Evaluation of a radiation-based empirical model for estimating hourly reference evapotranspiration for high-altitude climatic conditions: A case study for the state of California

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High-altitude (>800 m) climatic conditions for the four stations in arid, semiarid and subhumid climatic zones were examined to evaluate their influence on radiation-based empirical estimations of reference evapotranspiration (ET_o) on an hourly time step. The empirical method utilises the incoming solar radiation and the relationship between a function of relative humidity and vapour pressure deficit. The empirical method overestimated ET_o by 21.4%, on a yearly basis, 27.0% for the winter period and 16.3% for the summer period, compared with the estimations of the American Society of Civil Engineers Penman Monteith (ASCE PM) (2005) method. Various meteorological variables included in the energy and the aerodynamic term of the ASCE PM (2005) method were investigated with respect to altitude. The increasing trend of incoming solar radiation combined with the decreasing trend of relative humidity, both with respect to altitude were the main causes for the underestimation of the empirical radiation method. The empirical method was adjusted for high-altitude climatic conditions by multiplying the values by the ratio of the atmospheric pressure corresponding to the altitude of the station to the atmospheric pressure at sea level. The adjusted values were overestimated by 3.4% compared to the estimations of the ASCE PM (2005) method (higher overestimation: 9.1% and lower overestimation: 0.8%). The value of 0.073 mm h^{-1} was considered as the upper limit for the satisfactory performance of the empirical method. The root mean square error (RMSE) values ranged from 0.038 to 0.054 mm h^{-1} and the R^2 values ranged from 0.95 to 0.97. The values of the wind speed and vapour pressure deficit (not included in the empirical method) were divided into intervals and the RMSE values between the values of the estimations of the empirical method and the values of the estimations of the ASCE PM (2005) were calculated for each interval. The RMSE values calculated for the intervals of the values of the wind speed ranged from 0.036 to 0.065 mm h^{-1} and were satisfactory. The vapour pressure deficit values <2.5 kPa also yielded satisfactory RMSE values and accounted for 96.1% of the data.

Keywords. Altitude; reference evapotranspiration; high-altitude meteorology.

1. Introduction

High-altitude climatic conditions and their relationship with evapotranspiration (ET) and the climatic parameters that determine it, i.e., net radiation, solar radiation, actual vapour pressure, relative humidity, etc., have been studied by many authors for daily or greater time steps. [Martínez-Cob and Cuenca \(1992\)](#) and [García *et al.* \(2004\)](#) have investigated the influence of altitude on ET . [Budyko \(1974\)](#) and [Marty *et al.* \(2002\)](#) have investigated the relationship between net radiation and altitude. [Lacis and Hansen \(1974\)](#), [Müller \(1985\)](#), [Bosch *et al.* \(2008\)](#) and [Ye *et al.* \(2009\)](#) examined the relationship between solar radiation and altitude. [Feld *et al.* \(2013\)](#) examined the relationship between the actual vapour pressure of the atmosphere and altitude. [Manabe and Wetherald \(1967\)](#), [Peixoto and Oort \(1996\)](#) and [Sakai *et al.* \(2000\)](#) investigated the relationship between relative humidity and altitude.

Accurate estimations of reference evapotranspiration (ET_o) are essential for climatologic and hydrologic studies and for efficient irrigation. A large number of methods for the calculation of ET have been proposed in the literature. The empirical methods use limited data to estimate ET ([Thornthwaite 1948](#); [Blaney and Criddle 1950](#); [Makkink 1957](#); [Jensen and Haise 1963](#); [Priestley and Taylor 1972](#); [Linacre 1977](#); [Alexandris and Kerkides 2003](#); [Irmak *et al.* 2003](#); [Alexandris *et al.* 2006](#)). At the same time, because of the reduced amount of data required, these methods are lacking in accuracy and their application in different climatic conditions needs to be evaluated before they are used ([Meyer 1999](#)). The empirical methods have been evaluated against various forms of Penman–Monteith (PM) method by many authors ([Amatya *et al.* 1995](#); [Xu and Singh 2002](#); [Itenfisu *et al.* 2003](#); [Trajkovic 2005](#); [Gavilán *et al.* 2006](#); [Alexandris *et al.* 2008](#); [Trajkovic and Kolakovic 2009](#); [Sentelhas *et al.* 2010](#); [Aschonitis *et al.* 2015](#)) to determine the accuracy of these methods.

