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Regionalization of the Hargreaves coefficient to estimate long-term reference evapotranspiration series in SE Spain

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Abstract

This study employs a methodological approach for estimating long-term series of monthly reference evapotranspiration (ET_o) from historical data. To carry it out a regionally calibrated version of the Hargreaves equation was applied at old ordinary weather stations which only provide data of air temperature and precipitation. The proposed approach was based on the analysis of: (1) the Hargreaves coefficient obtained by local calibration from data of 66 modern automatic weather stations; (2) the regional characterization of the spatial variability of that coefficient by means of a "regional function"; and (3) the final application of this function to the old ordinary weather stations. This approach was assessed under the semiarid conditions of the Segura River Basin (south-eastern Spain) by comparing ET_o estimates against those obtained with the Penman-Monteith method, which was used as reference. Spatial variability of the Hargreaves coefficient was well correlated with the annual and monthly means of daily temperature range, so they were selected as explanatory variables for the regionalization of the Hargreaves coefficient following two approaches: a global regional function and monthly regional functions. The regionally calibrated version of the Hargreaves equation by monthly functions clearly improved the performance of its original parameterization (average relative error decreased from 19.8% to 10.1%) although, as expected, estimates were not as good as those obtained with the local calibration (average relative error = 7.7%).

Additional key words: monthly evapotranspiration; Hargreaves coefficient; regional function, climate change; semi-arid climate.

Introduction

Evapotranspiration is a key point in many fields of science, such as geography, meteorology, hydrology, ecology and agronomy (Brutsaert, 1982). Reference evapotranspiration (ET_o) represents an integrated climate parameter that gives a measure of the evaporation demand of the air, and this knowledge is especially valuable for predicting crop water requirements (Doorenbos & Pruitt, 1977). ET_o can be estimated by a wide range of methods that vary in data requirements. The FAO-56 version of the Penman-Monteith (PM) method was established as a standard for calculating ET_o (Allen *et al*., 1998) because of its relatively accurate and consistent performance in both arid and humid climates (Jensen *et al*., 1990; Allen &

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Abbreviations used. **Nomenclature**: AEMET (National Meteorology Agency); AWS (Automatic Weather Station); ET_o (reference evapotranspiration); HG (Hargreaves); MBE (mean bias error); OWS (Ordinary Weather Station); PM (Penman-Monteith); RE (relative error); RMSE (root mean square error); SIAM (Agricultural Information Service of Murcia Region); SIAR (National Agroclimatic Information System for Irrigation); SRB (Segura River Basin). **Parameters**: C (Hargreaves coefficient); C_g (globally calibrated Hargreaves coefficient); $C_{m,j}$ (monthly calibrated Hargreaves coefficients [j = month of the year; 1,…, 12]); $ET_{o,PM}$ (monthly-averaged ET_o calculated by Penman Monteith [mm day^{-1}]); $ET_{o,HG}$ (monthly-averaged ET_o calculated by Hargreaves equation [mm day^{-1}]); $ET_{o,HGg}$ (monthly-averaged ET_o calculated by Hargreaves equation with C_g [mm day^{-1}]); $ET_{o,HGm}$ (monthly-averaged ET_o calculated by Hargreaves equation with $C_{m,j}$ [mm day^{-1}]); $\overline{T}$ (annual mean of daily temperature); $\Delta\overline{T}$ (annual mean of daily temperature range); $\overline{P}$ (mean annual precipitation); $\overline{T_i}$ (monthly mean of daily temperature [j = month of the year; 1,…, 12]); $\Delta\overline{T_i}$ (monthly mean of daily temperature range [j = month of the year; 1,…, 12]); $\overline{P_j}$ (mean monthly precipitation [j = month of the year; 1,…, 12]).

Pruitt, 1991; López-Urrea *et al*., 2006a; Jabloun & Sahli, 2008; Sentelhas *et al*., 2010). It is a physically-based method that requires data for a large number of meteorological variables which are not often all available. In those situations, the Hargreaves (HG) equation is one of the most popular temperature-based methods that provides reasonable ET_o estimates with a global validity (Allen *et al*., 1998).

The knowledge of long-term series of ET_o is currently of great interest for studying and modelling hydrological and agricultural systems under dynamic scenarios related to land use and/or climate change (Elgaali *et al*., 2007; Sánchez-Toribio *et al*., 2010; Bae *et al*., 2011; Espadafor *et al*., 2011; Rey *et al*., 2011). However, determining long-term series of ET_o from historical data presents a major drawback: the lack of reliable records for long periods due to the progressive changes in measuring devices and sitting of weather stations throughout the 20^{th} century. In addition, applying the PM method is even more limited since weather stations with the required data for long periods are still very scarce (Droogers & Allen, 2002; Pereira & Pruitt, 2004; Simolo *et al*., 2010). For instance, in the Segura River Basin (SRB), a semiarid region located in south-eastern Spain, there are only a handful of meteorological stations with more than 30 years of records with the required data for applying the PM method. Besides, those records are often incomplete and not very reliable. However, long records (> 50 years) of precipitation and air temperature are available at about 50 old ordinary weather stations (OWSs), some of which even have records going back more than 90 years. The international standardisation of the PM method has promoted the implementation of new agrometeorological networks in the SRB since 2000, consisting of modern automatic weather stations (AWSs) specifically equipped for applying the PM method. However, they were mainly located in irrigation districts and far from the site of the old OWSs, not making it possible to relate the historical records of the old OWSs with the new readings at the AWSs.

Given the difficulty of applying the PM method for calculating long-term ET_o series in the SRB (similar to other Spanish and worldwide regions), other alternative low data demanding methods must be used. The HG equation (Hargreaves & Samani, 1985) is an appealing method for estimating ET_o at meteorological stations when ordinary weather data are available, as it only requires air temperature data. This equation can be extremely useful for both determining long-term series of ET_o from historical records, as well as for generating projected ET_o series from monthly temperature projections provided by climate change models (Milzow *et al*., 2010).

Previous works have demonstrated that, in general, the HG equation can provide precise estimations for weekly or longer time predictions (Hargreaves, 1994; Hargreaves & Allen, 2003; López-Urrea *et al*., 2006a). Moreover, other scientists such as Shuttleworth (1993) recommend that the HG method should not be used for shorter periods than 1 month. The original parameterization of the HG equation (Hargreaves & Samani, 1985) usually overestimates ET_o in humid regions, and underestimates it in dry areas (Saeed, 1986; Jensen *et al*., 1990; Amatya *et al*., 1995; Temesgen *et al*., 2005). It has also been reported that the HG equation overestimates ET_o at low evapotranspiration rates, and vice versa (Droogers & Allen, 2002; Xu & Singh, 2002; Itenfisu *et al*., 2003). Those reports make it clear that the HG equation performance is strongly influenced by the climatic conditions where it was parameterised. Therefore, such equation must be evaluated and, if it is necessary, calibrated for accurate use in other zones (Jensen *et al*., 1997; Gavilán *et al*., 2006; Shahidian *et al*., 2013).

An appropriate re-parameterization of the HG equation must be carried out by local calibration of the HG coefficient. The adjustment of the HG coefficient has usually been carried out twofold: by comparison with weighing lysimeter measurements of the reference crop (Jensen *et al*., 1997; Martínez-Cob & Tejero-Juste, 2004; López-Urrea *et al*., 2006b), or more frequently by comparison against the ET_o estimations provided by the application of the PM method at the same weather station (Itenfisu *et al*., 2003; Martínez-Cob & Tejero-Juste, 2004; Gavilán *et al*., 2006; Jabloun & Sahli, 2008; Sentelhas *et al*., 2010; Espadafor *et al*, 2011; Mendicino & Senatore, 2013). However, when the HG equation is applied at weather stations where it cannot be locally calibrated, as occurs at the old OWSs of the SRB, other approaches for its regional calibration should be considered.

Several solutions of different complexity were proposed for the regionalization of the HG equation, most of them adopting a regression based calibration of the HG coefficient using auxiliary parameters such as temperature range (Samani, 2000; Vanderlinden *et al*., 2004; Lee, 2010; Mendicino & Senatore, 2013), relative humidity (Hargreaves & Allen, 2003), wind speed (Jensen *et al*., 1997; Martínez-Cob & Tejero-Juste, 2004), presence of large water bodies or distance to coast (Vanderlinden *et al*., 2004; Mendicino & Senatore, 2013), and rainfall (Droogers & Allen, 2002). Shahidian *et al*. (2013) carried out an in-depth analysis of the parameters previously used for the spatial and seasonal calibration of the HG method, concluding that it is possible to improve the precision of the estimates for new sites where no reliable records of climatic data exist by using regional averages of such parameters.

