Modifying Hargreaves–Samani equation with meteorological variables for estimation of reference evapotranspiration in Turkey

Murat Cobaner, Hatice Citakoğlu, Tefaruk Haktanir and Ozgur Kisi

ABSTRACT

The Food and Agriculture Organization advocates the Penman–Monteith (FAO-56 PM) equation as the standard model for estimation of the reference evapotranspiration (*ET₀*) because it is considered to have better accuracy. However, in regions where meteorological variables such as solar radiation, wind speed, and relative humidity are not gauged, the Hargreaves–Samani (HS) equation is resorted to as an alternative simply because it needs minimum and maximum air temperatures only as the explanatory variables. In this study, first the HS equation is applied to the monthly means of measured temperature data recorded at 275 meteorology stations in Turkey. Next, the coefficients of the HS equation are calibrated using the *ET₀* values given by the FAO-56 PM equation at all these stations. Next, the HS equation is modified by adding the wind speed as an extra explanatory variable, separately in each one of seven geographical regions of Turkey, which is observed to yield smaller error statistics as compared to the original HS equation. It is concluded that for estimation of the *ET₀* in regions where meteorological measurements are scarce, the HS equation modified in a similar manner can be used with better precision.

Key words | calibration, evapotranspiration, HS equation, Penman–Monteith

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INTRODUCTION

Evapotranspiration is the summation of evaporation from wet soil plus transpiration from the leaves of plants existing on that soil, expressed in depth of water in mm over a certain area in daily, weekly, monthly, or yearly periods. Because it is needed for calculation of the irrigation water requirement, accurate estimation of evapotranspiration is vitally important due to the steadily increasing demand for food.

The first phase of evapotranspiration estimation is the calculation of the reference evapotranspiration (ET_0). Allen *et al.* (1998) defined ET_0 as the evapotranspiration from land covered by grass having an average length of 12 cm with a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, and they developed the Penman–Monteith (FAO-56 PM) method, which is rated by the Food and Agricultural Organization (FAO) as the standard model for estimation of ET_0. This method gives more accurate and consistent results compared to other empirical models such as Turc, Hargreaves–Samani (HS), Ritchie, Valiantzas, etc. (Turc 1961; Hargreaves & Samani 1985; Jones & Ritchie 1990; Trajkovic & Kolakovic 2009; Valiantzas 2013). The equation to compute ET_0 by the FAO-56 PM method is:

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \dfrac{900}{T + 273} U_2 \cdot (e_a - e_d)}{\Delta + \gamma \cdot (1 + 0.34 \cdot U_2)} \quad (1)$$

where ET_0 is reference evapotranspiration (mm day^{-1}), Δ is the slope of the saturation vapor pressure function (kPa $^\circ$C^{-1}), R_n is net solar radiation (MJ m^{-2}day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), γ is the psychometric constant (kPa $^\circ$C^{-1}), T is the mean air temperature ($^\circ$C), U_2 is the average 24 h wind speed at 2 m height (m s^{-1}), e_a is the

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saturation vapor pressure (kPa), and e_d is the actual vapor pressure (kPa).

The FAO-56 PM formula relates the daily ET_0 to net solar radiation, relative humidity, and wind speed next to air temperature. However, in Turkey and in many other countries, the weather stations measure the air temperature but some of them are not equipped to gauge the other variables. Owing to the paucity of meteorological data, Hargreaves & Samani (1985) developed a simpler formula relating ET_0 to air temperature only, known as the HS equation, which is:

$$\mathrm{ET}_{0,\mathrm{HS}} = 0.408 K_H R_a (T_{\max} - T_{\min})^{e_H} \left[\frac{T_{\max} + T_{\min}}{2} + K_T\right] \tag{2}$$

Here, $ET_{0,HS}$ is the reference evapotranspiration (mm day^{-1}) estimated by the HS equation, R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}), T_{max} is the maximum daily temperature (°C), T_{min} is the minimum daily temperature (°C), K_H and K_T are the empirical Hargreaves calibration and temperature coefficients, e_H is the empirical Hargreaves exponent, and 0.408 is the factor converting from (MJ m^{-2} day^{-1}) to (mm day^{-1}). Originally, these coefficients are given as: $K_H = 0.0023$, $K_T = 17.8$, and $e_H = 0.5$. Because the HS equation does not comprise all the effective parameters but only air temperatures, its K_H, K_T, e_H coefficients may need to be adjusted for site-specific conditions, and the HS equation is considered to be less accurate when used with the original coefficients compared to the FAO-56 PM formula. For example, Martinez-Cob & Tejero-Juste (2004) determined that in non-windy areas of a semi-arid region in Spain, the HS equation overestimated by 14% to 20%. The HS equation is reported to give unreliable estimates for daily ET_0, and therefore it should be used for 10-day periods at the shortest. For monthly periods, Almorox *et al.* (2015) conclude that the HS equation yields more accurate global average performance in arid, semiarid, temperate, and cold and polar climates compared to other models using air temperature as the main explanatory variable. According to some other studies, even with monthly periods the HS equation generally tends to overestimate in humid regions and underestimate in dry and especially windy regions (e.g., Saeed 1986; Amatya *et al.* 1995; Allen *et al.* 1998; Temesgen *et al.* 1999; Samani 2000; Xu & Singh 2001, 2002; Droogers & Allen 2002; Trajkovic 2005; Fooladmand & Haghighat 2007). Hence, alternative forms of the HS equation are suggested, taking into account local conditions. For example, Fooladmand & Haghighat (2007) calibrated the coefficients of the HS equation using the data measured at 14 stations in the south of Iran, assuming the monthly ET_0 values given by the FAO-56 PM formula were the true values. Maestre-Valero *et al.* (2013), using the FAO-56 PM formula as the reference, modified the coefficients of the HS equation for a region in southeastern Spain and reported a drop in relative error in monthly periods to 8% from 20% with regionalized coefficients. After analyzing relevant data in daily, weekly, monthly periods recorded at 30 stations in eastern Spain along the Mediterranean coast, Marti *et al.* (2015a) concluded that the HS equation modified by incorporating geographical inputs and also wind speed as extra predictor variables into it yielded appreciably improved results. Marti *et al.* (2015a) developed various multiple linear regression equations for coefficient K_H relating it to various explanatory variables such as geographical inputs and wind speed in their region of study, and the best regression turned out to be the one including the longitude and altitude, temperature range between maximum and minimum, and the wind speed as predictor variables (determination coefficient: $R^2 = 0.97$). The same regression excluding the wind speed, which was intended for those sites where the wind speed data were not available or not reliable, was slightly less significant but still close ($R^2 = 0.90$) (Marti *et al.* 2015a). Although betterment occurred with every time step, Marti *et al.* (2015a) reported that the modified HS equation was most successful with monthly periods. Mendicino & Senatore (2013) using the measured relevant data at 137 stations in southern Italy, related the K_H coefficient of the HS equation to temperature range and the average temperature only, assuming, similar to many other studies, the values given by the FAO-56 PM formula as the reference and reported an average of 22% improvement in ET_0 estimates. Using relevant data in monthly periods at 22 stations in Florida, Thepadia & Martinez (2012) performed a regional calibration of the HS equation and reported plausible results by the modified equation. Droogers & Allen (2002) attempted to calibrate the coefficients of the HS equation worldwide for estimation of monthly ET_0 values. Mohawesh & Talozi (2012), compared ET_0 values calculated by Droogers and Allen's HS equations and by the original HS equation. They reported that the modified HS equation could be used for ET_0 estimates instead of the FAO-56 PM equation with reasonable accuracy. Fooladmand *et al.* (2008) noted that the original HS equation yielded better estimates at only three out of 14 stations in the south of Iran. Samani (2000) suggested 0.0135 for the K_H coefficient; however, Vanderlinden *et al.* (2004) reported that such a modified HS equation did not produce better results in southern Spain. Trajkovic (2007) proposed 0.424 for the exponent coefficient in the Western Balkans region on the basis of the data recorded in the cities of Varazdin, Zagreb, Bihac, Novi Sad, Negotin, Kragujevac, Nis, and Vranje. Gocic & Trajkovic (2010) used 0.424 instead of 0.5 for the exponent coefficient in the HS equation. They compared the original and the modified HS equations in the humid Serbian region, and concluded that the proposed 0.424 for the exponent coefficient had a very good agreement with the full-set of FAO-56 PM in the humid Serbian region. Subburayan *et al.* (2011) suggested 0.653 for the exponent coefficient after analyzing 22 years of recorded data in a hot and humid location in India. For the K_H coefficient, Xu & Singh (2001) offered the value of 0.0029 for the Rawson Lake weather station in northeastern Ontario, and Martinez-Cob & Tejero-Juste (2004) suggested the value 0.0020 for the non-windy region of the Ebron River valley in Spain. Berti *et al.* (2014) reported that usage of 0.002 instead of 0.0023 for the K_H coefficient in the Veneto plain region in northeastern Italy reduced the overestimation of the HS equation from 19% down to 3%. Almorox & Grieser (2016) calibrated the coefficients of the HS equation for different climatic regions all over the world in accordance with the Köppen climate classification using measured data at 4,368 stations worldwide. They calibrated five different versions of the HS equation for 12 subclimates as defined by the Köppen classification, and they concluded that the best estimates are obtained with the calibration of the K_H and e_H coefficients while taking 17.8 for K_T and adding a third coefficient as a free intercept value at the end of the equation. The magnitudes of the coefficients of the calibrated HS equations according to Köppen climate regions are given in Table 4 of their paper (Almorox & Grieser 2016). The values suggested for the coefficients of the HS equation for estimation of monthly ET_0 by various studies published over the period 2000–2012 are summarized in Table 1.