The combination methods use a theoretical background ([Penman 1948](#); [Monteith 1965](#); [Allen *et al.* 1998](#); [Walter *et al.* 2005](#)) and need more data to estimate ET rates. These methods, compared to the empirical ones, are more accurate and reliable for a much wider range of climatic regimes and altitudes. [Jensen *et al.* \(1990\)](#) evaluated the PM method for a variety of climatic

regimes and altitudes and found that the estimations were sufficiently accurate against lysimeter data. American Society of Civil Engineers Penman Monteith (ASCE PM) (2005) is the standardised form of the PM method ([Walter *et al.* 2005](#)) for the calculation of ET_o . ASCE PM (2005) is a method widely accepted as the benchmark against which other methods can be evaluated.

California has a significant agricultural sector ([Faunt *et al.* 2015](#); [Tolomeo *et al.* 2015](#)) and is characterised by a wide variety of local climates ([Temesgen *et al.* 2005](#)). Several researchers have investigated the methods estimating ET for the State of California ([Hargreaves *et al.* 2003](#); [Mutziger *et al.* 2005](#); [Snyder *et al.* 2005](#); [Trajkovic 2010](#); [Gabriela Arellano and Irmak 2015](#)).

[Chatzithomas and Alexandris \(2015\)](#) proposed a new method for the estimation of the hourly ET_o rate for semiarid climatic conditions and evaluated it with data from Davis station of the California Irrigation Management Information System (CIMIS) network (California) and from the experimental grass reference station of the Agricultural University of Athens located in central Greece. The method utilises the direct measurements of incoming solar radiation, which bypasses the empiricism of the estimation of net radiation, which can lead to 5–6% overestimation on average, when we estimate hourly values of ET_o or its daily sums, relative to ET calculated from measured R_n ([Blonquist *et al.* 2010](#)).

In this paper, we examine the influence of high-altitude climatic conditions on the performance of a radiation-based empirical method ([Chatzithomas and Alexandris 2015](#)) for estimating the hourly value of ET_o . Data were taken in the case of high-altitude stations of the CIMIS network in California. The ASCE PM (2005) method was used as the benchmark.

2. Materials and methods

2.1 Methods

The ASCE PM (2005) ([Walter *et al.* 2005](#)) method for calculating ET_o for short crop (grass) and for hourly time step is used in this paper. The values of ET_o are taken as they are from the CIMIS database. All the equations used for

the calculation of the hourly rate of ET_o are given below:

$$ET_o = \frac{\Delta(R_n - G)}{\lambda(\Delta + \gamma(1 + C_d u_2))} + \frac{\gamma \left(\frac{37}{273.16 + T_a} \right) u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}, \quad (1)$$

where ET_o is the reference evapotranspiration (in mm h^{-1}); R_n is the net radiation flux density (in $\text{MJ m}^{-2} \text{h}^{-1}$), calculated according to [Duffie et al. \(1994\)](#); G is the soil heat flux density (in $\text{MJ m}^{-2} \text{h}^{-1}$): $G = 0.1R_n$ when $R_n > 0$ (daytime) and $G = 0.5R_n$ when $R_n < 0$ (night-time); u_2 is the average hourly wind speed at 2 m (in m s^{-1}); T is the average hourly temperature at 2 m (in $^{\circ}\text{C}$); C_d is the denominator constant with values $C_d = 0.24$ when $R_n > 0$ (daytime) and $C_d = 0.96$ when $R_n < 0$ (night-time); and e_s is the saturation vapour pressure of the atmosphere at T_a (in kPa)

$$e_s = 0.6108 \exp \left(\frac{17.27T_a}{237.3 + T_a} \right), \quad (2)$$

where e_a is the actual vapour pressure of the atmosphere (in kPa)

$$e_a = e_s \frac{\text{RH}}{100}, \quad (3)$$

where RH is the relative humidity of the atmosphere (in %) and Δ is the slope of the saturation vapour pressure curve (in $\text{kPa } ^{\circ}\text{C}^{-1}$)

$$\Delta = \frac{4099e_s}{(T + 237.3)^2}, \quad (4)$$

γ is the psychrometric constant (in $\text{kPa } ^{\circ}\text{C}^{-1}$)

$$\gamma = 0.00163 \frac{P}{\lambda}, \quad (5)$$

$$P = 101.3 \left(\frac{293 - 0.0065A}{293} \right)^{5.26}, \quad (6)$$

where P is the atmospheric pressure (in kPa) and A is the altitude of the station (in m).

$$\lambda = 2.501 - 0.002361T, \quad (7)$$

where λ is the latent heat of vaporisation (in MJ kg^{-1}).