The purpose of this study was to develop a methodological approach for obtaining long-term series of monthly ET_o by applying the HG equation, with a regionally calibrated HG coefficient, in old OWSs, where historical air temperature data are available. In contrast to previous analysis of the HG equation, monthly-averaged weather data were used to estimate monthly-averaged ET_o. This approach was selected since a monthly time step is usual in long-term hydrological and agricultural modelling, especially if future projections of weather data are used. The proposed methodology was based on the estimation of locally calibrated HG coefficients at a set of modern AWSs; the regionalization of the HG coefficient based on the formulation of a suitable function linking it to available information at the OWSs; and the final application of this function at the OWSs. The approach was evaluated under the semiarid conditions of the SRB.

Material and methods

Study area and weather data

The Segura River Basin (SRB) is characterised by a Mediterranean semi-arid climate with warm, dry summers and mild winter conditions. The average annual temperature is 17.5°C, reaching maximum temperatures of 38ºC in summer, and minimum temperatures of 1°C in winter. Annual rainfall averaged 350 mm during the study period, with high seasonal and inter-annual variability. Most precipitation occurred during the fall and winter months, but inter-annual droughts were also common.

Data for an eight-year study period (2001-2008) from two sets of weather stations were used in the study. On the one hand, 66 modern AWSs with available daily data of air temperature, relative humidity, wind speed, and global solar radiation over the study period were selected. These AWSs belong to three different weather and agro-meteorological services: 38 stations are managed by the Agricultural Information Service of Murcia Region (SIAM, http://siam.imida.es); 16 stations are part of the National Agroclimatic Information System for Irrigation (SIAR, http://www.mapa.es/siar); and the remaining 12 stations pertain to the National Meteorology Agency (AEMET, http://www.aemet.es). Most stations in this set were remotely monitored and specifically equipped for calculating ET_o with the PM method. Air temperature and relative humidity were measured from 1.5 to 2.0 m above soil surface, whereas wind speed was usually recorded at 2.0 m height. Some of the AEMET stations measured wind speed at higher heights and then their data were adjusted to 2.0 m height by means of a logarithm wind profile equation. The reader is referred to the aforementioned web pages for detailed information about the sensor type and model for recording each meteorological variable at the AWSs. Fig. 1 depicts their location in the SRB as squares.

On the other hand, a set of 77 old OWSs were available. These provided historical long-term series of daily maximum and minimum air temperature, and precipitation. The oldest of them have records from 1913 and is even today still in operation. The OWSs belong to the National Meteorological Agency and are graphed as triangles in Fig. 1. They are equipped with traditional analogical thermometers and rain gauges.

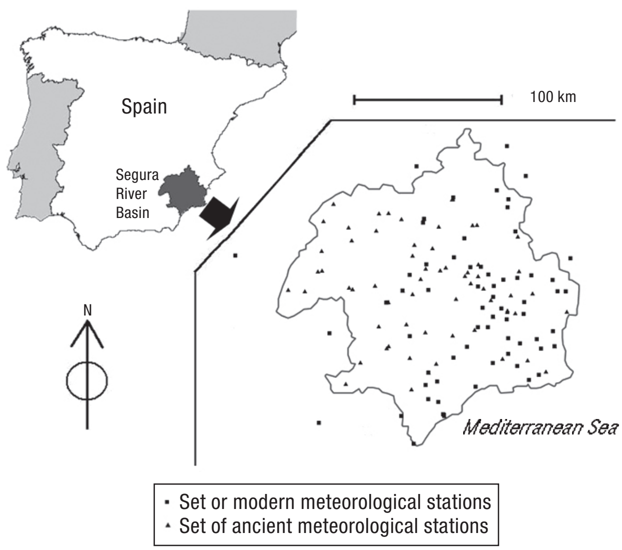

Figure 1. Distribution of the two sets of weather stations in the Segura River Basin. Squares represent the 66 modern automatic weather stations (AWSs) with reliable data from 2001 to 2008, and triangles depict the 77 old ordinary weather stations (OWSs) providing long-term series of air temperature.

Table 1. Summary of weather station characteristics used in the study. Only 12 stations selected from the 66 modern automatic weather stations (AWSs) are presented

Station name and code	Latitude (N)	Longitude (W)	Elevatation (m)	$\overline{T}$ (°C)	$\overline{\Delta T}$ (C)	$\overline{P}$ (mm)
Abanilla-Jaira (SIAM-MO41)	38° 10' 14"	1° 03' 09"	138	17.3	10.7	251
Águilas (SIAM-LO51)	37° 25' 11"	1° 35' 27"	25	18.5	8.2	236
Alcantarilla (AEMET-7228)	37° 57' 28"	1° 13' 47"	85	18.5	12.7	288
Almoradí (SIAR A-10)	38° 05' 27"	0° 46' 17"	40	18.0	9.5	316
Beniel (SIAR MU-17)	38° 02' 07"	1° 00' 28"	27	17.5	13.5	271
Caravaca (SIAM CR-12)	38° 02' 43"	1° 58' 44"	872	13.0	12.2	330
Cehegín (SIAM CR-32)	38° 06' 43"	1° 40' 54"	432	15.7	15.4	346
Hellín (SIAR AB-04)	38° 29' 12"	1° 42' 44"	495	15.4	14.8	339
Murcia (AEMET-7118I)	38° 00' 10"	1° 10' 10"	18.6	18.6	12.7	288
San Cayetano (SIAM-TP73)	37° 49' 39"	0° 55' 32"	95	18.2	10.8	272
Totana (SIAR MU-02)	37° 44' 01"	1° 30' 44"	237	17.0	12.4	272
Yecla (AEMET-7275B)	38° 36' 30"	1° 05' 14"	590	16.1	11.9	323
All stations	—	—	302 ± 269	17.0 ± 1.5	11.8 ± 1.9	296 ± 61

$\overline{T}$: annual mean of daily temperature. $\overline{\Delta T}$: annual mean of daily temperature range. $\overline{P}$: mean annual precipitation.

The three networks (SIAM, SIAR and AEMET) are responsible for quality control procedures, including sensor calibration and data validation. Since showing and discussing the results for all the stations would be unfeasible in a scientific paper, twelve stations of the AWSs were chosen for displaying the results of the local calibration and for assessing the regional calibration performance. A summary of the main features of these stations is provided in Table 1.

ET_o estimates

For both sets of weather stations, monthly-averaged data throughout the study period were derived from the daily observations, assuming that a monthly average value was valid if at least 25 daily observations were available. These monthly values of the meteorological variables were used to compute monthly-averaged ET_o using the PM and HG equations. The value of the ET_o calculated with monthly-averaged weather data is indeed very similar to the average of the daily ET_o values calculated with daily weather data for that month (Allen *et al*., 1998).

The FAO-56 version of the PM method is considered the most precise and standard method to estimate ET_o (Allen *et al*., 1998), such as it was corroborated in the study region (López-Urrea *et al*., 2006a). It refers the ET_o concept to the rate of evapotranspiration from an extensive area with an ideal 0.12 m high crop with a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, that is well provided with water and nutrients. The PM equation is as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_m + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad [1]$$

where ET_o is the reference evapotranspiration (mm day^{-1}); Δ is the slope of the saturated vapour pressure curve (kPa °C^{-1}); R_n is the net radiation (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^{-2} day^{-1}); T_m is the mean air temperature (°C) at 2.0 m; U_2 is the average wind speed at 2.0 m height (m s^{-1}); e_s is the saturation vapour pressure (kPa) at temperature T_m; e_a is the actual vapour pressure (kPa); $(e_s - e_a)$ is the vapour pressure deficit (kPa); and γ is the psychrometric constant (kPa °C^{-1}). The soil heat flux (G) was assumed to be negligible over the calculation time step period (1 month). Eq. [1] was used in this study, adopting the procedure suggested by Allen *et al*. (1998) for calculating monthly-averaged ET_o, starting from the monthly-averaged values of temperature, solar radiation, air relative humidity, and wind speed.