In compliance with the suggestion by Allen *et al.* (1998), Trajkovic (2005), Kisi (2008), Cobaner (2011, 2013), Ngongondo *et al.* (2013), and Shiri *et al.* (2014) used the linear regression method for calibrations of such empirical formulas at some specific local geographic locations. Gocic & Trajkovic (2011) proposed the FAO-56 PM and Hargreaves models based on web services using Davis weather station data. Their web services either directly provide the measured data or suggest methods to estimate values of the meteorological variables required by the FAO-56 PM and Hargreaves formulas. Patel *et al.* (2014) calibrated and

Table 1 | Values of the coefficients of the Hargreaves equation according to various studies during the period 2000–2012

Authors and publication	K_H	e_H	K_T	Study area
Hargreaves & Samani (1985)	0.0023	0.5	17.8	
Smith (1993)	**0.0030**	**0.4**	**20.0**	California
Samani (2000)	**0.0135**	0.5	17.8	
Xu & Singh (2001)	**0.0029**	0.5	17.8	North-Eastern Ontario
Droogers & Allen (2002)				
First equation	**0.0030**	**0.4**	**20.0**	World
Second equation	**0.0025**	0.5	**16.8**	
Vanderlinden *et al.* (2004)				
Coastal regions	**0.0022**	0.5	17.8	Southern Spain
Interior regions	**0.0030**	0.5	17.8	
Martinez-Cob & Tejero-Juste (2004)	**0.0020**	0.5	17.8	Zaragoza
Trajkovic (2007)	0.0023	**0.424**	17.8	Western Balkans
Sepaskhah & Razzaghi (2009)	**0.0026**	0.5	17.8	Iran
Subburayan *et al.* (2011)	0.0023	**0.653**	17.8	India
Tabari & Hosseinzadeh Talaee (2011)				
Arid zones	**0.0031**	0.5	17.8	Iran
Cold regions	**0.0028**	0.5	17.8	
Mohawesh & Talozi (2012)	**0.6957**	**0.58**	**16.6**	Jordan

Modified K_H, K_T, and e_H coefficients are in bold font.

validated the empirical Hargreaves coefficient and the exponent coefficient in the HS equation with a fuzzy-logic-based approach for diverse climate locations of India. They reported that the modified HS equation resulted in improved ET_0 estimates, and the location-specific calibration methodology presented in their paper increased the accuracy of the HS equation. Marti *et al.* (2015b) applied a gene expression programming (GEP)-based approach for estimating ET_0, considering lysimetric records taken at two stations in Spain which actually measured ET_0 along with other pertinent meteorological variables over the period 2007–2012, and reported that the locally trained, what they called GEP4 and GEP6 models, estimated ET_0 even better than FAO-56 PM. Shiri *et al.* (2015) also applied a GEP-based model for ET_0 estimation in daily periods in Iran using relevant data having a record length of nine years measured at eight coastal and 21 inland stations in Iran. Similarly to many relevant studies, Shiri *et al.* (2015) also took the FAO-56 PM results as true values and assessed a few different versions of their GEP-based model by various comparison statistics like determination coefficient and mean absolute relative error. Shiri *et al.* (2015) noted usually underestimations at coastal stations and overestimations at inland stations by the original HS equation, and they reported that with locally calibrated coefficients the modified HS equation was better. For the GEP-based model, Shiri *et al.* (2015) developed different equations involving fairly long analytical expressions individually pertaining to each single station. According to Marti *et al.* (2015a) however, application of such data-driven models 'requires the implementation of specific software, and the obtained models can generally not be expressed in straightforward simple equations' like that of HS.

Originally, the HS equation was developed for semiarid environments (Hargreaves & Samani 1985). Some studies showed that the HS equation overestimated ET_0 in warm humid areas, such as the southeastern USA (Lu *et al.* 2005) and India (Kashyap & Panda 2001). Therefore, numerous attempts were made to improve the estimation capability of the HS equation, some of which are already mentioned above (e.g., Martinez-Cob & Tejero-Juste 2004; Ravazzani *et al.* 2012; Shahidian *et al.* 2012; Hosseinzadeh Talaee 2014). Jensen *et al.* (1997) noted a significant correlation between the wind speed and the slope of the PM/HS regression with a determination coefficient: $R^2 = 0.88$. Droogers & Allen (2002), after having collected and analyzed pertinent weather data in many meteorological stations all over the world, stated that by adding the precipitation as an extra term in it the modified HS equation yielded better ET_0 estimates in monthly periods than its original form. Fooladmand *et al.* (2008) further modified the HS equation, which was analytically extended by Droogers & Allen (2002) by inclusion of the monthly precipitation term, for some stations in the south of Iran.

Calculation of suitable magnitudes for the coefficients of the modified HS equation for estimation of monthly mean ET_0 for seven geographical regions of Turkey has been the main objective of this study. Seven distinct climate regions are spread throughout Anatolia and the Balkans part of Turkey. The Marmara Region in the northeast has a climate similar to that in the Balkans, which has precipitation throughout the year with cold winters. The Aegean Region in the west has a mild climate similar to that of Mediterranean shores at coastal areas, but has a land climate towards the inner parts. The Mediterranean Region in the south has a typical mild climate similar to that in Greece and Italy, which receives considerable orographic precipitation year-round. Its upper boundary is delineated by the peaks of the Taurus Mountain ranges, which mostly extend parallel to the shoreline. The Southeastern Anatolia Region has hot and dry summers and cold winters receiving less than overall average precipitation. The Eastern Anatolia Region is a mountainous area covered by extensions of both the Taurus and the Black Sea Mountains, and it has hot but short summers, long winters with harshly low temperatures with a lot of snow. The Black Sea Region receives much higher precipitation than the average of Turkey, which is mostly orographic type, and it has a somewhat similar climate to the Mediterranean Region. The Inner Anatolia Region, the seventh region, receives much lower precipitation than the average of Turkey because the Black Sea Mountain ranges, mostly running parallel to the shoreline of the Black Sea in the north, and the Taurus Mountain ranges, mostly running parallel to the shoreline of the Mediterranean Sea in the south, prevent passage of moisture-laden clouds inwards. In this region the continental climate prevails, with hot and mostly dry summers and cold winters.

