Calibration of the Hargreaves–Samani method for the calculation of reference evapotranspiration in different Köppen climate classes

Javier Almorox and Jürgen Grieser

ABSTRACT

The Penman–Monteith equation (FAO-56) is accepted as the standard model for estimating reference evapotranspiration (ETo). However, the major obstacle to using FAO-56 widely is that it requires numerous climatic data. The Hargreaves–Samani (HS) method is frequently used for the calculation of ETo since it is based on measurements of daily minimum and maximum air temperature alone. Those are commonly recorded at many meteorological stations throughout the world. It is the objective of this paper to evaluate the quality of HS and calibrate the coefficients of this method for different climates as represented by the Köppen classification. Estimated values are compared with Penman–Monteith ETo values in terms of the coefficient of efficiency C_{eff} as well as the root mean square error, the mean absolute error and the Bayes information criterion. The Penman–Monteith equation for ETo (FAO-56) is based on physics and known to provide best estimates of ETo. The results of our work show that the correlation between long-term monthly means of HS and FAO-56 can be improved significantly by introducing climate-class specific coefficients.

Key words | FAO-56 Penman–Monteith, Hargreaves–Samani, Köppen classification, recalibrated equations, reference evapotranspiration

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INTRODUCTION

Evapotranspiration (ET) from the Earth's surface is the driver of the global atmospheric water cycle. Accurate irrigation water requirement estimations are crucial for efficient management and planning of water resources and therefore the estimation of reference evapotranspiration (ETo) is important for irrigation management. The knowledge of monthly ET is of great importance in the study and management of present and future water resources and for solving many theoretical problems in the field of hydrology, climatology and geographical ecology. As an agroclimatic index, long-term monthly means of ETo have been widely used to assess the effect of water in agronomy, irrigation planning as well as climate change impact.

Many estimation methods based on meteorological variables have been developed. Numerous formulations, classified as radiation based, temperature based, pan-evaporation based, mass-transfer based as well as combinations of those have been developed (Jensen *et al.* 1990).

The FAO-56 Penman–Monteith (hereafter FAO-56) equation is recommended as the standard model for estimating ETo (Allen *et al.* 1998) in all climates. Many researchers have confirmed that FAO-56 is superior to other estimation methods (Hargreaves & Allen 2003; Berengena & Gavilán 2005; Sentelhas *et al.* 2010; Tabari & Talaee 2011; Rahimikhoob *et al.* 2012; Maestre-Valero *et al.* 2013; Tabari *et al.* 2013; Valiantzas 2013). Due to the absence of experimental records, data-driven models are often calibrated to calculate FAO-56 ETo targets. This procedure is also adopted for calibrating more conventional empirical approaches (Marti *et al.* 2015).

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FAO-56 is of the best quality since it models evaporation based on physics. This is possible only if daily minimum and maximum temperature, humidity, wind speed and sunshine duration are known. However, observations of these variables are often not available. This is the major obstacle to using FAO-56 widely.

Among many other methods, the Hargreaves–Samani (HS) equation, which employs only maximum and minimum temperature data, can be used to approximate ETo. This empirical model is one of the most commonly used. It is recommended by Allen *et al.* (1998) and again by Allen (2006) as the best approximation to FAO-56. As an empirical method, HS involves empirical coefficients. While HS can be applied with some standard values of these coefficients, several authors (Allen *et al.* 1998) recommended calibrating HS with respect to FAO-56 at locations with comparable climate.

Samani (2000) found that factors other than solar radiation, wind speed and humidity can influence local observations of the difference in maximum and minimum temperature and thus the results of HS. These factors include latitude, elevation, topography, storm pattern, advection and proximity to large water bodies. At low latitudes, for example, the diurnal temperature range can become very small and, consequently, HS can significantly underestimate both solar radiation and ET.

Several attempts to improve the accuracy of HS have been made, mainly by using wind speed, elevation, precipitation, distance to coastline, air humidity or solar radiation data (Shahidian *et al.* 2013). However, it is not desirable to use these climatic variables directly in the HS equation because this would take away the ease of implementation and simplicity of the model.

HS modifications in the literature include modifying the original calibration coefficients by a linear regression with or without a constant term. Some authors include more variables that could be fit to observations or FAO-56 (Allen *et al.* 1998; Droogers & Allen 2002; Trajkovic 2007; Tabari & Talaee 2011; Razzaghi & Sepaskhah 2012; Mohawesh & Talozi 2012; Ngongondo *et al.* 2013; Raziei & Pereira 2013; Heydari & Heydari 2014). According to Alexandris *et al.* (2006), HS is often unable to capture the effect of some important climatic variables. Some authors have found overestimations of ET by HS under humid environments and underestimation under windy conditions, compared to the Penman–Monteith equation (Allen *et al.* 1998; Droogers & Allen 2002). Hargreaves & Allen (2003) have shown that the HS ET estimation differences are caused primarily by impacts of local humidity on the computed vapor pressure deficit.

