapotranspiration estimation in Georgia, USA. Journal of Irrigation and Drainage Engineering 133, 175–182.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geographical Review 38, 55–94.

Widmoser, P., 2009. A discussion on and alternative to Penman–Monteith equation. Agricultural Water Management 96, 711–721.

Xing, Z., Chow, L., Meng, F.R., Rees, H.W., Stevens, L., Monteith, J., 2008. Validating evapotranspiration equations using Bowen Ratio in New Brunswick. Maritime Canada. Sensors 8, 412–428.

Xiaoying, L., Erda, L., 2005. Performance of Priestley–Taylor equation in the semiarid climate of north China. Agricultural Water Management 71, 1–17.