Various agricultural activities, including citrus fruit crops, banana plantations, pistachio plantations, tea plantations, cereal crops, sugar beets, etc. in all these seven regions of Turkey take place at an ever-increasing rate. Some large-scale irrigation projects in Turkey, like the Southeastern Anatolia Project (known as GAP in Turkey), have already been completed and are operational, while construction of some others is still continuing at a rapid pace (see www.dsi.gov.tr). Turkey is said to be one of the few self-sufficient countries from an agricultural products' standpoint. In recent years, various crops have been exported to many countries. In short, accurate estimation of irrigation water requirements in those seven regions, and hence of the evapotranspiration from cultivated lands, has become a significantly important issue for Turkey.

The purpose of the studies summarized in the above paragraphs is calculation of suitable magnitudes for the coefficients of the modified HS equation pertinent to the local conditions of a specific geographical area. All these calibrated HS equations are for the regions whose data are used, and they cannot be valid at different meteorological conditions, such as the geographical regions of Turkey. Hence, the main objective of this study is to improve the ET_0 estimation capability of the HS equation by determining the magnitudes of its coefficients most suitable to each one of the seven geographical regions in Turkey, using the relevant meteorological data measured at the weather stations throughout Turkey so as to match the ET_0 value given by it to that of the FAO-56 PM equation as much as possible. Moreover, as summarized above, most studies on a similar theme attempted to calibrate the K_H coefficient while leaving the other two intact, keeping their original magnitudes assigned by Hargreaves and Samani. In our study, we will extend the calibration of these three parameters in all possible combinations, namely: first, modifying only one of the three while keeping the other two at their original values; second, modifying any two as the third one is at its original value; and third, modifying all three coefficients to enable the HS equation to estimate the ET_0 values with better accuracy anywhere in any one of the seven regions of Turkey. Further, by incorporating the wind speed as an extra predictor for those meteorology stations where reliable wind speed data are available, we will search for the possibility of further improvement in its capability for ET_0 estimation. The contribution of the wind speed for betterment of the HS equation will be taken into account by multiplying the value given by the HS equation by an extra coefficient, which will be related to the wind speed by linear regression, an approach not practiced before by any similar studies.

MATERIALS AND METHODS

As shown in Figure 1, there are 275 weather stations in Turkey owned and operated by the General Directorate of Meteorology (known as MGM in Turkey) (www.mgm.gov.tr)

Figure 1 | Geographical locations of the meteorological stations in Turkey. Open circle, training data; black circle, validation data.

which regularly measures at daily, even at hourly periods many meteorological variables. Turkey was segmented into seven geographical regions in the early 1930s, and those boundaries were delineated by topographic and climatic considerations. Turkey, with a surface area of 814,578 km^2, lies within 36°–42° latitudes and 26°–45° longitudes. According to the World Meteorological Organization (WMO), the location density of meteorological stations in a geographical area has a direct effect on depicting the climatic peculiarity and variability over that region. Recommended minimum network densities for various physiographic regions are specified in the *Guide to Hydrological Practices* (WMO 1976, 2008) separately for each one of six types of physiographic regions, such as coastal, mountains, inner plains, etc. According to these WMO guidelines, the density of stations should be at least one station per 600–900 km^2 for plain regions of temperate Mediterranean and tropical zones, and one station per 100–250 km^2 for mountainous regions of temperate Mediterranean zones (WMO 1976). Under the present circumstances, Turkey has a poor station network condition because on average there is one station for a 2,962 km^2 area, which is far greater than both 900 and 250 km^2, and is not sufficient to provide discrete representations of climatic variability meaningfully.

Turkey is located between the temperate zone and the subtropical belt, and it experiences all four seasons. A large part of Turkey is the Anatolian Peninsula, which is surrounded by the Black, Marmara, Aegean, and Mediterranean seas. The extent of the mountains and the diversity of landforms have led to the creation of differing climate patterns. According to the world-wide climate classifications, the climate types distinguishable in Turkey are: (1) Continental (a, b, c, d), (2) Mediterranean, (3) Marmara (Transition), and (4) Black Sea climates. By the Köppen climate classification method also (Almorox & Grieser 2016), Turkey has many different climates (Figure 2). The most prevalent ones are Csa (warm temperate climate with dry summers) for the coastal regions, and Dsb (snow climate with warm summers) for the inner regions (Peel *et al.* 2007; Almorox & Grieser 2016). The elevations of the weather stations in Turkey vary from 3 m up to 5,137 m from mean sea level. The recorded highest air temperature is +48.6 °C, measured at Cizre, and the recorded lowest temperature is −42.8 °C, measured at Agri. The average annual temperature of Turkey is 12.8 °C according to the data gauged from 1971 through 2000. The total average annual rainfall is 642.8 mm/year in the same period, which results in an average water volume of 500 billion m^3/year to Turkey. 274 Billion m^3/year of water returns to the atmosphere by evapotranspiration, which is about 55% of the precipitation.

FAO-56 PM equation

Due to the lack of experimental ET_0 measurements, the numbers given by the FAO-56 PM equation have been accepted as the true values, and this equation has been used for calibrating the modified versions of the HS equations (e.g., Allen *et al.* 1998; Almorox & Grieser 2016). Step-by-step calculation of the FAO-56 PM equation

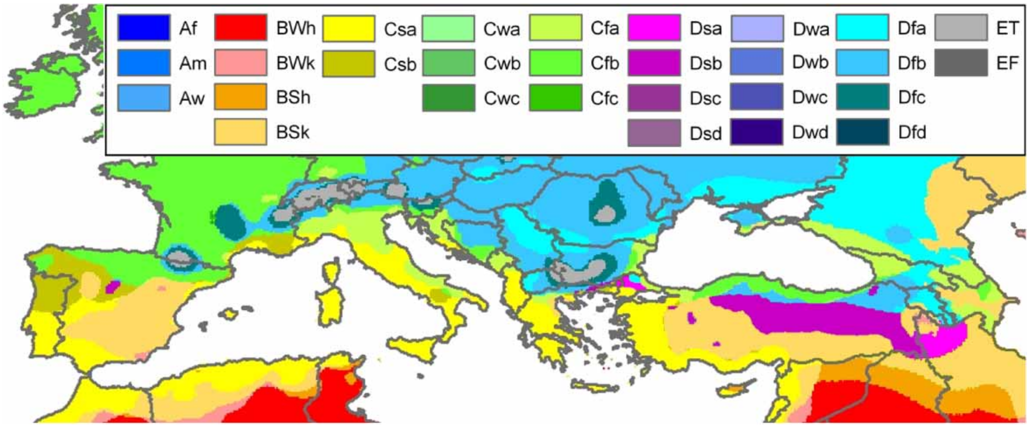

Figure 2 | Köppen-Geiger climate type map of Europe and Turkey (after Peel *et al.* 2007).

(Equation (1) here) is done in this study as summarized below.