As aforementioned, the Hargreaves (HG) equation requires only maximum and minimum air temperature, as well as extraterrestrial radiation. The monthly-averaged ET_o (mm day^{-1}) were calculated using the following equation (Hargreaves, 1994):

$$ET_o = C R_a (T_{max} - T_{min})^{0.5} (T + 17.8) \quad [2]$$

where C refers to the HG coefficient, which value is 0.0023 according to the original parameterization proposed by Hargreaves & Samani (1985); R_a is the water equivalent of the monthly-averaged daily extraterrestrial radiation (mm day^{-1}), calculated according to Allen *et al.* (1998); T_{max}, and T_{min} are the monthly-averaged maximum and minimum values of daily air temperature (°C); and T is the monthly-averaged daily temperature, calculated as the average of T_{max} and T_{min}.

Calibrations of the Hargreaves equation

Monthly-averaged ET_o for the study period was calculated with the PM and HG methods ($ET_{o,PM}$ and $ET_{o,HG}$, respectively) at the AWSs. $ET_{o,HG}$ estimations were assessed by comparison against $ET_{o,PM}$, which was selected as a standard reference for ET_o. The assessment at each station entailed analysing the relationship between the reference and the estimated values of ET_o by means of linear regressions $y = a + b \cdot x$, where $y = ET_{o,PM}$ and $x = ET_{o,HG}$. Additionally, the performance of the HG equation was evaluated using the mean bias error (MBE), the root mean square error (RMSE) and the relative error (RE) in accordance with the following expressions (Willmott, 1982):

$$MBE = \frac{\sum_{i=1}^{n}(ET_{o,PM} - ET_{o,HG})}{n} \quad (mm\ day^{-1}) \qquad [3]$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(ET_{o,PM} - ET_{o,HG})^2}{n}\right]^{0.5} \quad (mm\ day^{-1}) \qquad [4]$$

$$RE = \frac{100 \cdot RMSE}{\overline{ET_{o,PM}}} \quad (\%) \qquad [5]$$

where n is the sample size (96 months); and $\overline{ET_{o,PM}}$ is the average value of $ET_{o,PM}$ for the sample.

After assessing the performance of $ET_{o,HG}$, HG equation was re-parameterized by local calibration of the Hargreaves coefficient C at each AWS. This local calibration was performed at global and monthly scales.

Local calibration of the Hargreaves equation

The first approach for locally calibrating the HG equation consisted of the estimation of a globally calibrated HG coefficient (C_g) for each single available AWS, which minimizes the differences with the estimates provided by the PM method ($ET_{o,PM}$). This was achieved by using a simple optimization technique aimed at minimizing the MBE at each AWS. The monthly-averaged values of ET_o obtained with the global local calibration of HG coefficient are referred to as $ET_{o,HGg}$. As a result, a set of 66 C_g values for the SRB were obtained.

The other approach was the fitting of twelve monthly calibrated HG coefficients ($C_{m,j}$) for each single available AWS. $C_{m,j}$ minimizes the MBE with the estimates provided by the PM method for month j at each AWS:

$$MBE = \frac{\sum_{i=j}^{n}(ET_{o,PM} - ET_{o,HG})}{n} \quad (mm\ day^{-1}) \qquad [6]$$

where n is the sample size and j denotes the month of the year (j=1,…, 12). The monthly-averaged values of ET_o obtained with the monthly local calibration of HG coefficient are referred to as $ET_{o,HGm}$. As a result, 792 $C_{m,j}$ values, one for each month of the year at each AWS were obtained.

The performance assessment for both calibrations proposals was carried out by comparison with $ET_{o,PM}$, in the same way as the original parameterization of the HG equation.

Regional estimation of the Hargreaves coefficient

In the SRB, the OWSs were located in different sites than the modern AWSs considered for the local analysis and hence, the local calibration of the HG coefficient alone was not enough for this study purpose. Nevertheless, it would be easy to solve this problem if a relationship between the calibrated HG coefficients (C_g or $C_{m,j}$) and other data also available at the OWSs could be established, such as elevation, the mean daily temperature, the mean daily temperature range, or the mean precipitation. Therefore, the regionalization of the HG coefficient was based on the formulation of a suitable mathematical equation (regional function) linking it to the aforementioned data. This approach was similar to that followed in other regions for previous regionalization of the HG coefficient attempts (Samani, 2000; Vanderlinden *et al.*, 2004; Lee, 2010; Mendicino & Senatore, 2013; Shahidian *et al.*, 2013).

The regional function of the HG coefficient was incorporated to Eq. [2] for obtaining the regionally calibrated version of the HG equation, which was validated in terms of ET_o at the twelve selected AWSs using cross-validation. This procedure consisted of (i) recalculating the regional function removing each time one of the AWS from the analysis, and (ii) assessing for the removed AWSs the ET_o estimates achieved with that regional function by comparison with $ET_{o,PM}$. Finally, the regionally calibrated version of the HG equation was applied to the set of OWSs, from which historical time series of monthly-averaged ET_o were obtained from ancillary records of air temperature.

Results

Performance of the original parameterization of the Hargreaves equation

The results of the linear regressions between the values of $ET_{o,PM}$ and $ET_{o,HG}$ at the 12 AWSs chosen for displaying the results are shown in Table 2. This table also shows the average values for all the AWSs. The coefficients of determination were always over 0.96, thus representing a high and steady correlation between both ET_o estimation methods. The slope of the adjusted linear functions, b, was > 1 for all the stations except for Almoradí, where it was 0.948. On average, b was 13.5% higher than the unity, indicating a systematic ET_o underestimation of the original parameterization of the HG equation. It should be noted that the regression slopes were statistically different than 1 (Ttest, $\alpha = 0.95$) for most AWSs. The analysis of the performance statistics (MBE, RMSE, and RE) showed substantial errors and a great variability of results among stations. Considering all locations, the MBE values ranged from 0.397 to 1.132 mm day^{-1}, with a mean of 0.741 ± 0.268 mm day^{-1}, RMSE ranged from 0.471 to 1.210 mm day^{-1}, with a mean of 0.862 ± 0.264 mm day^{-1} and RE ranged from 12.03 to 26.98%, with a mean of 19.78 ± 5.05%. The positive values of MBE again clearly showed the systematic underestimation of $ET_{o,HG}$. The comparison of these statistics with the reported by Gavilán *et al*. (2006) in the nearby region of Andalusia indicated that although the average RMSE and RE were almost the same (similar scatter with respect to the reference method), the MBE was higher and with opposite sign (very different bias with respect to the reference method). This MBE behaviour was expected since the SRB is considerably arider than Andalusia.

Fig. 2 plots the monthly $ET_{o,HG}$ values versus the $ET_{o,PM}$ ones, as well as the adjusted linear regressions, for two specific AWSs: Murcia and Alcantarilla. The departure from the straight line 1:1 (dashed line) confirmed the unsatisfactory performance of $ET_{o,HG}$. The monthly evolution of $ET_{o,PM}$ and $ET_{o,HG}$ during the

Table 2. Statistics and parameters of the linear regressions between monthly-averaged ET_o calculated with the Penman-Monteith method ($ET_{o,PM}$) and with the Hargreaves equation ($ET_{o,HG}$). Only 12 stations selected from the 66 modern automatic weather stations (AWSs) are presented

Weather station	R^2	*a* (mm day^{-1})	*b*	*MBE* (mm day^{-1})	*RMSE* mm (d^{-1})	*RE* (%)
Abanilla (SIAM-MO41)	0.96	0.339^d	1.077^f	0.612	0.735	17.65
Águilas (SIAM-LO31)	0.97	0.778^d	1.032^f	0.897	0.959	21.16
Alcantarilla (AEMET-7228)	0.98	0.011^c	1.256^f	0.956	1.124	24.21
Almoradí (SIAR A-10)	0.97	0.599^d	0.948^f	0.413	0.515	12.82
Beniel (SIAR MU-17)	0.99	–0.005^c	1.113^f	0.397	0.497	12.52
Caravaca (SIAM CR-12)	0.96	–0.063^c	1.209^f	0.598	0.807	21.47
Cehegín (SIAM CR-32)	0.99	–0.083^c	1.217^f	0.663	0.826	20.16
Hellín (SIAR AB-04)	0.98	–0.008^c	1.150^f	0.502	0.627	16.09
Murcia (AEMET-7118I)	0.98	0.101^d	1.251^f	1.035	1.194	25.10
San Cayetano (SIAM-TP73)	0.96	0.089^c	1.099^f	0.445	0.644	15.83
Totana (SIAR MU-02)	0.98	0.287^d	1.123^f	0.720	0.810	19.06
Yecla (AEMET-7275B)	0.98	0.451^d	1.147^f	0.960	1.039	23.45
All stations	0.97 ± 0.01	0.38 ± 0.29	1.13 ± 0.11	0.74 ± 0.27	0.86 ± 0.26	19.8 ± 5.0

R^2: coefficient of determination of the simple linear regression $y = a + bx$, where a is the intercept and b the regression slope. MBE: mean bias error. RMSE: root mean square error. RE: relative error. ^{c,e}: no significantly different than 0 and 1 ($\alpha = 0.95$), respectively. ^{d,f} = significantly different than 0 and 1 ($\alpha = 0.95$), respectively.