[Chatzithomas and Alexandris \(2015\)](#) method, referred to as the empirical method from now on, was also used to estimate hourly reference ET_o .

The empirical method utilises two meteorological variables, namely, R_s and RH. It also takes into account the daylight hours (N) as a fraction of the 24-hr period (fN), e.g., a daylight duration (N) of 12 hr would give an fN value of $(12/24) = 0.5$.

The equation is

$$ET_o = \begin{cases} 0.200382744 + 0.000411692R_s - 0.002353982\text{RH} \\ + 0.0002321 (R_s^{1+\text{fN}-\text{fNmin}}) \left(\frac{1}{\ln(\text{RH})} \right), R_s \geq 0 \\ 0, R_s < 0, \end{cases} \quad (8)$$

where ET_o the hourly reference evapotranspiration (in mm h^{-1}), R_s is the incoming solar radiation (in W m^{-2}), RH is the relative humidity (in %), fN is the theoretical daylight duration as a fraction of the 24 hr and fN_{min} is the minimum theoretical daylight duration of the year as a fraction of the 24 hr.

2.2 Statistical and climatic indices

2.2.1 Coefficient of determination

This is given by

$$R^2 = \frac{\sum (y - y_{av})(\hat{y} - \hat{y}_{av})}{\sqrt{\sum (y - y_{av})^2 (\hat{y} - \hat{y}_{av})^2}}, \quad (9)$$

where y is the ASCE PM value, y_{av} is its average, $\hat{y}$ is the estimation of the empirical method and $\hat{y}_{av}$ is its average. The coefficient of determination is a correlation-based measure of evaluating the goodness of fit of models. It indicates the part of the total variance that is explained by the model, and it is used in conjunction with other measures because it is very sensitive to extremely large values and insensitive to additive and multiplicative differences between the estimation and the actual value ([Legates and McCabe 1999](#)).

2.2.2 Slope

The slope of the regression line is calculated according to the following equation:

$$\text{Slope} = \frac{\sum (y - y_{av})(\hat{y} - \hat{y}_{av})}{\sum (y - y_{av})^2}, \quad (10)$$

variables have the same meaning as in equation (9).

2.2.3 Intercept

It is the value of the point of the y -axis, where the regression line intersects it. It is calculated according to the following equation:

$$\text{Intercept} = y_{\text{av}} - \text{slope} * x_{\text{av}}, \quad (11)$$

variables have the same meaning as in equation (9).

2.2.4 Root mean square error (RMSE)

This is a measure of the magnitude of the error:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum (y - \hat{y})^2}, \quad (12)$$

variables have the same meaning as in equation (9).

Ventura *et al.* (1999) considered a value of 0.073 mm h^{-1} satisfactory for the RMSE between the estimations of the empirical method and the estimations of the ASCE PM (2005).

2.2.5 Index of agreement (IoA)

This was introduced by Willmott (1982) with values between 0 and 1, where 1 means perfect agreement between simulated and observed values:

$$\text{IoA} = 1 - \frac{\sum (\hat{y} - y)^2}{\sum (|\hat{y} - y_{\text{av}}| + |y - y_{\text{av}}|)^2}. \quad (13)$$

2.2.6 Aridity index (AI)

This is a climatic index used to assess the dryness of a geographical location (Kukal and Irmak 2016; Shan *et al.* 2016). We calculated the AI as the ratio of the annual amount of precipitation (in mm) to the annual amount of ET_o (in mm) according to the following equation:

$$\text{AI} = \frac{P}{ET_o}, \quad (14)$$

where AI is the aridity index (dimensionless), P is the precipitation (in mm yr^{-1}) and ET_o is the ET calculated using grass as the reference crop (in mm yr^{-1}). The author used the yearly value of ET_o of grass as it is in the CIMIS database. ET_o values have been used in the literature for the calculation of AI (van der Schrier *et al.* 2011; Todorovic *et al.* 2013; Kukal and Irmak 2016). The dryness is categorised according to the AI values. The AI values were used to classify an area as hyper-arid ($\text{AI} \leq 0.05$), arid ($0.05 < \text{AI} \leq 0.20$), semiarid ($0.20 < \text{AI} \leq 0.50$) and subhumid ($0.50 < \text{AI} \leq 0.75$).