The effect of the atmospheric pressure, P, on ET_0 is small, and an average value for a location is sufficient. A simplification of the ideal gas law, assuming 20 °C for a standard atmosphere, can be employed to calculate P in kPa at a particular elevation by:

$$P = 101.3 \cdot \left(\frac{293 - 0.0065 \cdot z}{293}\right)^{5.26} \tag{3}$$

where P is atmospheric pressure [kPa], and z is elevation above sea level [m]. Next, the psychrometric constant, γ, is computed by:

$$\gamma = 0.665 \times 10^{-3} \times P \tag{4}$$

Saturation vapor pressure is a physical peculiarity of air related to air temperature only, and it is calculated by:

$$e^o(T) = 0.6108 \cdot \exp\left(\frac{17.27 \cdot T}{T + 237.3}\right) \tag{5}$$

where T is the air temperature [°C]. Another term, the slope of the relationship between saturation vapor pressure and temperature, Δ, is calculated by:

$$\Delta = \frac{4098 \cdot \left[0.6108 \cdot \exp\left(\frac{17.27 \cdot T_{\mathrm{mean}}}{T_{\mathrm{mean}} + 237.3}\right)\right]}{(T_{\mathrm{mean}} + 237.3)^2} \tag{6}$$

where Δ is the slope of the saturation vapor pressure curve [kPa °C^{-1}] at the air temperature of T_{mean} [°C]. With equipment which is not sensitive, involving large errors in RH_{min}, or when the relative humidity data integrity is in doubt, then only RH_{max} should be used:

$$e_a = e^o(T_{\mathrm{min}}) \cdot \frac{RH_{\mathrm{max}}}{100} \tag{7}$$

where RH_{max} is the monthly average daily maximum relative humidity [%], and the other terms are as explained before. The mean saturation vapor pressure for a monthly period is computed as the average of saturation vapor pressures at monthly average daily maximum and minimum air temperatures in that month as:

$$e_S = \frac{e^o(T_{\mathrm{max}}) + e^o(T_{\mathrm{min}})}{2} \tag{8}$$

where e° (T_{max}) is the saturation vapor pressure at monthly average daily maximum temperature [kPa]. Based on the idea that the soil temperature is directly related to air temperature, for monthly periods, soil heat flux is calculated by:

$$G_{\mathrm{month},i} = 0.07 \cdot (T_{\mathrm{month},i+1} - T_{\mathrm{month},i-1}) \tag{9}$$

where $T_{month,i+1}$ and $T_{month,i\text{-}1}$ are the mean air temperatures of the next and previous months [°C].

In this study, the extraterrestrial radiation (R_a) is estimated using an equation recommended by Allen *et al.* (1998). The R_a values for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination, and the time of the year by:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \sin(\omega_s)] \tag{10}$$

where Ra is extraterrestrial radiation [MJ m^{-2} day^{-1}], G_{sc} is the solar constant = 0.0820 MJ m^{-2} min^{-1}, d_r, is the inverse relative distance Earth–Sun (Equation (11)), ω_s is the sunset hour angle (Equation (13)) [rad], φ is latitude [rad], and δ is solar declination (Equation (12)) [rad].

The inverse relative distance Earth–Sun, d_r, and the solar declination, δ, are given by:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \tag{11}$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \tag{12}$$

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos[-\tan(\phi) \tan(\delta)] \tag{13}$$

Generally, the HS equation is calibrated by linear regression using the ET_0 values given by the FAO-56 PM equation or using the lysimeter measurements, if available, at quite a few locations in a homogeneous region plotted on the ordinate, and the ET_0 values computed by the HS equation plotted on the abscissa axes. The intercept α and the slope β of the best fit regression line then are used as regional calibration coefficients (Allen *et al.* 1998):

$$\mathrm{ET}_0(PM) = \alpha + \beta \cdot \left(\mathrm{ET}_{0,\mathrm{HS}}\right) \tag{14}$$

where ET_0 *(PM)* is the reference evapotranspiration calculated by the FAO-56 PM equation, and $ET_{0,HS}$ is the ET_0 estimated by the HS equation.

Alternatively, some researchers calibrated the K_H coefficient while leaving the others at their original values, and just a few studies calibrated all three coefficients (K_H, K_T, and e_H) of the HS equation specific to a geographical location (e.g., Trajkovic 2007; Adeboye *et al.* 2009; Sepaskhah & Razzaghi 2009; Maestre-Valero *et al.* 2013; Lee 2015). In our study, the K_H, e_H, and K_T coefficients of the HS equation are adjusted in all possible combinations with the help of the Solver menu of Microsoft Excel using the monthly average values of all the pertinent meteorological variables recorded at 275 stations over the period 1975–2010 and assuming the ET_0 values computed by the FAO-56 PM equation were the true ET_0 values, which is a common practice pursued by many studies as summarized in the Introduction. Excel Solver is part of a broader system of commands called Simulation Solver in Excel, and it is used to determine the most suitable form of the analytical expression chosen in a window known as target cell. The Solver utilizes the data in another cell pertaining to the chosen analytical model input by the user. Constraints for the coefficients of the analytical expression can also be specified [Excel–Help]. The Microsoft Office Excel Solver tool was developed by Lasdon & Waren (1978) using the generalized reduced gradient (GRG2) algorithm, which is an improved state of the simplex method for non-linear programming (Lasdon *et al.* 1978, 1996). The GRG2 algorithm is explained in Lasdon *et al.* (1978) and Ecker & ve Kupferschmid (1991).

Further, we have calibrated the HS equation by adding extra meteorological variables (relative humidity, wind speed, precipitation, etc.) to it for each one of the seven geographical regions of Turkey, which experience various climates such as dry, sub-humid, and semi-arid climates for southern coastal regions and inner parts of Anatolia, respectively (Turkes 1999). Among the potential meteorological variables, inclusion of the wind speed as an extra explanatory variable brought about much better ET_0 estimations than the others. Citakoglu *et al.* (2014) also reported similar results, which indicated that adding the wind speed data increased the model performance more significantly than the relative humidity. Inclusion of the wind speed (WS) to the HS equation was not done directly as an extra term inserted in its analytical form, but rather was done as a second step as depicted by Equation (15) below. Here, the value yielded by the HS equation is multiplied by a correcting coefficient which is to be determined as a function of the wind speed at that location by simple linear regression. Hence, a and b coefficients of Equation (15) were computed using the ET_0 values provided by the FAO-56 PM equation as the reference values with the monthly averages of pertinent meteorological data recorded at 275 stations over the period 1975–2010. The numerical operations for this purpose were performed with the help of the Solver menu of Microsoft Excel [Excel–Help].

$$\mathrm{ET}_0(PM) = (a + b \cdot WS) \cdot \mathrm{ET}_{0,\mathrm{HS}} \tag{15}$$

Here, $ET_0(PM)$ is the reference evapotranspiration computed by the FAO-56 PM equation, and $ET_{0,HS}$ is ET_0 computed by both the original HS and also by the HS equation whose coefficients are modified in that region, applied separately, both at the same station in a homogeneous region.

Various versions of the HS equation were modified based on the ET_0 values computed by the FAO-56 PM equation using the long-term monthly averages of the relevant meteorological variables recorded at those 275 stations over the period 1975–2010. For validation of the modified HS equations, three meteorological stations from each one of the seven regions of Turkey were selected randomly. The remaining 254 stations were used in the modification procedure of the HS equation. With the help of Excel Solver, suitable magnitudes for the K_H, e_H, and K_T coefficients of the HS equation (Equation (2)), and for the *a* and *b* coefficients of the linear regression (Equation (15)) were computed. First, each one of these three coefficients was modified while keeping the original magnitudes of the other two (calibration combinations 1–3). Next, the values were computed for combinations of pairs of the coefficients, while keeping the original magnitude of the third one (calibration combinations 4–6). Finally, suitable new values for all the three coefficients were computed (calibration combination 7). After that, the original and the modified HS equations were also calibrated by including the wind speed data (Equation (15)) for all meteorological regions (calibration combinations 8 and 9, respectively). In addition to these nine combinations, the HS equations modified by Almorox & Grieser (2016) for the Köppen climate classes were also applied to all seven geographic regions in Turkey, which is the final combination (calibration combination 10). The predictive abilities of these ten different combinations of the modified HS equation were quantitatively evaluated by the commonly used test statistics of mean absolute

Table 2 | Summary statistics of long-term monthly meteorological data in coastal regions of Anatolia