HS performed better in semi-arid and arid regions (López-Urrea *et al.* 2006), while it performed poorly in humid climates (Yoder *et al.* 2005; Wang *et al.* 2014). In this regard, the performance of the HS model and its calibration have been widely assessed in different climatic zones. The study was carried out using a monthly timescale and FAO-56 benchmarks.

The main objective of the present study is the evaluation of the HS global performance for all climate zones and the fit of a calibrated Hargreaves equation (HSc) for different climate conditions. The goal is to provide optimized versions of the Hargreaves formulation for each individual Köppen class as an alternative to FAO-56 when only maximum and minimum daily temperatures are available.

MATERIALS AND METHODS

Global climate data set

The models are applied using the climate database from the Agromet Group of United Nations Food and Agriculture Organization (FAO). The data set of long-term monthly means can be downloaded together with the interpolation tool New_LocClim from http://www.fao.org/nr/climpag/. Monthly mean values are available for 4,368 stations worldwide. Table 1 shows how the stations are distributed among the continents.

This data set is considered to be an excellent source of information to compare different ET estimates for different climate zones.

Table 1 | Number of stations per continent within the FAO Agromet database

Continent	No. of stations
Africa	1,042
America	1,026
Asia	1,254
Europe	764
Oceania	282

Köppen climate classification

Climate classifications are introduced to organize large amounts of climatic information and provide a concise description. A widely accepted system of climate classification is summarized by Köppen (1936). Recently updated world maps are available (Kottek *et al.* 2006; Peel *et al.* 2007). Although introduced in the nineteenth century, the Köppen classification was published in substantially its present form in 1918. It is still the most widely used since it reflects natural vegetation as an expression of climate. This climate–vegetation association provides a relation between a multivariate description of climate and an easily visualized landscape.

The Köppen classification identifies five main groups of climates: tropical climates (A), dry climates (B), temperate climates (C), boreal climates (D) and polar climates (E). All these main groups are further divided by Köppen in order to better classify sub-climates. In this paper we use the Köppen classes as provided in Table 2.

The Köppen system of climate classification was found to be particularly suitable for disaggregating the correlations between FAO-56 and HS because it is a system with global applicability and is still the most widely used since it only depends on temperature and precipitation (De Pauw 2008). Figure 1 shows the number of stations of the FAO climate database for each of the sub-climate types considered. Data are available for 12 calendar months per station. Hence the analysis is based on 52,416 data pairs.

Table 2 | Köppen classes used in this paper

Class	Definition
Af	Equatorial full humid rainforest
As	Equatorial savannah with dry summer
Aw	Equatorial savannah with dry winter
BS	Steppe climate
BW	Desert climate
Cs	Warm temperate climate with dry summer
Cw	Warm temperate climate with dry winter
Cf	Warm temperate fully humid climate
Ds	Snow climate with dry summer
Dw	Snow climate with dry winter
Df	Snow climate
E	Polar climate

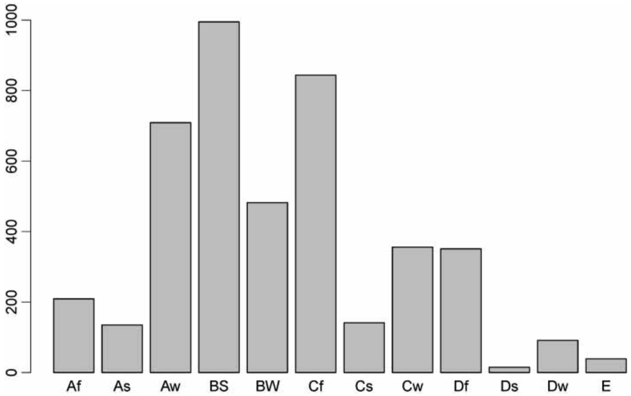

Figure 1 | Number of stations in the FAO Agromet database per Köppen climate class.

FAO-56 Penman–Monteith ETo

ETo is defined in Allen *et al.* (1998) as the rate of ET from a hypothetical grass reference with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s m^{-1} implies a moderately dry soil surface resulting from about a weekly irrigation frequency. Standardized parameterizations of the FAO-56 formulation are described for calculating ET for grass and alfalfa references. The ETo, despite some shortcomings, can be a consistent and reproducible index for a weather-based potential ET. ETo computed using a short crop reference is abbreviated as ETo (Allen 2006). The variables used in the computation of ETo are net radiation, wind speed, air humidity and temperature. As the ETo computation is always made for the same reference surface, the crop type, stage of development and soil moisture do not change and cannot affect the ETo formulation. FAO-56 ETo is computed as (Allen *et al.* 1998; Allen 2006):

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{Cn}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + Cd \cdot u_2)} \tag{1}$$

with the ETo (mm day^{-1}), the slope of the saturation vapor pressure Δ (kPa $^{\circ}\mathrm{C}^{-1}$), the net radiation R_n (MJ m^{-2} day^{-1}), the soil heat flux density G, for monthly periods it is not 0 and was computed from surface temperature of previous and next month (MJ m^{-2} day^{1}), the mean daily air temperature T at 2 m height in (°C), the short grass reference coefficients $C_n = 900$ and $C_d = 0.34$, the wind speed at 2 m height u_2 (m s^{-1}), the saturation vapor pressure e_s (kPa), the actual vapor pressure e_a (kPa) and the psychrometric constant γ (kPa °C^{-1}). The net radiation is the sum of the net short-wave radiation and the net long-wave radiation.