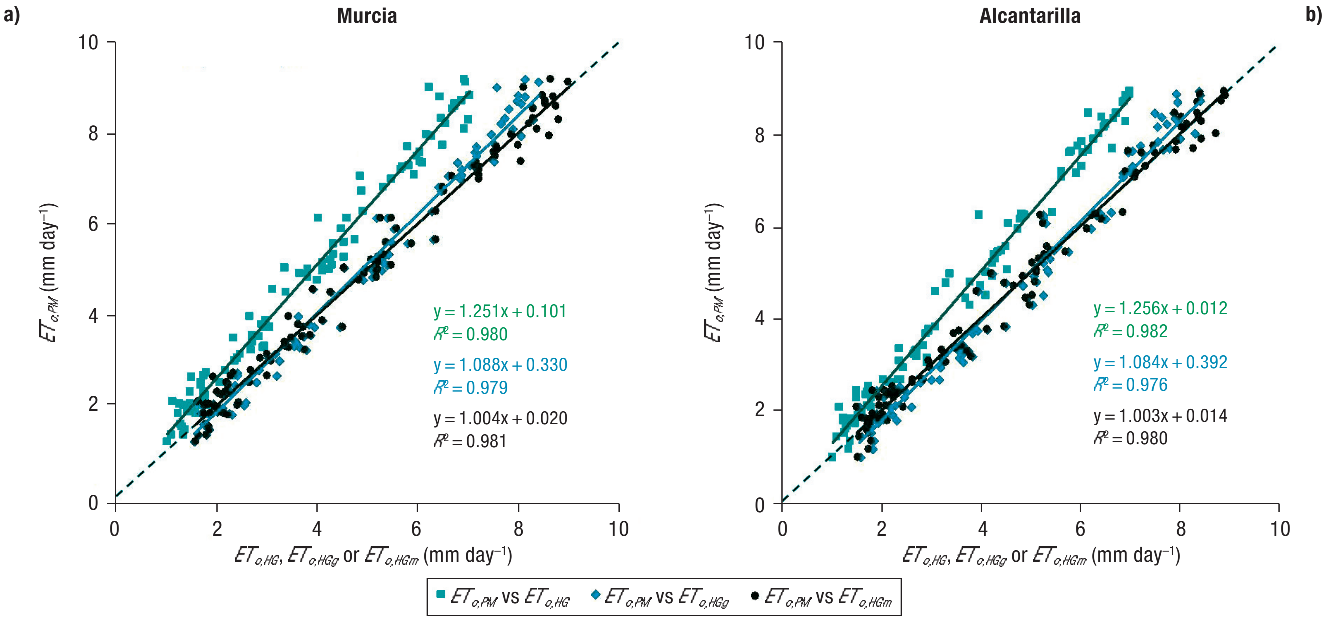

Figure 2. Linear regression between monthly-averaged ET_o calculated with the Penman-Monteith method ($ET_{o,PM}$) and with the Hargreaves equation ($ET_{o,HG}$), the Hargreaves equation locally calibrated by a global coefficient ($ET_{o,HGg}$) and the Hargreaves equation locally calibrated by monthly coefficients ($ET_{o,HGm}$) for (a) Murcia and (b) Alcantarilla weather stations in the period 2001-2008.

study period is depicted in Fig. 3 for Murcia AWS. The underestimation of the HG equation was systematic, but higher in summer than in winter, in agreement with previous reports indicating the increasing underestimation of the HG equation with increasing ET_o rates (Amatya *et al.*, 1995; Xu & Singh, 2002).

Performance of the Hargreaves equation locally calibrated by a global coefficient

The results of the linear regressions between the monthly values of $ET_{o,HGg}$ and $ET_{o,PM}$ are shown in Table 3. $ET_{o,HGg}$ values were very close to those provided by the

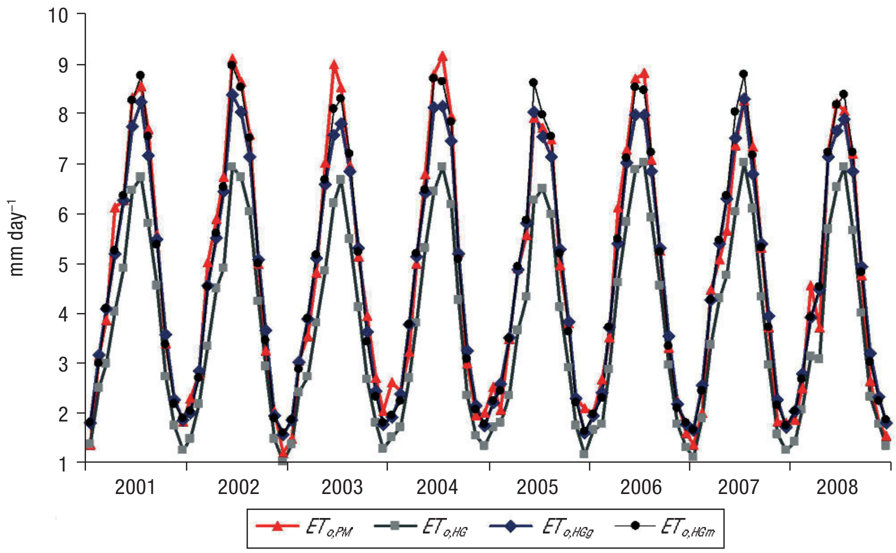

Figure 3. Monthly-averaged ET_o calculated with the Penman-Monteith method ($ET_{o,PM}$), the Hargreaves equation in its original parameterization ($ET_{o,HG}$), the Hargreaves equation locally calibrated by a global coefficient ($ET_{o,HGg}$) and the Hargreaves equation locally calibrated by monthly coefficients ($ET_{o,HGm}$) for Murcia weather station in the period 2001 to 2008.

Table 3. Statistics (MBE, RMSE and RE) and parameters of the linear regressions between monthly-averaged ET_o calculated with the Penman-Monteith method ($ET_{o,PM}$) and with the Hargreaves equation locally calibrated by a global coefficient ($ET_{o,HGg}$)

Weather station	R^2	*a* (mm day^{-1})	*b*	MBE (mm day^{-1})	RMSE (mm day^{-1})	RE (%)
Abanilla (SIAM-MO41)	0.95	0.162[d]	0.961[f]	0.000	0.443	10.63
Águilas (SIAM-LO31)	0.97	0.064[c]	0.985[f]	–0.003	0.336	7.42
Alcantarilla (AEMET-7228)	0.98	–0.392[d]	1.084[f]	0.001	0.419	9.04
Almoradí (SIAR A-10)	0.97	0.137[d]	0.966[f]	–0.000	0.295	7.35
Beniel (SIAR MU-17)	0.98	–0.353[d]	1.088[f]	–0.005	0.310	7.83
Caravaca (SIAM CR-12)	0.95	0.008[c]	0.998[e]	0.001	0.470	11.51
Cehegín (SIAM CR-32)	0.98	–0.273[d]	1.067[e]	–0.001	0.369	9.02
Hellín (SIAR AB-04)	0.98	–0.029[c]	1.008[e]	0.000	0.331	8.48
Murcia (AEMET-7118I)	0.98	–0.330[d]	1.090[f]	0.089	0.417	8.78
San Cayetano (SIAM-TP73)	0.95	–0.336[d]	1.082[f]	0.000	0.474	11.66
Totana (SIAR MU-02)	0.98	0.106[d]	0.975[f]	0.000	0.300	7.06
Yecla (AEMET-7275B)	0.97	0.535[d]	0.899[f]	0.001	0.478	10.79
All stations	0.96 ± 0.01	0.09 ± 0.36	0.98 ± 0.09	0.01 ± 0.03	0.41 ± 0.10	9.6 ± 2.1

R^2: coefficient of determination of the simple linear regression y: $a + bx$, where a is the intercept and b the regression slope. MBE: mean bias error. RMSE: root mean square error. RE: relative error. [c,e]: no significantly different than 0 and 1 ($\alpha = 0.95$), respectively. [d,f]: significantly different than 0 and 1 ($\alpha = 0.95$), respectively.