Variables	X_{ort}	S_x	C_v	C_{sx}	C_k	X_{mak}	X_{min}
Mediterranean Region							
Maximum temperature	32.29	7.71	0.24	−0.36	−0.84	46.7	12.5
Minimum temperature	0.86	10.41	12.12	−0.64	0.42	20.6	−33.5
Average temperature	16.35	7.95	0.49	−0.25	−0.79	30.2	−3.8
Maximum humidity	73.84	7.49	0.10	−0.43	−0.39	90.1	53.8
Minimum humidity	7.92	5.62	0.71	1.27	2.63	38.0	0.0
Wind speed	2.03	0.79	0.39	1.39	2.70	5.6	0.7
Black Sea Region							
Maximum temperature	31.04	6.95	0.22	−0.48	−0.37	45.1	10.3
Minimum temperature	−3.04	10.17	−3.34	−0.53	−0.18	17.0	−30.8
Average temperature	12.32	7.15	0.58	−0.14	−0.97	25.1	−6.4
Maximum humidity	78.77	5.90	0.08	−0.08	−0.66	94.1	64.2
Minimum humidity	14.61	9.51	0.65	0.85	0.12	44.0	0.0
Wind speed	1.88	0.79	0.42	1.18	2.53	5.4	0.4
Marmara Region							
Maximum temperature	31.14	7.43	0.24	−0.25	−1.01	45.4	11.6
Minimum temperature	−2.18	9.06	−4.17	−0.24	−0.71	15.0	−27.8
Average temperature	13.30	7.08	0.53	0.02	−1.20	26.8	−4.0
Maximum humidity	81.89	5.64	0.07	−1.32	2.68	91.7	56.0
Minimum humidity	16.94	7.77	0.46	0.35	−0.18	40.0	0.0
Wind speed	2.37	1.14	0.48	1.40	2.62	7.40	0.6
Aegean Region							
Maximum temperature	31.98	7.75	0.24	−0.19	−1.08	45.7	14.2
Minimum temperature	−0.66	9.03	−13.62	−0.28	−0.32	18.5	−24.6
Average temperature	15.29	7.66	0.50	−0.02	−1.08	28.7	0.0
Maximum humidity	76.03	7.48	0.10	−0.56	−0.45	89.6	54.3
Minimum humidity	11.43	6.52	0.57	0.75	0.27	35.0	1.0
Wind speed	2.13	0.75	0.35	0.78	0.53	4.8	0.6

X_{ort}: arithmetic average, S_x: standard deviation, C_v: variation coefficient, C_{sx}: skewness coefficient, C_k: kurtosis coefficient.

error (MAE), mean absolute relative error (MARE), and root mean square error (RMSE), which are, with the relevant quantities of this study, expressed as:

$$MAE = \frac{1}{n}\sum \left|ET_{0,MH} - ET_0(PM)\right| \times 100 \quad (16)$$

$$MARE = \frac{1}{n}\sum \left|\frac{ET_{0,MH} - ET_0(PM)}{ET_0(PM)}\right| \times 100 \quad (17)$$

$$RMSE = \sqrt{\frac{1}{n}\sum \left(ET_{0,MH} - ET_0(PM)\right)^2} \quad (18)$$

where n is the number of elements (number of stations), $ET_0(PM)$ is the reference evapotranspiration computed by the FAO-56 PM equation, and $ET_{0,MH}$ is ET_0 computed by a modified HS equation.

APPLICATIONS AND RESULTS

The averages for each one of the seven regions of salient statistical characteristics of the meteorological data used are given in Tables 2 and 3. Adjusted K_H, e_H, and K_T coefficients of the modified HS equations and the performance measures (MAE, mm day^{-1}; MARE, %; and RMSE, mm day^{-1}) of the original and modified HS equations for all combinations are presented in the Appendix, Tables A1–A7 (available with the online version of this paper). The values of the performance statistics for, first, the original HS equation, next, for the best combination with all three calibrated coefficients (combination 7), for the ones including the wind speed (combinations 8 and 9), and for the one given by Almorox & Grieser (2016) (combination 10) are summarized in Tables 4 and 5. As seen in these tables, first of all, the original HS equation estimates the

Table 3 | Summary statistics of long-term monthly meteorological data in inner regions of Anatolia

Variables	X_{ort}	S_x	C_v	C_{sx}	C_k	X_{mak}	X_{min}
Inner Anatolia Region							
Maximum temperature	29.10	7.85	0.27	−0.28	−1.13	42.5	12.4
Minimum temperature	−9.32	11.58	−1.24	−0.26	−1.19	10.2	−34.2
Average temperature	10.59	8.26	0.78	0.00	−1.33	25.3	−6.2
Maximum humidity	77.78	7.37	0.09	−0.60	−0.39	90.7	53.8
Minimum humidity	9.90	6.41	0.65	1.35	2.80	44.0	0.0
Wind speed	2.22	0.69	0.31	0.05	−0.26	4.2	0.5
Eastern Anatolia Region							
Maximum temperature	27.26	9.55	0.35	−0.2	−1.08	46.3	7.6
Minimum temperature	−9.82	13.45	−1.37	−0.31	−0.97	16.0	−42.8
Average temperature	9.82	10.21	1.04	−0.02	−1.07	31.0	−11.3
Maximum humidity	71.97	11.23	0.16	−0.93	0.18	90.7	36.0
Minimum humidity	10.07	7.21	0.72	1.14	1.18	40.0	0.0
Wind speed	1.78	0.72	0.40	1.54	4.99	5.9	0.4
Southeastern Anatolia Region							
Maximum temperature	33.71	9.04	0.27	−0.29	−1.15	48.6	15.2
Minimum temperature	−0.06	9.95	−165.8	0.00	−0.89	18.4	−24.0
Average temperature	16.99	9.50	0.56	0.11	−1.38	34.4	1.6
Maximum humidity	65.66	13.99	0.21	−0.50	−0.84	87.6	35.3
Minimum humidity	7.65	5.74	0.75	1.01	0.45	26.0	0.0
Wind speed	1.79	0.78	0.44	1.46	2.13	4.5	0.5

X_{ort}: arithmetic average, S_x: standard deviation, C_v: variation coefficient, C_{sx}: skewness coefficient, C_k: kurtosis coefficient.

Table 4 | Performance statistics of the original and modified HS equations in reference to the ET_0 values given by the FAO-56 PM equation for coastal regions of Turkey

		Training stations			**Validation stations**		
Regions	**Combinations**	**MAE (mm day^{-1})**	**MARE (%)**	**RMSE (mm day^{-1})**	**MAE (mm day^{-1})**	**MARE (%)**	**RMSE (mm day^{-1})**
Mediterranean Region	Orig.	1.12	20.71	1.39	1.09	22.1	1.34
	7	0.81	15.24	1.02	1.04	20.46	1.23*
	8	0.80	17.16	0.97	0.75	16.23	0.98
	9	0.62	11.62	0.81	0.58	11.11	0.77**
	10	1.61	31.14	1.85	1.27	26.2	1.61
Marmara Region	Orig.	1.48	27.72	1.78	1.20	24.95	1.42
	7	1.19	21.19	1.48	0.92	17.99	1.17*
	8	1.17	23.21	1.38	1.01	22.81	1.15
	9	0.84	15.51	1.03	0.65	13.52	0.78**
	10	2.32	41.35	2.60	1.19	21.19	1.48
Aegean Region	Orig.	1.15	21.17	1.39	1.14	24.70	1.44
	7	0.89	14.77	1.19	0.9	19.03	1.17*
	8	0.95	19.28	1.11	0.89	20.88	1.00
	9	0.65	11.52	0.83	0.58	11.99	0.72**
	10	2.02	36.47	2.27	1.38	31.00	1.54
Black Sea Region	Orig.	1.18	24.96	1.47	1.23	24.96	1.56
	7	0.99	20.07	1.27	1.00	19.06	1.36*
	8	1.06	23.51	1.25	0.99	22.97	1.22
	9	0.79	16.46	0.99	0.73	15.75	0.98**
	10	1.89	38.44	2.15	1.84	37.53	2.10

*Best calibration result of HS equation by modification of the coefficients.