HS method

The empirical HS method (Hargreaves & Samani 1982, 1985) is given as:

$$\mathrm{ET_{HS}} = 0.0135 \cdot k_{RS} \cdot (Tm + 17.8) \cdot (Tx - Tn)^{0.5} \cdot 0.408 \cdot R_a \quad (2)$$

where $\mathrm{ET_{HS}}$ is the evapotranspiration estimated by the HS method (mm day^{-1}), R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}), k_{RS} is an empirical coefficient, T_m is the mean air temperature (°C), T_x is the daily maximum air temperature (°C) and T_n is the daily minimum air temperature (°C). The setoff of 17.8 °C sets $\mathrm{ET_{HS}} = 0$ for $T_m = -17.8$ °C which corresponds to 0 Fahrenheit. For $T_m < -17.8$ °C $\mathrm{ET_{HS}}$ is kept at 0. The factor 0.408 converts MJ m^{-2} day^{-1} into mm day^{-1}. 0.0135 is the original empirical coefficient proposed by Hargreaves & Samani (1985).

The empirical coefficient k_{RS}, was initially fixed at 0.17 for arid and semi-arid regions. Hargreaves (1994) recommended using 0.16 for inland areas and 0.19 for coastal regions. With R_a in mm day^{-1} and $k_{RS} = 0.17$ this leads to:

$$\mathrm{ET_{HS}} = 0.0023 \cdot (Tm + 17.8) \cdot (Tx - Tn)^{0.5} \cdot R_a. \quad (3)$$

The equation is based on the assumption that the difference between daily maximum and minimum temperatures provides a general indication of cloudiness. HS modifications in the literature include modifying the original empirical coefficients.

Modified HS equations

For the purpose of this work, HS is re-written in the general form:

$$\mathrm{ET_{HS}} = k_1 \cdot (Tm + 17.8) \cdot (Tx - Tn)^{k_2} \cdot R_a + k_3 \quad (4)$$

where k_1, k_2 and k_3 are calibration coefficients, with original, un-calibrated values of $k_1 = 0.0023$, $k_2 = 0.5$ and $k_3 = 0$. For an optimization all three coefficients can be fit. Alternatively, one or two of them can be fixed at their given value while the other coefficients can be optimized.

In this study we compare the five different versions:

$$\mathrm{ET_{HS1}} = k_1 \cdot (Tm + 17.8) \cdot (Tx - Tn)^{0.5} \cdot R_a \quad (5)$$

$$\mathrm{ET_{HS2}} = 0.0023 \cdot (Tm + 17.8) \cdot (Tx - Tn)^{k_2} \cdot R_a \quad (6)$$

$$\mathrm{ET_{HS3}} = k_1 \cdot (Tm + 17.8) \cdot (Tx - Tn)^{k_2} \cdot R_a \quad (7)$$

$$\mathrm{ET_{HS4}} = k_1 \cdot (Tm + 17.8) \cdot (Tx - Tn)^{0.5} \cdot R_a + k_3 \quad (8)$$

$$\mathrm{ET_{HS5}} = k_1 \cdot (Tm + 17.8) \cdot (Tx - Tn)^{k_2} \cdot R_a + k_3 \quad (9)$$

Statistical analysis

In order to quantify the performance of the different versions we use four measures. Those are the root mean square error (RMSE), the mean absolute error (MAE), the coefficient of efficiency (C_{eff}) and the Bayes information criterion (BIC). They are given as:

$$Ceff = 1.0 - \frac{\sum_{i=1}^{n} (ETm - ETc)^2}{\sum_{i=1}^{n} (ETm - ETav)^2} \quad \text{unitless} \quad (10)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (ETm - ETc)^2} \quad \mathrm{mm \cdot day^{-1}} \quad (11)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} (|ETm - ETc|) \quad \mathrm{mm \cdot day^{-1}} \quad (12)$$

$$BIC = n \ln RMSE^2 + k \ln n \quad \text{unitless} \quad (13)$$

where ET_m is the ETo estimate from FAO-56, ET_c is the reference evapotranspiration $\mathrm{ET_{HSc}}$ estimate from the respectively corrected HS equation, ET_{av} is the mean of the FAO-56 ET for the respective climate class, n is the number of data pairs used and k is the number of free coefficients of the model.