2.3 Data

2.3.1 CIMIS network

The CIMIS is operated by the Water Use and Efficiency Branch, Division of Statewide Integrated Water Management, California Department of Water Resources (DWR). It consists of a network of over 145 automated weather stations in California. CIMIS network of weather stations collects weather data on a minute-by-minute basis and averages them on an hourly basis. The hourly averages concern data collected during the previous 60 min. A computer at the DWR headquarters retrieves data at predetermined time intervals.

CIMIS data are checked for their accuracy of the measured weather data and for quality. ET_o is calculated along with other parameters needed for this end. Measured and calculated parameters are flagged and stored in the CIMIS database. The data are freely available online for registered users.

For the selection of high-altitude stations from arid, semiarid and subhumid climatic conditions, all available monthly data for all the CIMIS stations were downloaded from the CIMIS database. In total, 26,364 monthly records were used for 139 stations. For each of the 139 stations of the

Table 1. CIMIS meteorological stations used for this paper. In total, 33,383 hourly records from the four meteorological stations (altitudes $>800 \text{ m}$) were analysed.

Station ID	Name	Latitude	Longitude	Altitude (m)	Year	No. of records	Remarks
199	Big Bear Lake	34.24	-116.87	2106	2008	8701	Altitude
91	Tulelake	41.96	-121.47	1230	2000	8545	Altitude
43	McArthur	41.06	-121.46	1008	2000	8057	Altitude
13	Camino	38.75	-120.73	874	2000	8080	Altitude
Total no. of records						33,383	

The CIMIS stations were selected based on their altitude.

Table 2. Yearly and seasonal (winter and summer) sums of the estimations of the hourly reference evapotranspiration calculated with the empirical method and the ASCE PM (2005) method, their difference, their difference as a percentage of the ASCE PM (2005) sum and the statistical indices of the empirical method against the ASCE PM (2005) method for all the four high-altitude stations).

	Empirical (mm yr ⁻¹)	ASCE PM (2005) (mm yr ⁻¹)	Empirical- ASCE PM	Empirical- PM (%)	R^2	RMSE	Slope	IoA
Big Bear Lake	1847.6	1316.2	531.4	40.4	0.95	0.080	1.07	0.966
Tulelake	1324.8	1108.9	215.9	19.5	0.96	0.060	1.17	0.980
McArthur	1295.9	1148.7	147.2	12.8	0.97	0.051	1.09	0.987
Camino	1520.5	1360.8	159.8	11.7	0.97	0.048	1.00	0.989
Average	1497.2	1233.6	263.6	21.1				
Total	5988.8	4934.5	1054.2	21.4	0.96	0.062	1.08	0.981

Stations in the first column were placed from higher (Big Bear Lake) to lower (Camino) altitude.

CIMIS network, averages were calculated from the 26,364 downloaded monthly records for ET_o and for precipitation. The AI was calculated according to equation (14).

Four CIMIS weather stations (see table 1) were selected according to the altitude of the station (altitude ranged from 874 to 2016 m). One station (Big Bear Lake, AI = 0.20) had arid climatic conditions. Two stations (Tulelake, AI = 0.25 and McArthur, AI = 0.39) had semiarid climatic conditions and one station (Camino, AI = 0.65) had subhumid climatic conditions. The station with the highest altitude (Big Bear Lake, station ID 199) also had the lowest average temperature. Hourly data for these four CIMIS meteorological stations were downloaded from the CIMIS database. In total, 33,383 hourly records were downloaded for all the four stations. Years with complete records were preferred as much as possible.