**Best calibration result of the HS equation by inclusion of the wind speed.

Table 5 | Performance statistics of the original and modified HS equations in reference to the ET_0 values given by the FAO-56 PM equation for inner regions of Turkey

		Training stations			**Validation stations**		
Regions	**Combinations**	**MAE (mm day^{-1})**	**MARE (%)**	**RMSE (mm day^{-1})**	**MAE (mm day^{-1})**	**MARE (%)**	**RMSE (mm day^{-1})**
Inner Anatolia Region	Orig.	1.18	24.15	1.38	1.20	23.43	1.47
	7	0.80	15.07	1.01	0.76	13.16	0.98*
	8	1.01	21.85	1.15	1.16	22.74	1.32
	9	0.60	11.54	0.72	0.65	12.22	0.80**
	10	1.39	27.55	1.61	1.50	28.27	1.75
Eastern Anatolia Region	Orig.	0.94	21.82	1.21	0.72	17.19	0.90
	7	0.53	12.17	0.69	0.49	13.13	0.55*
	8	0.76	22.06	0.88	0.72	22.04	0.80
	9	0.41	10.08	0.52	0.49	12.37	0.55**
	10	0.82	20.93	1.00	0.56	16.56	0.65
Southeastern Anatolia Region	Orig.	1.03	19.14	1.32	0.89	17.1	1.09
	7	0.85	14.74	1.09	0.56	12.84	0.70*
	8	0.86	19.05	1.00	0.69	16.91	0.81
	9	0.55	10.82	0.7	0.47	9.82	0.58**
	10	1.07	20.04	1.29	0.56	13.28	0.72

*Best calibration result of HS equation by modification of the coefficients.

**Best calibration result of the HS equation by inclusion of the wind speed.

ET_0s in all seven regions with fairly high MARE values (about 20–25%). For combinations which modified the magnitudes of K_H, e_H, and K_T coefficients (combinations 1–7), the best combination having the smallest RMSE statistic is the last one (combination 7), which allows all the three coefficients to assume different magnitudes from those of the original HS equation. RMSE is known as the standard error of the estimates in the regression, which is a major criterion of superiority in most similar studies. MARE values in our study were mostly in parallel with those of RMSE also. Calibration of the original and modified HS equations by inclusion of the wind speed (WS-HS and WS-MHS, combinations 8 and 9, respectively) enhanced the accuracy of the HS equation. The best estimations are obtained from the ninth combination, which allows calibration of all three coefficients of the HS equation along with inclusion of the wind speed (WS-MHS) (Equation (15)). The second best estimation results are obtained from the original HS equation with the wind speed data included (WS-HS) for the coastal regions. The HS equation with three calibrated coefficients but not including the WS gives the second best estimation for the

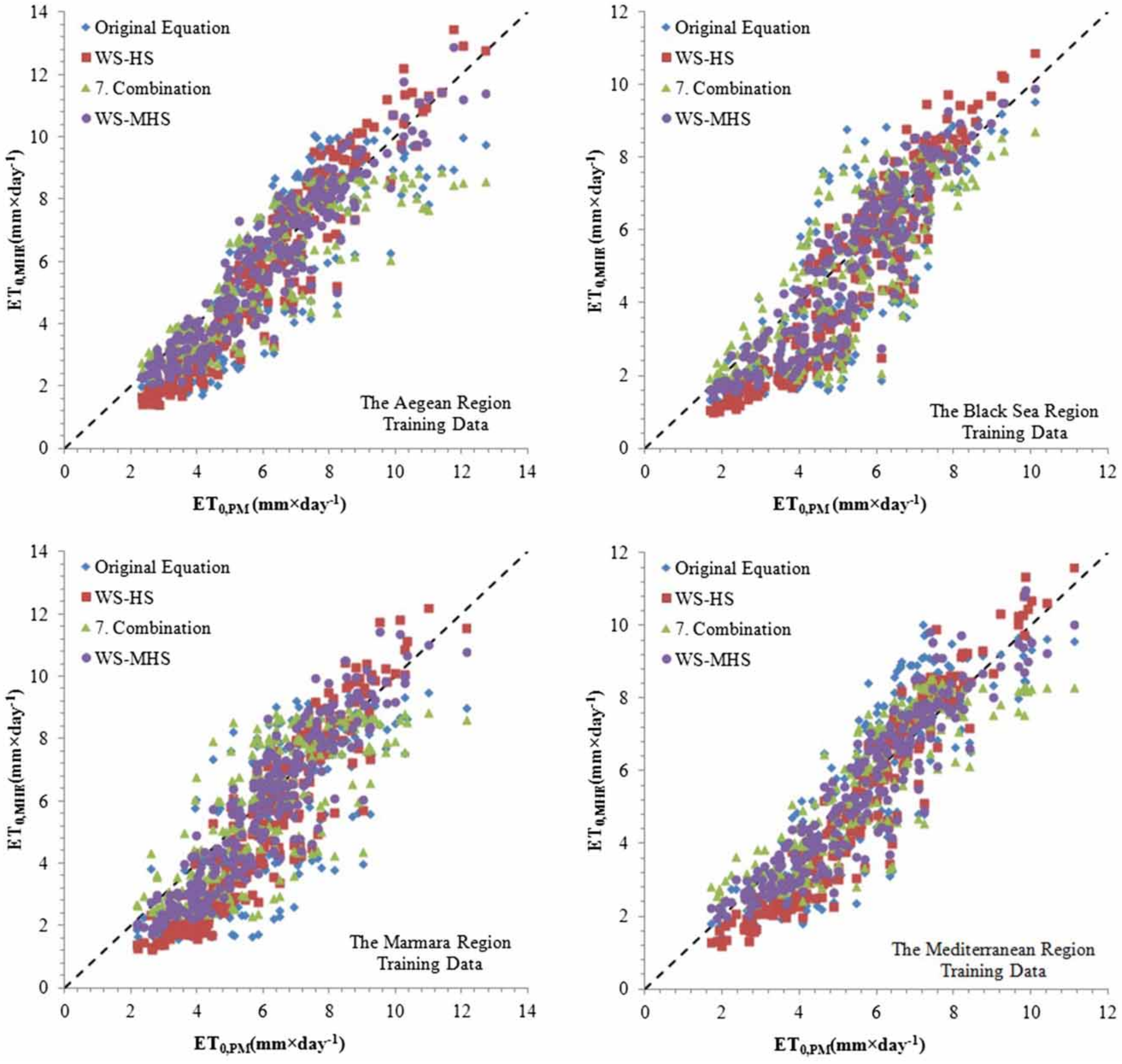

Figure 3 | Scatter diagram of the ET_0 values computed by the original and modified HS equations for coastal regions of Turkey.

inner regions of Turkey. It is also concluded from Tables 4 and 5 that calibration of coefficients of the HS equation reduces the MARE statistics by an average of 5%. In addition to that, calibration of the modified HS equation with inclusion of the wind speed decreases the MARE statistics almost 10%.