Legates & McCabe (1999) suggested using the coefficient of efficiency for evaluating the goodness of fit. C_{eff} ranges from minus infinity to 1.0 with larger values indicating better agreement. The coefficient of efficiency is recommended by several authors to evaluate the performance of a model. Moriasi *et al.* (2007) classified model performance as very good if $C_{\mathrm{eff}} > 0.75$, good if $0.65 < C_{\mathrm{eff}} \leq 0.75$, satisfactory if $0.50 < C_{\mathrm{eff}} \leq 0.65$ and poor if $C_{\mathrm{eff}} \leq 0.50$.

In this work the coefficient of efficiency is used in conjunction with the RMSE and MAE. The RMSE is one of the commonly used error indices. Willmott & Matsuura (2005) indicate that MAE is the most natural measure of average error magnitude.

While RMSE, MAE and C_{eff} provide information on the quality of ET_{HSc}, BIC (Schwarz 1978; Beal 2007) is especially useful for model selection since it penalizes models with a higher degree of freedom, i.e., more free coefficients. Usually models with the lowest BIC are preferred, according to the parsimony principle.

RESULTS AND DISCUSSION

Köppen climate class, ETo by FAO-56, HS and the five versions of ET_{HSc} are calculated for the 4,368 stations of the FAO Agromet global climate database. All stations are grouped by the 12 Köppen climate classes considered. The five calibrated ET_{HSc} equations are optimized with respect to FAO-56 for each Köppen climate class separately.

The results of the best fit of the different ET_{HSc} versions are provided in Table 3. It shows the RMSE, the MAE, the coefficient of efficiency (C_{eff}) and the BIC value and the best estimates of k_1, k_2, k_3 for different Köppen climate zones and each ET_{HSc}.

Both MAE and RMSE are lowest for ET_{HS5} (sometimes together with ET_{HS3} or ET_{HS4}). Improvements compared to the original HS method in MAE and RMSE are in the order of 20 to 50% for all three Köppen A classes. For other climate classes improvements are in the order of 10 to 40%.

In the ET_{HS5} model, the highest errors are observed in the dry B classes with RMSE $(ET_{HS5}) = 1.211$ mm day^{-1} for climate class BW (desert) followed by the class BS with RMSE $(ET_{HS5}) = 0.881$ mm day^{-1}. The lowest errors are observed in the class Ds with RMSE $(ET_{HS5}) = 0.327$ mm day^{-1} followed by the E climates with RMSE $(ET_{HS5}) = 0.378$ mm day^{-1}.

Mean ETo per climate class ranges from 1.91 mm day^{-1} in polar climates to 5.13 mm day^{-1} in deserts. Given this wide range of more than factor 2.5 in mean ETo it is reasonable to look at a relative MAE, defined as MAE over ET_{av} per climate class. Figure 2 shows these relative values of MAE. For ET_{HS5} highest relative MAE occurs in Df climates with 18.7% of the mean ETo followed by BW with 17.9%. The lowest MAE with respect to mean ETo occurs in climate class Af with 9%, followed by Ds with 10.1% and As with 11%. These ratios are considerably higher for the original HS method. Since HS was originally calibrated for semi-arid climates no substantial improvements are achieved for the BS climate class.

The results of statistical indices obtained are similar to the ranges obtained by Gavilán *et al.* (2006), Tabari & Talaee (2011) and Shahidian *et al.* (2013). For all climate classes, C_{eff} values of ET_{HS5} are highest, indicating that this calibrated version performs best. For A climates C_{eff} is below 0.5 for all versions, i.e., all versions perform poorly. This indicates that the proxy $(T_x - T_n)^{k2}$ is not optimal for the estimation of ETo in tropical climates. C_{eff} is 0.714 for ET_{HS5} and climate class Cw meaning that HS5 performs well for this climate. For all other climate classes ET_{HS5} performs very well with C_{eff} values larger than 0.75 (Figure 3).

Since ET_{HS5} fits three free coefficients and therefore has more degrees of freedom than all other ET_{HSc} versions, it is also important to look at BIC. BIC values depend on the number of data pairs used. This number is very different for each climate class (Figure 1). For better visualization we therefore standardize all BIC values within each climate class. The resulting values are depicted in Figure 4. In 5 out of 12 climate classes BIC is lowest for ET_{HS5} indicating that the full freedom of three coefficients is not needed in all climate classes. For the climate classes Af, As, BW and Cs the additive constant k_3 leads to no significant improvement. In Cw and E climates the variation of k_2 is less important than the additive constant k_3 while for climate class Ds the major improvement is due to k_2. In these cases, RMSE and MAE of ET_{HS5} are not significantly lower than for ones of the other calibrations with less freedom. Including the free coefficient k_3 as an additive constant, however, leads to an unbiased estimate. This is a major advantage of ET_{HS5}.