PM method. High coefficients of determination ($R^2 >$ 0.95) again confirmed the high correlation between both ET_o methods. The global local calibration led the slope of the regression to be quite close to the unit in all the stations, correcting the systematic underestimation of $ET_{o,HG}$. In this case, the regression slopes were not statistically different than 1 (T-test, $\alpha = 0.95$) for most AWSs. Moreover, the underestimation in the monthly evolution of the $ET_{o,HG}$ disappeared in winter and was reduced in summer, as can be observed when depicting the monthly evolution of $ET_{o,HGg}$ (Fig. 3).

The comparison between $ET_{o,HGg}$ and $ET_{o,PM}$ for Murcia and Alcantarilla AWSs (Fig. 2) evidenced an improvement in the estimations with respect to $ET_{o,HG}$, although a slight underestimation for high ET_o rates (summer months) was still observed. The F-test ($\alpha = 95\%$) stated that the regression slopes and intercepts were statistically significantly different than the provided with the original HG equation for both AWSs. Considering the 66 AWSs, the MBE values ranged from –0.031 to 0.089 mm day^{-1}, with a mean of 0.007 ± 0.028 mm day^{-1}, RMSE ranged from 0.285 to 0.615 mm day^{-1}, with a mean of 0.412 ± 0.095 mm day^{-1} and RE ranged from 7.02 to 14.14%, with a mean of 9.61 ± 2.13 %. It should be noted that the RE decreased on average about 51% with respect to $ET_{o,HG}$.

The globally calibrated HG coefficient (C_g) values were higher than the proposed in the original HG equation ($C = 0.0023$) for all the stations with the exception of Almoradí, where it was 0.00227. C_g ranged between 0.00227 and 0.00362, with an average value of 0.00285 ± 0.00035. Fig. 4 shows the spatial variation of C_g in the SRB, calculated from its values at the 66 AWSs and by applying an inverse distance weighting interpolation method (Watson & Philip, 1985). An important regional variation of C_g was observed, with a marked decreasing gradient from the coast to inland, inversely related to the altitude va-

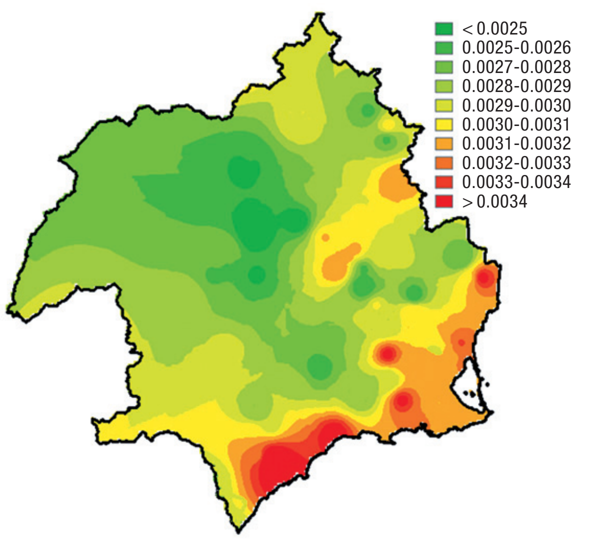

Figure 4. Spatial distribution of the global locally calibrated HG coefficient (C_g) in the Segura River Basin. Average values in the period 2001-2008.

riation in the basin. The highest values were found in the coastal plains and presented increasing values for more southern locations. The lower values corresponded with interior rangelands, and were decreasing with increasing altitude. The wide area with relatively high values in the central part of the basin corresponded with the Segura and Guadalentín rivers valleys, an important area of irrigated agriculture.

Performance of the Hargreaves equation locally calibrated by monthly coefficients

The results of the linear regressions between $ET_{o,HGm}$ and $ET_{o,PM}$, as well as the performance statistics MBE, RMSE, and RE are included in Table 4. As expected, the $ET_{o,HGm}$ values fitted with $ET_{o,PM}$ even better than $ET_{o,HGg}$ in all studied stations. The slope of the regression ranged from 0.99 to 1.01, thus indicating that the slight underestimation observed with $ET_{o,HGg}$ was eventually corrected by the monthly local calibration. The negligible MBE value at all stations confirmed this circumstance. The monthly trend of $ET_{o,HGm}$ and $ET_{o,PM}$ (Fig. 3) also depicted very small differences between them, without any clear systematic error for both winter and summer months. Additionally, the $ET_{o,HGm}$ *versus* $ET_{o,PM}$ relationship for Murcia and Alcantarilla stations (Fig. 2) was very near the straight line 1:1. The F-test ($\alpha = 95\%$) also stated that the regression slopes and intercepts were significantly different than the provided by $ET_{o,HGg}$ for both stations.

The RMSE of $ET_{o,HGm}$ ranged from 0.217 to 0.443 mm day^{-1}, with a mean of 0.338 ± 0.071 mm day^{-1}, and RE ranged from 5.42 to 10.68%, with a mean of $7.71 \pm 1.67\%$. These values entailed an average RE decrease of 61.24% and 19.77% with respect to $ET_{o,HG}$ and $ET_{o,HGg}$, respectively. These results evidence than the monthly local calibration, which was not considered in previous similar studies, performs better than the global local calibration.

The monthly evolution of the average value and the standard deviation for the 66 AWSs of the monthly calibrated HG coefficient ($C_{m,j}$) is displayed in Fig. 5. The average $C_{m,j}$ presented an increasing trend during the spring, reaching its maximum value in July ($C_{m,July} = 0.00312$). Subsequently, it decreased steadily throughout the autumn and showed its minimum value in January ($C_{m,January} = 0.00273$). $C_{m,j}$ pattern was similar to that observed for the average monthly temperature (T_m, secondary axis in Fig. 5), in correspondence with the reported overestimation and underestimation of the HG equation for low and high ET_o rates (Xu & Singh, 2002), since higher $C_{m,j}$ were observed in the hottest months to correct the higher underestimation of the HG equation. It should be noted that all average $C_{m,j}$ values were above 0.0023, indicating again that the original parameterization of the HG equation underestimated it throughout the whole year (Fig. 3). The

Table 4. Statistics (MBE, RMSE and RE) and parameters of the linear regressions between monthly-averaged ET_o calculated with the Penman-Monteith method ($ET_{o,PM}$) and with the Hargreaves equation locally calibrated by monthly coefficients ($ET_{o,HGm}$)

Weather station	R^2	*a* (mm day^{-1})	*b*	MBE (mm day^{-1})	RMSE (mm day^{-1})	RE (%)
Abanilla (SIAM-MO41)	0.96	-0.026^c	1.006^e	0.000	0.410	9.84
Águilas (SIAM-LO31)	0.98	0.005^c	0.999^e	0.000	0.294	6.49
Alcantarilla (AEMET-7228)	0.98	-0.014^c	1.003^e	0.000	0.344	7.41
Almoradí (SIAR A-10)	0.98	-0.023^c	1.006^e	0.000	0.259	6.47
Beniel (SIAR MU-17)	0.99	0.001^c	0.999^e	0.000	0.220	5.55
Caravaca (SIAM CR-12)	0.96	-0.031^c	1.008^e	0.000	0.438	10.66
Cehegín (SIAM CR-32)	0.98	-0.017^c	1.004^e	0.000	0.320	7.82
Hellín (SIAR AB-04)	0.98	-0.001^c	1.000^e	0.000	0.300	7.70
Murcia (AEMET-7118I)	0.98	-0.023^c	1.004^e	0.000	0.331	6.97
San Cayetano (SIAM-TP73)	0.96	0.005^c	0.999^e	0.000	0.431	10.58
Totana (SIAR MU-02)	0.98	-0.027^c	1.006^e	0.000	0.280	6.59
Yecla (AEMET-7275B)	0.97	-0.001^c	1.000^e	0.000	0.358	8.09
All stations	0.97 ± 0.01	0.00 ± 0.01	1.00 ± 0.00	0.00 ± 0.00	0.34 ± 0.07	7.71 ± 1.67

R^2: coefficient of determination of the simple linear regression y: $a + bx$, where a is the intercept and b the regression slope. MBE: mean bias error. RMSE: root mean square error. RE: relative error. ^{c,e}: no significantly different than 0 and 1 ($\alpha = 0.95$), respectively. ^{d,f}: significantly different than 0 and 1 ($\alpha = 0.95$), respectively.