Figures 3 and 4 show the scatter diagrams of the ET_0 values computed by the FAO-56 PM equation versus those computed by the original and modified HS equations for the training stations of the calibration procedure for each region of Turkey. The original HS equation underestimates the small ET_0 values by between 2.0 mm/day and 6 mm/day for all regions of Anatolia, and overestimates the high ET_0 values above 6 mm/day for the Eastern Anatolia Region. It is seen from the scatter plots that the original HS equation results show large scatter around the exact line (dashed line). After calibration of the original HS equation with inclusion of the wind speed, the scatter plots become closer to the exact line especially for the inner regions. Only adjusting the coefficients of the HS equation improves the estimation capability, especially at inner regions and slightly at coastal regions. It is also seen from the scatter plots that calibration with inclusion of the wind speed data both for the original and the modified HS equations results in good agreement with the FAO-56 PM values. The scatter points are much closer to the

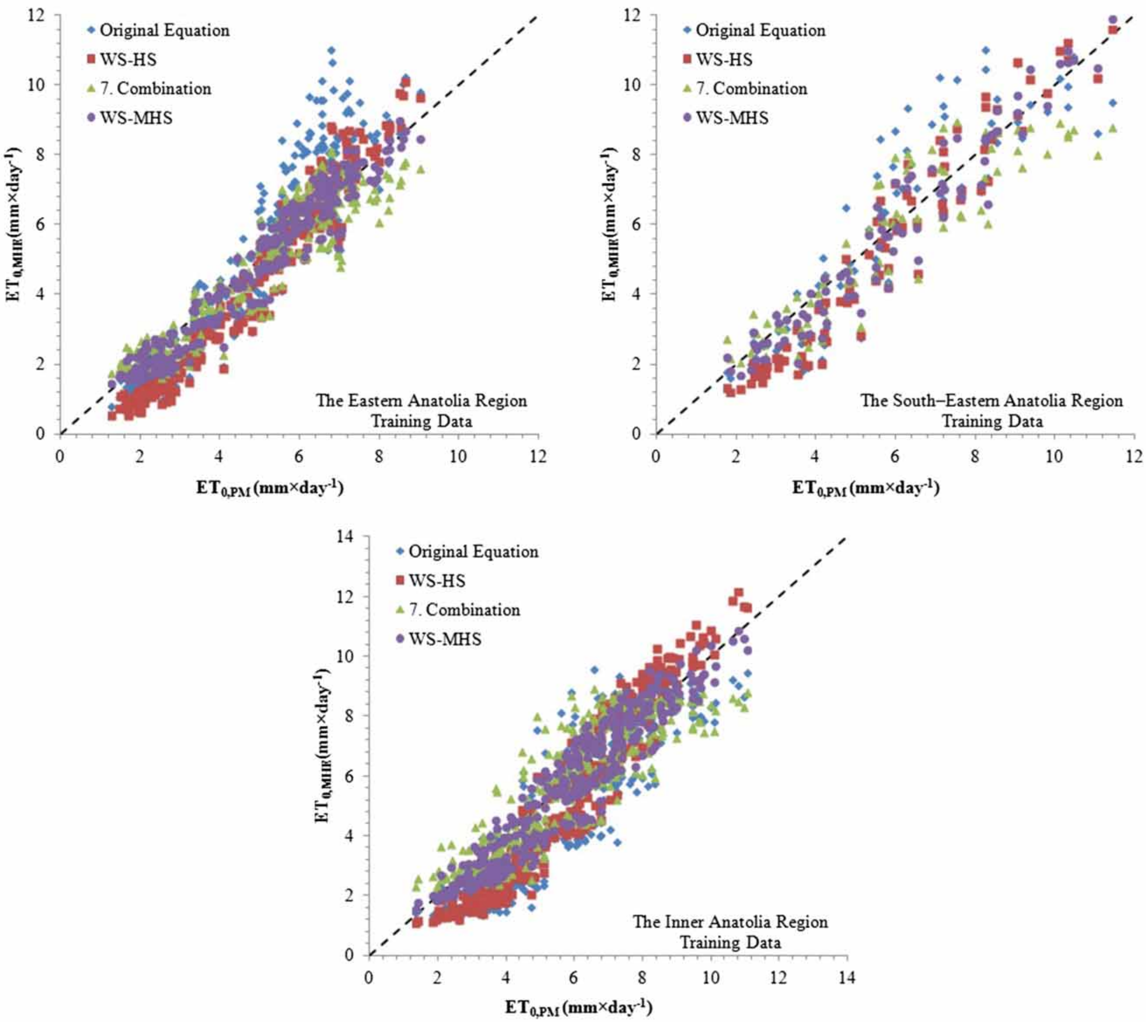

Figure 4 | Scatter diagram of the ET_0 values computed by the original and modified HS equations for inner regions of Turkey.

exact line, especially for coastal regions and partly for inner regions. To check the reliability of the modified HS equation, a total of 21 randomly chosen weather stations in seven regions were used. The results of the original and modified HS equations for validation data are also compared in Table 4 and the scatter plots are shown in Figures 5 and 6. In general, the modified HS equation estimates are closer to the exact line equation (dashed line). The modified HS equation with adjusted coefficients and calibration with inclusion of the wind speed data reduces the MARE statistics by almost 11% for the Mediterranean, 13% for the Marmara, 12% for Aegean, 15% for the Black Sea, 12% for Inner Anatolia and Eastern Anatolia, and 9% for the Southeastern Anatolia regions with the validation data sets. The modified HS equation for the Eastern Anatolia Region cannot reduce the MARE statistic, but it lowers the MAE and RMSE statistics slightly. Modification of the coefficients of the HS equations based on the Köppen climate classes gives better estimations than the original HS equation. However, regional calibration of the coefficient of the HS equation based on the geographical regions in Turkey performs consistently better than the Almorox & Grieser (2016) method. This shows that calibration of the HS equation for wide areas improves the estimation