Table 3 | Performance measures (RMSE, mm day^{-1}, MAE, mm day^{-1}, C_{eff} and BIC) of ET_{HSc} as compared to FAO-56 ET as well as the respective coefficients k_1, k_2, k_3 of the different corrections

Class	Model	RMSE	MAE	C_{eff}	BIC	k_1	k_2	k_3
Af	HS1	0.575	0.451	0	−2,768	**0.002**	*0.5*	
Af	HS2	0.537	0.419	0.129	−3,113	*0.0023*	**0.43222**	
Af	HS3	0.425	0.335	0.453	−4,273	**0.0051**	**0.07193**	
Af	HS4	0.491	0.391	0.271	−3,551	**0.0010**	*0.5*	**1.8778**
Af	HS5	0.425	0.335	0.454	−4,268	**0.0049**	**0.07415**	**0.1289**
Af	HS	0.804	0.663	−0.955	−1,093	*0.0023*	*0.5*	
As	HS1	0.709	0.523	0.104	−1,106	**0.00204**	***0.5***	
As	HS2	0.679	0.496	0.179	−1,247	*0.0023*	**0.44523**	
As	HS3	0.595	0.446	0.369	−1,666	**0.00458**	**0.15343**	
As	HS4	0.649	0.487	0.25	−1,386	**0.00116**	*0.5*	**1.7492**
As	HS5	0.594	0.444	0.371	−1,665	**0.00511**	**0.14317**	**− 0.3678**
As	HS	0.872	0.728	−0.355	−443	*0.0023*	*0.5*	
Aw	HS1	0.74	0.551	0.393	−5,120	**0.00208**	*0.5*	
Aw	HS2	0.726	0.537	0.416	−5,444	*0.0023*	**0.45534**	
Aw	HS3	0.706	0.523	0.448	−5,914	**0.00321**	**0.31546**	
Aw	HS4	0.719	0.54	0.426	−5,584	**0.00163**	*0.5*	**0.9053**
Aw	HS5	0.704	0.523	0.451	−5,954	**0.00283**	**0.33314**	**0.3466**
Aw	HS	0.859	0.702	0.181	−2,578	*0.0023*	*0.5*	
BS	HS1	0.893	0.664	0.764	−2,693	**0.00231**	*0.5*	
BS	HS2	0.893	0.663	0.764	−2,690	*0.0023*	**0.49988**	
BS	HS3	0.883	0.657	0.769	−2,946	**0.00296**	**0.40288**	
BS	HS4	0.886	0.657	0.768	−2,876	**0.00217**	*0.5*	**0.2921**
BS	HS5	0.881	0.654	0.77	−2,997	**0.00272**	**0.42152**	**0.1783**
BS	HS	0.893	0.663	0.764	−2,700	*0.0023*	*0.5*	
BW	HS1	1.22	0.92	0.749	2,312	**0.00262**	*0.5*	
BW	HS2	1.231	0.924	0.744	2,414	*0.0023*	**0.54699**	
BW	HS3	1.211	0.919	0.753	2,235	**0.00338**	**0.4038**	
BW	HS4	1.22	0.92	0.749	2,318	**0.00259**	*0.5*	**0.0719**
BW	HS5	1.211	0.918	0.753	2,237	**0.00354**	**0.39352**	**− 0.1157**
BW	HS	1.394	0.993	0.672	3,842	*0.0023*	*0.5*	
Cf	HS1	0.539	0.403	0.853	−12,499	**0.00212**	*0.5*	
Cf	HS2	0.531	0.396	0.858	−12,805	*0.0023*	**0.46412**	
Cf	HS3	0.516	0.384	0.866	−13,386	**0.00323**	**0.32259**	
Cf	HS4	0.517	0.387	0.865	−13,358	**0.00192**	*0.5*	**0.3199**
Cf	HS5	0.505	0.377	0.871	−13,813	**0.00277**	**0.35817**	**0.2345**
Cf	HS	0.594	0.45	0.822	−10,543	*0.0023*	*0.5*	
Cs	HS1	0.557	0.423	0.863	−1,974	**0.00214**	*0.5*	
Cs	HS2	0.545	0.412	0.868	−2,049	*0.0023*	**0.46837**	
Cs	HS3	0.497	0.376	0.89	−2,350	**0.00413**	**0.23782**	

(*continued*)