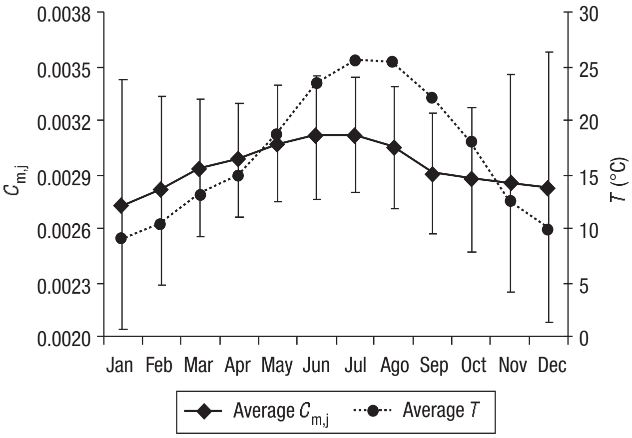

Figure 5. Average monthly locally calibrated HG coefficients ($C_{m,j}$) and the mean air temperature (T) throughout the year at the 66 automatic weather stations (AWSs). Vertical bars represent the standard deviation of $C_{m,j}$. Average values in the period 2001-2008.

link between $C_{m,j}$ and T_m also led to higher variations of $C_{m,j}$ at inland stations than at those located near the coast, due to the moderating effect of the sea. Moreover, the standard deviation of $C_{m,j}$ was higher in winter than in summer, similar again to T_m behaviour.

Regional calibration of the Hargreaves equation

Extrapolation of locally calibrated HG coefficients to the old OWSs location would be possible if a relationship between C_g or $C_{m,j}$ and another parameters measured at those OWSs could be established. Most recent HG coefficient regionalization attempts were proposed by Samani (2000) in USA; Vanderlinden *et al*. (2004) and Gavilán *et al*. (2004) in Andalusia; Lee (2010) in Korea; and Mendicino & Senatore (2013) in southern Italy. These authors found reliable formulations for C_g based on several parameters such as the annual mean of daily temperature ($\overline{T}$), the annual mean of daily temperature range ($\overline{\Delta T}$) or the ratio $\frac{\overline{T}}{\overline{\Delta T}}$, all of them being available at the OWSs.

Bearing in mind the results of these precedent studies, an overall correlation analysis including C_g, $\overline{T}$, $\overline{\Delta T}$, $\frac{\overline{T}}{\overline{\Delta T}}$, and other available parameters at the OWSs, such as elevation and the mean annual precipitation ($\overline{P}$), is shown in Table 5. It can be seen that C_g was highly correlated with some temperature related parameters, such as $\overline{\Delta T}$ and $\frac{\overline{T}}{\overline{\Delta T}}$, whereas the correlation with the other parameters was not statistically significant (p-value > 0.05, α = 95%). An equivalent correlation analysis including $C_{m,j}$; the monthly mean of daily temperature ($\overline{T}_j$); the monthly mean of daily temperature range ($\overline{\Delta T}_i$); $\frac{\overline{T}_j}{\overline{\Delta T}_j}$; the mean monthly precipitation ($\overline{P_j}$); and elevation also confirmed the high

Table 5. Correlation matrix of the variables considered in the regionalization of the globally calibrated HG coefficient. The results are from the 66 modern automatic weather stations (AWSs)

Variable	C_g	Elevation	$\overline{T}$	$\overline{\Delta T}$	$\overline{P}$	$\overline{T}/\overline{\Delta T}$
C_g	1					
p-value	0					
Elevation	–0.17	1				
p-value	0.16	0				
$\overline{T}$	0.18	–0.89	1			
p-value	0.14	< 0.01	0			
$\overline{\Delta T}$	–0.78	0.48	–0.52	1		
p-value	< 0.01	< 0.01	< 0.01	0		
$\overline{P}$	–0.10	0.33	–0.19	0.11	1	
p-value	0.38	0.06	0.20	0.41	0	
$\overline{T}/\overline{\Delta T}$	0.65	–0.64	0.73	–0.93	–0.17	1
p-value	< 0.01	< 0.01	< 0.01	0	0.17	0

C_g: globally calibrated Hargreaves coefficient. $\overline{T}$: mean annual temperature. $\overline{\Delta T}$: mean annual temperature range. $\overline{P}$: mean annual precipitation.

correlation with $\overline{\Delta T_j}$ and $\frac{\overline{T_j}}{\overline{\Delta T_j}}$ at monthly scale. Specifically, the correlations of C_g and $C_{m,j}$ with $\overline{\Delta T}$ and $\overline{\Delta T_j}$, were high in both cases: –0.78 for C_g, and ranging from –0.62 in January to –0.82 in June for $C_{m,j}$. These high correlation values indicated that linear equations would be sufficient to explain most of the regional variability of the HG coefficient. Consequently, the following relationships were found between C_g and $\overline{\Delta T}$, and between $C_{m,j}$ and $\overline{\Delta T_j}$, at each AWS:

$$C_g = a\,\overline{\Delta T} + b \quad [7]$$

$$C_{m,j} = a_j\,\overline{\Delta T_j} + b_j \quad [8]$$

where a, b, a_j and b_j are adjustment parameters and j denotes the month of the year (j = 1,…, 12). Opposite to other authors (Samani, 2000; Vanderlinden *et al*., 2004; Mendicino & Senatore, 2013) quadratic or power functions between C_g and $\overline{\Delta T}$, or between $C_{m,j}$ and $\overline{\Delta T_j}$, did not explain the variability of the HG coefficient significantly better than the linear functions. Fig. 6 graphically represents the relationship between C_g and $\overline{\Delta T}$, along with the regression curves proposed by Samani (2000), Vanderlinden *et al*. (2004) and Mendicino & Senatore (2013). It can be observed that none of the previous proposals fitted properly with C_g in the study region. The relationship proposed by Vanderlinden *et al*. (2004) in Andalusia was the best approximation, as it was expected due to the vicinity of both studied regions, but in any case it showed a satisfactory estimation. This result highlights regional functions for the HG coefficient cannot be extrapolated to other regions, even in their vicinity.

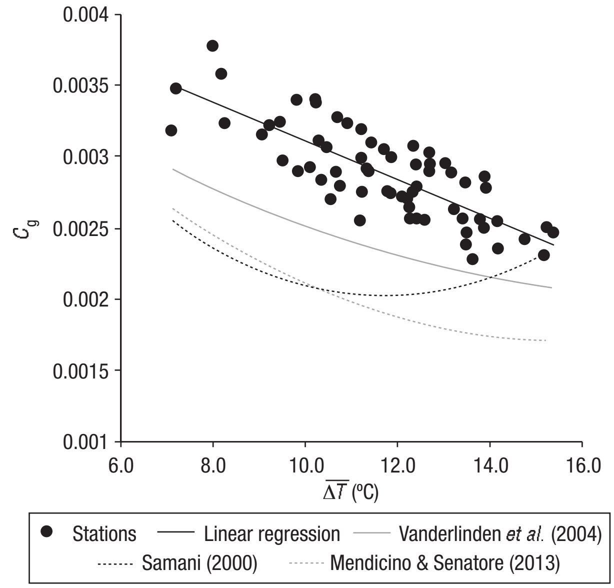

Figure 6. Relationship between the globally calibrated HG coefficient (C_g) and $\overline{\Delta T}$. Other regression curves proposed by Samani (2000), Vanderlinden *et al.* (2004) and Mendicino & Senatore (2013) are also depicted.