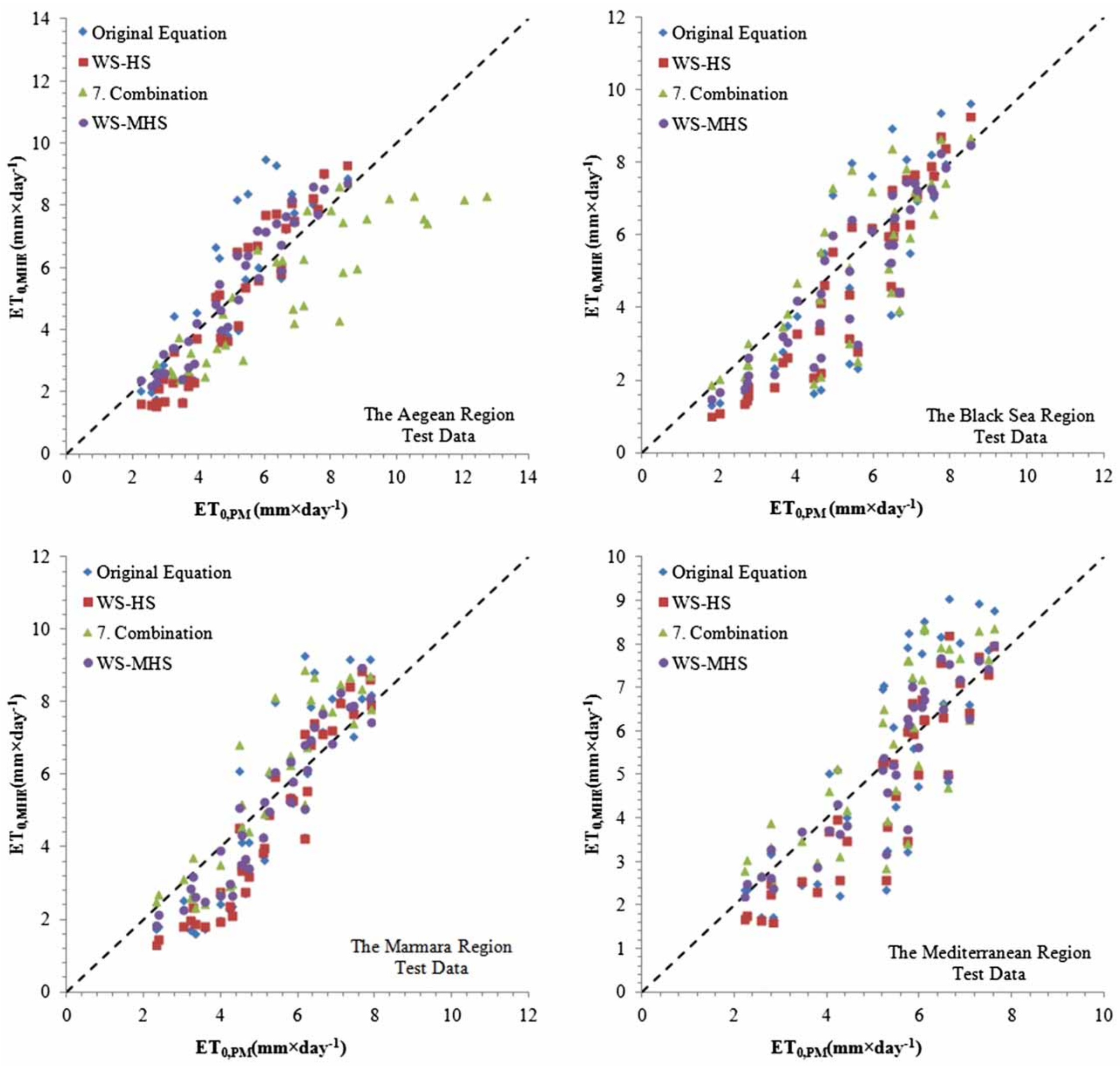

Figure 5 | Scatter diagram of the ET_0 values computed by the control, the reliability of modified HS equations for coastal regional of Turkey.

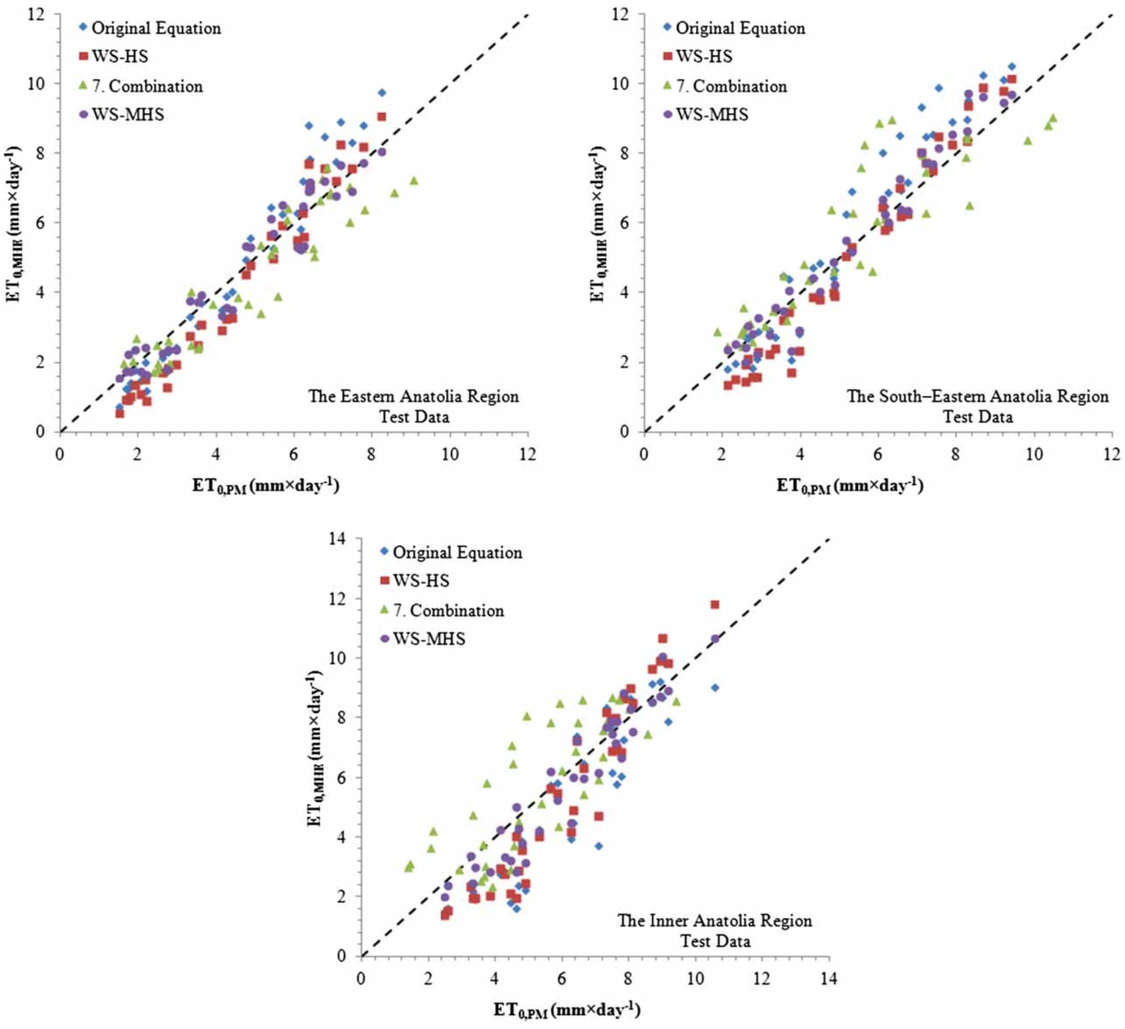

Figure 6 | Scatter diagram of the ET_0 values computed by the control, the reliability of modified HS equations for inner regions of Turkey.

capability of the HS equation to some extent, but regional calibration of the HS equation with FAO-56 PM has significant improvements in the estimation capability of the HS equation.

CONCLUSIONS

Here, the three coefficients of the original HS equation are modified for distinct climate regions of Turkey, which provide better ET_0 estimates. The results indicate that the best combination for modification of the HS equation, which allows all the three coefficients to assume different magnitudes from those of the original HS equation, provides the smallest values of RMSE statistics of those of the other coefficient adjusting combinations except for the Black Sea Region, where the best estimation is obtained by adjusting the other two coefficients while keeping the original magnitude for the e_H coefficient. With the purpose of further enhancing its accuracy, the wind speed is introduced as another explanatory variable to the HS equation by Equation (15) here, which has improved the estimation capability of the HS equation considerably.

When the results of all the combinations are compared, for all seven regions of Turkey, the best estimations are obtained from the ninth combination, which is the HS equation having all the three coefficients adjusted, which also has the wind speed as an extra explanatory variable. The effect of the wind speed is taken into account as a second step using Equation (15), which multiplies the ET_0 given by the modified HS equation by another coefficient, computed by a linear equation whose two coefficients are determined beforehand by regression. The second best estimation results are obtained by the original HS equation to which the wind speed is added for the coastal regions. Although the wind speed has similar statistical parameters for all regions, the results show that the coastal regions are more sensitive to the wind speed for estimation of ET_0 than the inner regions (Inner Anatolia, Southeastern Anatolia, and Eastern Anatolia regions) at which the continental climate prevails. The results indicate that the modified HS equation reduces the MAE and RMSE statistics for each region in Turkey more than the original HS equation. Calibration of coefficients of the HS equation reduces the MARE statistics on an average of 5%. In addition to that, calibration of the modified HS equation with wind speed data decreases the MARE statistics by almost 10%. Suitable magnitudes of the three coefficients of the HS equation can be computed by a similar analysis in other regions of the world as well. It should be kept in mind that the validity of the empirical equations is legitimate only in the regions where they are developed and within the ranges of the available data.

Although we have taken the results provided by the FAO-56 PM equation as the benchmark values throughout our study, it should still be borne in mind that this is also a calculation model, which may be inadequate for some cases. Also, some of the terms of the FAO-56 PM equation need to be calculated themselves, which may include some degree of uncertainty. It would be therefore much more reliable to attempt to improve either the HS equation or any other model based on actual lysimeter measurements naturally.

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