Table 3 | continued

Class	Model	RMSE	MAE	C_{eff}	BIC	k_1	k_2	k_3
Cs	HS4	0.543	0.42	0.869	−2,051	**0.00198**	*0.5*	**0.2663**
Cs	HS5	0.497	0.375	0.89	−2,343	**0.00419**	*0.2342*	**− 0.0208**
Cs	HS	0.608	0.471	0.836	−1,683	*0.0023*	*0.5*	
Cw	HS1	0.645	0.476	0.709	−3,740	**0.00210**	*0.5*	
Cw	HS2	0.645	0.476	0.709	−3,736	*0.0023*	**0.46359**	
Cw	HS3	0.645	0.475	0.71	−3,734	**0.00218**	**0.48548**	
Cw	HS4	0.64	0.471	0.714	−3,801	**0.00195**	*0.5*	**0.2863**
Cw	HS5	0.64	0.471	0.714	−3,794	**0.00191**	**0.50728**	**0.2939**
Cw	HS	0.737	0.598	0.62	−2,604	*0.0023*	*0.5*	
Df	HS1	0.474	0.33	0.903	−6,287	**0.00203**	*0.5*	
Df	HS2	0.475	0.33	0.902	−6,256	*0.0023*	**0.45044**	
Df	HS3	0.473	0.331	0.903	−6,292	**0.00174**	**0.56201**	
Df	HS4	0.467	0.322	0.906	−6,407	**0.00195**	*0.5*	**0.1309**
Df	HS5	0.463	0.323	0.907	−6,468	**0.00130**	**0.65944**	**0.1695**
Df	HS	0.559	0.39	0.865	−4,907	*0.0023*	*0.5*	
Ds	HS1	0.331	0.224	0.963	−393	**0.00210**	*0.5*	
Ds	HS2	0.33	0.222	0.963	−394	*0.0023*	**0.46617**	
Ds	HS3	0.329	0.221	0.963	−389	**0.00240**	**0.44976**	
Ds	HS4	0.327	0.216	0.964	−392	**0.00205**	*0.5*	**0.0854**
Ds	HS5	0.327	0.216	0.964	−386	**0.00211**	**0.48956**	**0.08**
Ds	HS	0.419	0.275	0.941	−313	*0.0023*	*0.5*	
Dw	HS1	0.534	0.409	0.873	−1,362	**0.00199**	*0.5*	
Dw	HS2	0.527	0.405	0.876	−1,391	*0.0023*	**0.44041**	
Dw	HS3	0.518	0.403	0.881	−1,424	**0.00358**	**0.26577**	
Dw	HS4	0.48	0.345	0.898	−1,589	**0.00171**	*0.5*	**0.4566**
Dw	HS5	0.464	0.335	0.904	−1,654	**0.00317**	**0.25526**	**0.4441**
Dw	HS	0.667	0.478	0.802	−884	*0.0023*	*0.5*	
E	HS1	0.44	0.346	0.843	−762	**0.00228**	*0.5*	
E	HS2	0.44	0.346	0.843	−763	*0.0023*	**0.49626**	
E	HS3	0.438	0.346	0.844	−760	**0.00256**	**0.45471**	
E	HS4	0.38	0.292	0.883	−894	**0.00188**	*0.5*	**0.4621**
E	HS5	0.378	0.29	0.884	−892	**0.00146**	**0.59181**	**0.5134**
E	HS	0.44	0.347	0.843	−768	*0.0023*	*0.5*	
All	HS1	0.846	0.599	0.785	−1,7548	**0.00223**	*0.5*	
All	HS2	0.845	0.599	0.785	−1,7588	*0.0023*	**0.48657**	
All	HS3	0.845	0.599	0.785	−1,7583	**0.00234**	**0.47934**	
All	HS4	0.844	0.595	0.786	−1,7743	**0.00216**	*0.5*	**0.1272**
All	HS5	0.844	0.595	0.786	−1,7734	**0.00219**	**0.49465**	**0.1214**
All	HS	0.855	0.625	0.78	−16,366	*0.0023*	*0.5*	

Best fit coefficients are in bold font while default values are in italics.

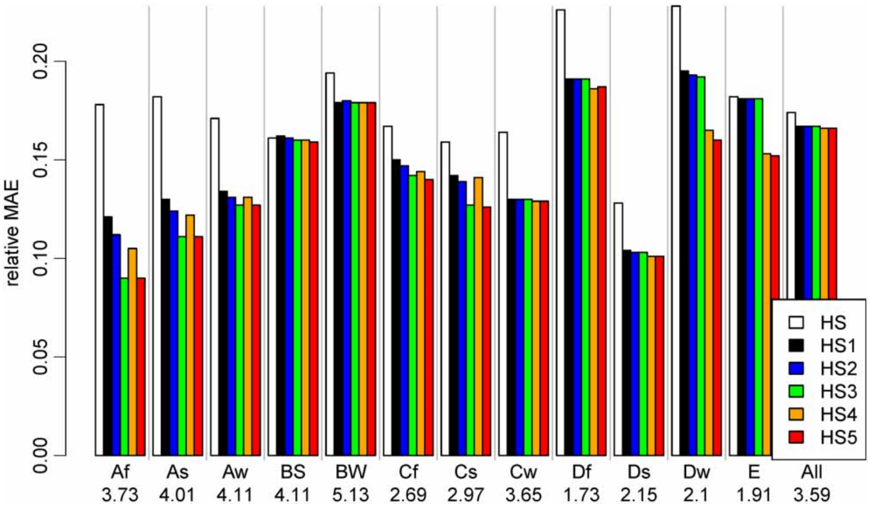

Figure 2 | Relative MAE (MAE over mean ETo per climate class) of HS and various calibrations of HS. Values of mean ETo per climate class in mm day^{-1} are provided as well.