Table 6 shows the parameters value, their standard errors, the correlation coefficient and the p-value for Eqs. [7] and [8]. The coefficients a and b for the global regional function were equal to –0.000132 and 0.00442, respectively. Taking into account that only one parameter was considered in Eq. [7], the value of the coefficient of determination (R^2 = 0.61) was slightly

Table 6. Parameters, correlation coefficients, p-values and standard errors for Eqs. [7] and [8]

	p-value	R^2	SE	a or a_j	SE_a	b or b_j	SE_b
Eq. [7] – C_g	< 0.01	0.61	$2.00 \cdot 10^{-4}$	$-1.32 \cdot 10^{-4}$	$1.32 \cdot 10^{-5}$	$4.42 \cdot 10^{-3}$	$1.04 \cdot 10^{-4}$
Eq. [8] – $C_{January}$	< 0.01	0.47	$4.80 \cdot 10^{-4}$	$-2.67 \cdot 10^{-4}$	$3.53 \cdot 10^{-5}$	$6.02 \cdot 10^{-3}$	$3.85 \cdot 10^{-4}$
Eq. [8] – $C_{February}$	< 0.01	0.41	$3.73 \cdot 10^{-4}$	$-1.64 \cdot 10^{-4}$	$2.81 \cdot 10^{-5}$	$5.01 \cdot 10^{-3}$	$3.13 \cdot 10^{-4}$
Eq. [8] – C_{March}	< 0.01	0.41	$2.83 \cdot 10^{-4}$	$-1.36 \cdot 10^{-4}$	$2.06 \cdot 10^{-5}$	$4.56 \cdot 10^{-3}$	$2.44 \cdot 10^{-4}$
Eq. [8] – C_{April}	< 0.01	0.56	$2.06 \cdot 10^{-4}$	$-1.28 \cdot 10^{-4}$	$1.43 \cdot 10^{-5}$	$4.37 \cdot 10^{-3}$	$1.70 \cdot 10^{-4}$
Eq. [8] – C_{May}	< 0.01	0.67	$1.80 \cdot 10^{-4}$	$-1.20 \cdot 10^{-4}$	$1.06 \cdot 10^{-5}$	$4.28 \cdot 10^{-3}$	$1.33 \cdot 10^{-4}$
Eq. [8] – C_{June}	< 0.01	0.67	$1.91 \cdot 10^{-4}$	$-9.55 \cdot 10^{-5}$	$8.45 \cdot 10^{-6}$	$4.18 \cdot 10^{-3}$	$1.17 \cdot 10^{-4}$
Eq. [8] – C_{July}	< 0.01	0.60	$2.02 \cdot 10^{-4}$	$-7.86 \cdot 10^{-5}$	$8.18 \cdot 10^{-6}$	$3.96 \cdot 10^{-3}$	$1.14 \cdot 10^{-4}$
Eq. [8] – C_{August}	< 0.01	0.59	$2.15 \cdot 10^{-4}$	$-9.17 \cdot 10^{-5}$	$9.58 \cdot 10^{-6}$	$4.05 \cdot 10^{-3}$	$1.17 \cdot 10^{-4}$
Eq. [8] – $C_{September}$	< 0.01	0.64	$2.01 \cdot 10^{-4}$	$-1.21 \cdot 10^{-4}$	$1.16 \cdot 10^{-5}$	$4.16 \cdot 10^{-3}$	$1.38 \cdot 10^{-4}$
Eq. [8] – $C_{October}$	< 0.01	0.58	$2.58 \cdot 10^{-4}$	$-1.73 \cdot 10^{-4}$	$1.89 \cdot 10^{-5}$	$4.62 \cdot 10^{-3}$	$2.06 \cdot 10^{-4}$
Eq. [8] – $C_{November}$	< 0.01	0.61	$3.66 \cdot 10^{-4}$	$-2.84 \cdot 10^{-4}$	$2.85 \cdot 10^{-5}$	$5.90 \cdot 10^{-3}$	$2.98 \cdot 10^{-4}$
Eq. [8] – $C_{December}$	< 0.01	0.60	$4.56 \cdot 10^{-4}$	$-3.59 \cdot 10^{-4}$	$3.67 \cdot 10^{-5}$	$6.74 \cdot 10^{-3}$	$3.70 \cdot 10^{-4}$

a, b, a_j and b_j are the adjustment parameters of Eqs. [7] and [8]. SE: standard error of the function. SE_i: standard error of parameter i.

Table 7. Statistics (MBE, RMSE and RE) of the comparison between the monthly-averaged ET_o calculated with the Penman-Monteith method ($ET_{o,PM}$) and the obtained with the proposed regional functions (Eqs. [7] and [8])

Weather station	Global regional function (Eq. [7])			Montly regional functions (Eq. [8])		
	MBE (mm day^{-1})	RMSE (mm day^{-1})	RE (%)	MBE (mm day^{-1})	RMSE (mm day^{-1})	RE (%)
Abanilla (SIAM-MO41)	0.095	0.501	12.05	0.077	0.439	10.50
Águilas (SIAM-LO31)	0.415	0.568	12.54	0.299	0.433	10.26
Alcantarilla (AEMET-7228)	0.253	0.661	14.26	0.187	0.490	10.41
Almoradí (SIAR A-10)	–0.121	0.386	9.62	–0.090	0.359	8.47
Beniel (SIAR MU-17)	–0.176	0.411	10.32	–0.096	0.276	7.15
Caravaca (SIAM CR-12)	–0.269	0.610	15.02	0.202	0.487	11.28
Cehegín (SIAM CR-32)	–0.224	0.525	12.83	–0.169	0.420	10.63
Hellín (SIAR AB-04)	–0.361	0.534	13.72	–0.134	0.365	8.82
Murcia (AEMET-7118I)	0.377	0.727	14.28	0.156	0.494	9.71
San Cayetano (SIAM-TP73)	–0.229	0.546	13.41	–0.111	0.511	12.38
Totana (SIAR MU-02)	–0.090	0.422	9.85	–0.123	0.360	7.89
Yecla (AEMET-7275B)	0.101	0.425	12.09	0.121	0.408	10.40
Averaged values	0.02 ± 0.26	0.52 ± 0.11	12.5 ± 1.9	0.03 ± 0.16	0.42 ± 0.07	10.11 ± 1.50

MBE: mean bias error. RMSE: root mean square error. RE: relative error.

high in comparison with the aforementioned precedent regionalization attempts, probably due to the smaller size and uniform climatology in the study area.

The slopes of the monthly regional functions, a_j, decreased from January ($a_{January}$ = –0.000267) to July (a_{July} = –0.000095), following an opposite behavior than the solar radiation. The interception, b_j, showed a similar trend, with the maximum value in December ($b_{December}$ = 0.00674) and the minimum in July (b_{July} 0.00396). The coefficient of determination presented similar values than for C_g throughout the year, with the exception of the winter months (January to March), when it presented lower values (0.41 to 0.47).

The regional estimation of the HG coefficient by means of a global regional function or monthly regional functions were validated by comparison with $ET_{o,PM}$ at the twelve selected AWSs using cross-validation. Table 7 shows the statistics (MBE, RMSE, and RE) for both the global (Eq. [7]) and the monthly (Eq. [8]) regional functions. Fig. 7 compares the RE value after both regionalization approaches with the original parameterization of the HG equation ($ET_{o,HG}$) and with the local calibrations ($ET_{o,HGg}$ and $ET_{o,HGm}$). The global regional function for the HG coefficient performed better than $ET_{o,HG}$, reaching lower values of MBE, RMSE and RE at the twelve AWSs. The average RE value achieved was 12.5%, leading to a reduction of the error with respect the $ET_{o,HG}$ of 36.9%. The average RE increased only a 30.2% with respect to the global local calibrations ($ET_{o,HGg}$).

The monthly regional functions for the HG coefficient performed even better than the global regional function, improving the results for the twelve AWSs. The average RE value achieved was 10.1%, leading to a reduction of 48.9% with respect to $ET_{o,HG}$, and to a rise of 31.2% with respect to $ET_{o,HGm}$. Moreover, the monthly regional functions performed better than the global local calibration of the HG coefficient at two location (Abanilla and Beniel), showing similar average RMSE and RE values. This circumstance is specially relevant for our study, as this implies that the regionalization by monthly regional functions can perform almost as well as a global local calibration, which usually was the followed approach in previous regionalization attempts.

Finally, long-term series of ET_o were estimated at the OWSs by combining Eqs. [2] and [8], since it clearly performed better than Eq. [7]. As an illustration for this practical application, Fig. 8 shows the historical series of monthly-averaged ET_o at the Mula-Embalse de la Cierva OWS. The series extends throughout the period 1933-2008 with the only noteworthy discontinuity being caused by the Spanish Civil War (1936-1939).