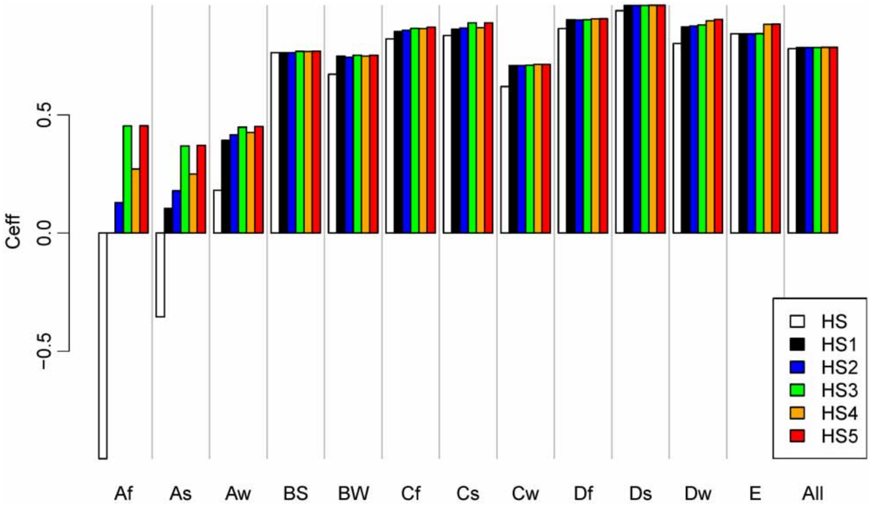

Figure 3 | Coefficient of efficiency (C_{eff}) of HS and various calibrations of HS.

Table 3 also presents the coefficients of the calibrated Hargreaves method by Köppen class. It can be seen that the regression coefficients vary widely by Köppen class indicating the importance of optimized coefficients.

The best estimate of the exponent k_2 depends strongly on the climate class. Its original value in the Hargreaves approach is 0.5. If all data are used the best fit is $k_2 = 0.495$ confirming that 0.5 is a good choice in general. However, for A climates much lower best-fit values are obtained, ranging from 0.074 for Af over 0.143 for As to 0.333 for Aw climates. This reflects the relatively weak dependence of ET on the daily temperature range $(T_x - T_n)$ in tropical climates. The good performance of $\mathrm{ET}_{\mathrm{HS3}}$ in these cases indicates that the inappropriately high value of $k_2 = 0.5$ in the original Hargreaves method is the major source of the relatively large errors for A climates. For E and Df climates best estimates of k_2 reach 0.592 and 0.659, respectively, and are therefore considerably higher than the original value of 0.5.

Although BIC values do not indicate that $\mathrm{ET}_{\mathrm{HS5}}$ is superior to simpler models in each climate class, we suggest this model for all climate classes with the best-fit coefficient values obtained from our analysis. Aside from providing the lowest estimation error (RMSE and MAE) and the best C_{eff}, this allows for one generalized formulation for all climate classes.

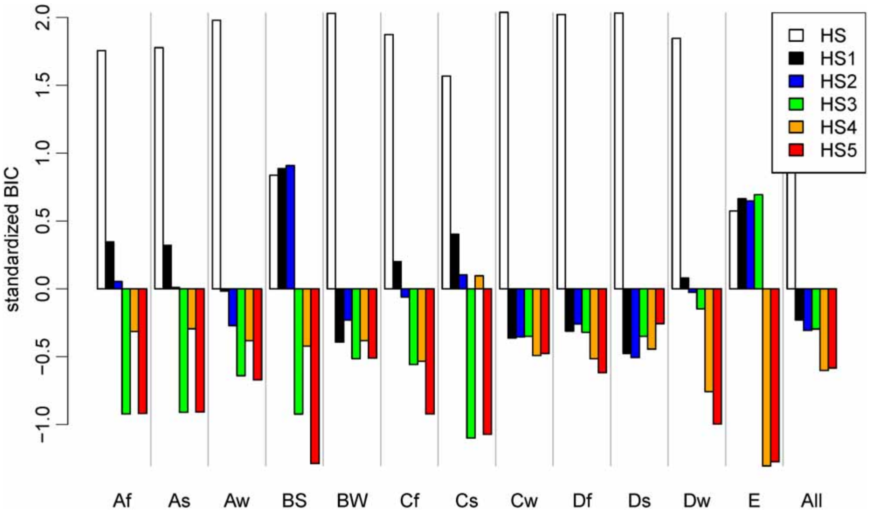

Figure 4 | Standardized values of BIC for HS and various calibrations of HS.