Discussion

The application of the original parameterization of the Hargreaves (HG) equation at 66 modern automatic

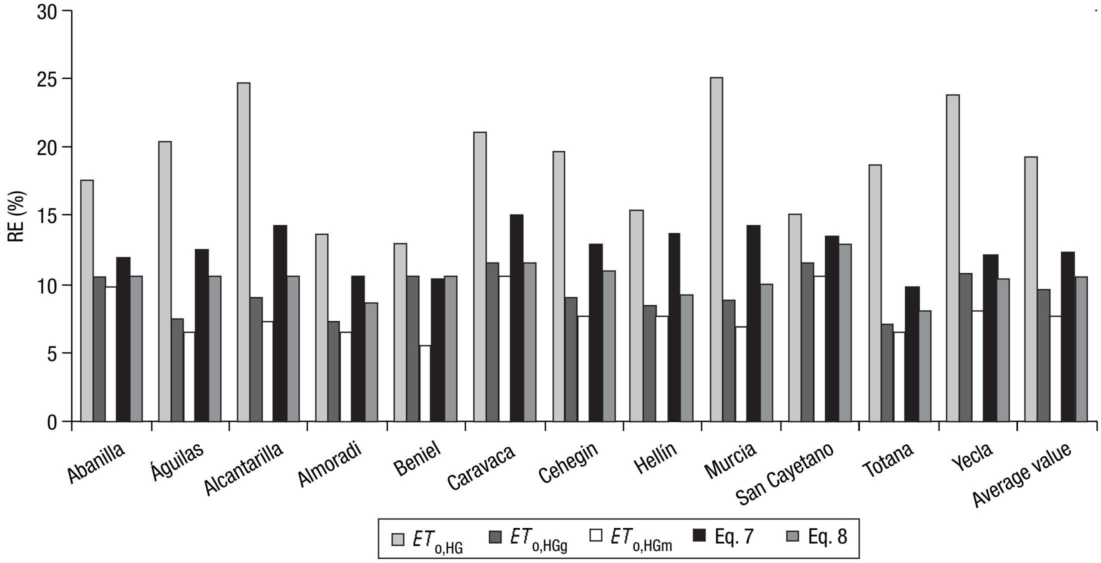

Figure 7. Comparison of the relative error (RE) in ET_o estimations according to different HG coefficient calculation approaches. $ET_{o,HG}$ corresponds to the original HG parameterization; $ET_{o,HGg}$ to the global local calibration of the HG coefficient; $ET_{o,HGm}$ to the monthly local calibration of the HG coefficient; Eq. [7] to the global regional function for the HG coefficient; and Eq. [8] to the monthly regional functions for the HG coefficient. The results are at the considered 12 modern automatic weather stations (AWSs).

weather stations (AWSs) of the Segura River Basin (SRB) resulted in a systematic underestimation of ET_o (average RE = 19.78%), as indicated by linear regressions and error analyses results obtained when comparing ET_o estimates ($ET_{o,HG}$) against those provided by the Penman-Monteith method ($ET_{o,PM}$). This result is in agreement with previous studies carried out in other arid and semiarid regions (Saeed, 1986; Hargreaves & Allen, 2003). Therefore, calibration of the HG coefficient is widely required in the study area.

The local calibration at each AWS by a global coefficient allowed estimating ET_o values ($ET_{o,HGg}$) very close to $ET_{o,PM}$ (average RE = 9.61%). This statistic represents a higher improvement than the observed by Vanderlinden *et al.* (2004) in Andalusia, where a similar calibration process was followed. The spatial variation of C_g in the SRB is in agreement with the results for other Mediterranean regions like Andalusia (Vanderlinden *et al.*, 2004) and southern Italy (Mendicino & Senatore, 2013), where significantly higher C_g values were found at coastal than at inland stations. This coastal effect was related with the habitual windier conditions at coastal locations (Vanderlinden *et al.*, 2004; Gavilán *et al.*, 2006), which usually produces systematic underestimations of HG equation (Martínez-Cob & Tejero-Juste, 2004; Shahidian *et al.*, 2013).

The local calibration with monthly coefficients ($ET_{o,HGa}$) resulted in even better estimations than those

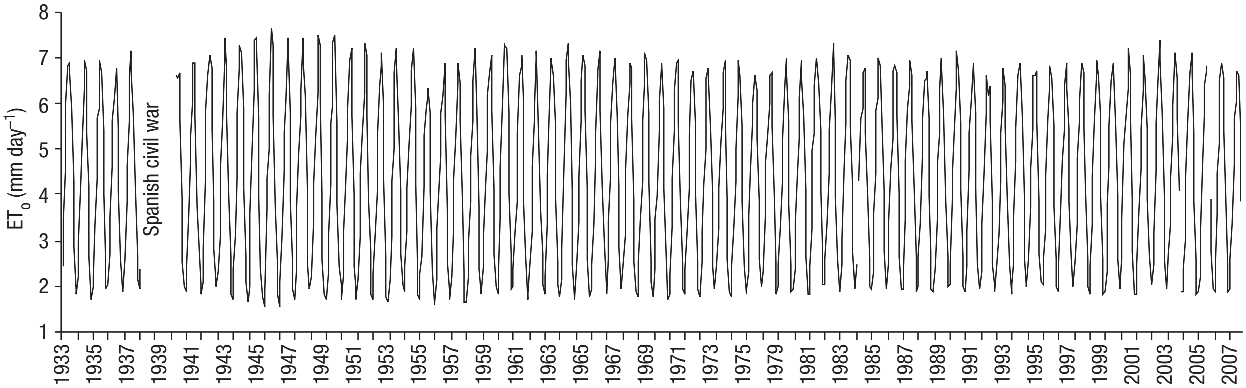

Figure 8. PLong-term series of monthly-averaged ET_o at the Mula-Embalse de la Cierva ordinary weather stations in the period 1933-2008.

obtained by the global coefficient (average RE = 7.71%), which meant an excellent behaviour, bearing in mind that only air temperature data were used. This satisfactory result was in accordance with previous attempts at locally calibrating the HG equation (*e.g.,* ASCE, 1996; Jensen *et al*., 1997; Itenfisu *et al*., 2003; Jabloun & Sahli, 2008; Sentelhas *et al*., 2010; Cobaner, 2011; Espadafor *et al.*, 2011). The annual pattern of $C_{m,j}$ agrees with that reported by Shahidian *et al.* (2013) in California, a location with similar climate to the SRB, and where a parabolic function was fitted to the $C_{m,j}$ annual trend.

In spite of those ET_o accurate estimates, the local calibration were not enough for the purpose of this study, which entailed the estimation of ET_o long-term series from historical temperature data in a set of old OWSs, which were placed in different locations that the AWSs. In that sense, two approaches for the regional estimation of the HG coefficient based on global and monthly regional functions were tested. Both methods were established in relation with the annual and the monthly means of daily temperature range, respectively, since they were highly correlated parameters with C_g and $C_{m,j}$. Contrary to other authors (Droogers & Allen, 2002) a good fitting with rainfall was not found, probably due to its high seasonal and inter-annual variability within the studied area. It should be noted that, in agreement with the results by Martínez-Cob & Tejero-Juste (2004) and Gavilán *et al*. (2006) in other semi-arid Spanish regions, a significant correlation was also found with wind speed, but it was not considered in the regionalization process because of the OWSs did not record such information.

Linear functions for global (Eq. [7]) and monthly (Eq. [8]) regional functions were used since, opposite to other authors (Samani, 2000; Vanderlinden *et al*., 2004; Mendicino & Senatore, 2013), quadratic or power functions did not provide significant correlation improvement. Other regional functions proposed in previous regionalization attempts systematically underestimated HG coefficient, even though some of them had been previously proposed for very nearby regions. This result could be ascribed to two main reasons: (i) the higher aridity of the study area with respect to the regions where the other regionalization attempts were developed, and (ii) the data treatment, since our study managed monthly-averaged weather data instead of daily data. However, the monthly data treatment did not affect the quality of the estimations after the regionalization of the HG coefficient, which was similar to that obtained in the aforementioned attempts.

The assessment of the regionalization process by cross validation clearly provided better ET_o estimations for the monthly (Eq. [8]) than for the global (Eq. [7]) regional function (average REs were 10.1 and 12.5% respectively). Moreover, the quality of the ET_o estimations provided by the monthly regional functions was only slightly lower than the obtained with the global local calibration, which can be considered a very satisfactory performance. Therefore, although both approaches for the regionalization of the HG coefficient allowed estimating ET_o values close to those obtained with the PM method (Table 7), the use of the monthly approach is highly recommended in the SRB as it clearly performed better than the global one.

In conclusion, this study demonstrates that the HG coefficient presents a great spatial variability throughout the SRB, which mainly depends on temperature related parameters. Eqs. [7] and [8] can be used as an approximation to estimate global or monthly HG coefficient, respectively, at stations in the SRB where only minimum and maximum temperature data are available, which hence can be incorporated into the HG equation to estimate long-term series of monthly ET_o. The proposed methodology appears the most straightforward and can be extended to other regions and climates, provided that the regional functions for calculating the HG coefficient are available. Therefore, the consideration of a regionally calibrated version of the HG equation is encouraged for the calculation of long-term series of ET_o when a full dataset of air temperature, relative humidity, wind speed and solar radiation is not provided.

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