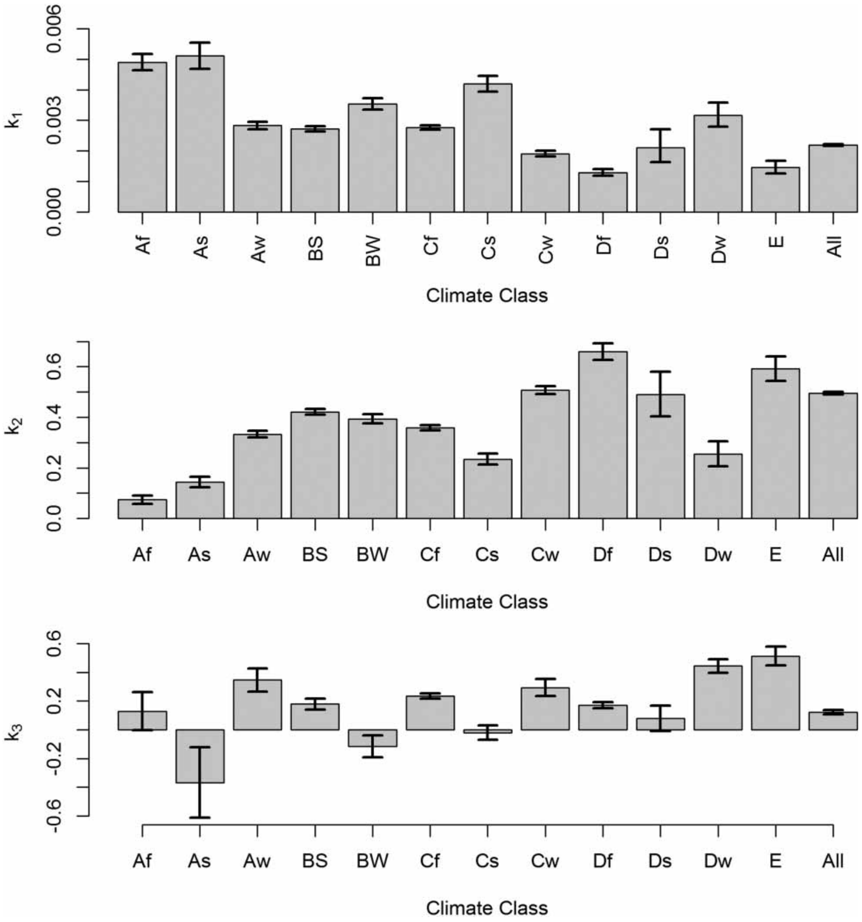

Figure 5 | Best estimates and 90% confidence intervals (5% and 95%) for the coefficients k_1 (upper panel), k_2 (middle panel) and k_3 (lower panel) by climate class.

Adjusted Hargreaves coefficients are usually very site specific. According to Table 3, part of these fluctuations can be attributed to the local climate expressed as Köppen climate class. The separation by climate class is meaningful since it reduces error measures like MAE and RMSE without increasing BIC. Estimates of optimal values for the coefficients k_1, k_2 and k_3 per climate class are provided in Table 3 as well. But are these values significantly different for different climate classes? In order to investigate this question we calculated the 90% confidence interval (5 to 95% range) for each of the coefficients and each climate class. Together with the best estimates they are depicted in Figure 5 and confirm that the separation by climate class is meaningful with respect to the long-term monthly averages used. We therefore recommend using the new HS coefficient values for agroclimatological studies.

It should be taken into account, however, that this study is based on the analysis of long-term monthly means. It is important to point out that the results encountered and conclusions drawn might only be valid for planning in general, whereas they might be unsuitable for monitoring applications.

The results show that HS deviates significantly from FAO-56 even for climatic values and that these deviations are climate-class specific. For some purposes that require long-term ET estimates the differences between models may not be significant to justify the extra effort. In tropical climates the differences between modified models are higher and the daily temperature range is not an efficient indicator of ETo in terms of C_{eff}. In these regions further research should be undertaken for evaluating the validity of other simple methods as suggested by De Pauw (2008).

CONCLUSIONS

Long-term monthly means of ET for 4,368 stations worldwide are estimated by the Penman–Monteith model (FAO-56) and several variations of the HS method. The comparison of the results by climate class showed that simple modifications of the HS model with climate-class specific coefficient values lead to significant improvements compared with the un-calibrated HS method. The addition of a constant term yields an unbiased estimator. Calibrating all the coefficients in HS and introducing a new constant term transforms HS into a highly efficient equation for estimating FAO-56 when only temperature data are available. This allows for a wide range of applications.

Considering the problems associated with the availability of meteorological data in the world, the HS temperature-based model is recommended as the most simple and practical method for estimating FAO-56 in the literature. Results obtained from the comparisons of ET estimates by the HS equation and its modifications against FAO-56 throughout different Köppen climate classes showed high variability even for long-term monthly means. For all but tropical climates the results indicate that monthly ET values estimated by the HS method are a suitable approximation of FAO-56 for agro-climatological studies.

In A climates the reduction of estimation errors due to calibration of the HS method is largest. This is most pronounced in the Af climate where MAE is reduced from its original value of 0.663 to 0.335 mm day^{-1} for $\mathrm{ET}_{\mathrm{HS5}}$. However, the low values of C_{eff} indicate the need for the search of other simple methods for the estimation of ET in tropical climates.

This study strongly supports the use of the calibrated Hargreaves equation $\mathrm{ET}_{\mathrm{HS5}}$ at different climatic conditions in the case when only maximum and minimum temperature data are available.

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