3. Results and discussion

The four CIMIS stations were selected according to their altitude (Big Bear Lake, altitude 2106 m, year 2008, 8701 records; Tulelake, altitude 1230 m, year 2000, 8545 records; McArthur, altitude 1008 m, year 2000, 8057 records; and Camino, altitude 874 m, year 2000, 8080 records) and climatic regime (semi-arid, arid and subhumid), totalling 33,383 hourly records for the four CIMIS stations. The value of the hourly rate of ET_o was calculated using the empirical method for all the hourly records. The values of the estimations of the hourly rate of ET_o with the ASCE PM (2005) method were those downloaded from the CIMIS database. To assess the precision of the estimations of the empirical method in high-altitude climatic conditions, yearly, winter and summer sums of hourly ET_o estimations for both the empirical method

Figure 1. Plot of the cumulative values of the estimations of the hourly reference evapotranspiration with the empirical method, and with cumulative values of the estimations of the ASCE PM (2005) method for the four CIMIS stations (33,383 hourly values), and we evaluate the empirical method for the high-altitude climatic conditions in the State of California.

and the ASCE PM (2005) method; their difference (empirical yearly sum – ASCE PM yearly sum); their difference as a percentage of the ASCE PM (2005) yearly sum; and the four statistical indices (R^2 , RMSE, slope and IoA) were also calculated (see table 2).

The sum of the estimations of the empirical method was found to be equal to 5988.8 mm compared to 4934.5 mm for the ASCE PM (2005) method. In figure 1, we can see the plot of the cumulative hourly values of both the methods. The difference between the sum of the estimations of the empirical method and the sum of the estimations of the ASCE PM (2005) method was found to be equal to 1054.2 mm or 21.4% of the sum of the estimations of the ASCE PM (2005) method for all the stations, which is not satisfactory. The bias (overestimation) of the radiation-based

empirical method is consistent for all high-altitude stations.

The statistical indices for the two methods were calculated. The coefficient of determination (R^2) between the estimations of the two methods was found to be equal to 0.96, the RMSE to 0.062 mm h^{-1} , the slope of the regression line to 1.08 and the IoA to 0.981. The two methods were found to be in satisfactory agreement, in terms of the values of R^2 , RMSE and IoA. The value of the slope of the regression line indicates the overestimation of the empirical method, in accordance with the cumulative values of both the methods, and it is not satisfactory.

The yearly sums of the estimations of both the empirical and ASCE PM (2005) methods were calculated for each station (see table 2) and found that in all high-altitude stations, the empirical method overestimates. The highest overestimation was in the highest altitude station, Big Bear Lake, 2016 m, where the yearly sum of the values of the hourly ET_o estimations of the empirical method was 40.4% or 531.4 mm. The lowest overestimation was in the lowest altitude station, Camino, 874 m, where the yearly sum of the hourly estimations of the empirical method was 11.7% or 159.8 mm. The increase in the bias of the empirical-based model with altitude indicates the

effect of high-altitude climatic conditions on the radiation-based estimations of ET_o .

The coefficient of determination (R^2) was calculated for each of the stations (see table 2 and figure 2). The lowest value of the coefficient of determination for the four stations was equal to 0.95 (Big Bear Lake station, altitude 2106 m) and the highest value of the coefficient of determination for the four stations was equal to 0.97 (McArthur station, altitude 1008 m and Camino station, altitude 874 m). The coefficient of determination between the estimation of the empirical method and the estimations of the ASCE PM (2005) method was satisfactory for all the four high-altitude stations. The RMSE was also calculated for each station and ranged from 0.048 mm h^{-1} (Camino station) to 0.080 mm h^{-1} (Big Bear Lake station). The value of the RMSE is satisfactory (below the 0.073 mm h^{-1} limit) for the three high-altitude stations (Tulelake, McArthur and Camino) and not for Big Bear Lake station.

We also calculated the value of the IoA between the values of the hourly ET_o estimations of the two methods, for each of the four stations. The highest value was found to be equal to 0.989 (Camino station), and the lowest value was found to be equal to 0.966 (Big Bear Lake station). The values of the IoA were satisfactory and showed a very

Figure 2. Scatterplots of the values of the hourly ET_o estimations of the ASCE PM (2005) method (independent variable, x-axis) against the values of the hourly ET_o estimations of the empirical method (dependent variable, y-axis) for the four high-altitude stations. The solid line is the regression line (red). The dotted (black) line is the 1:1 line.

good agreement between the estimations of the empirical method and the estimations of the ASCE PM (2005) method.

The same indices were calculated for the winter and summer periods for all the stations (see supplementary table S1). The overestimation of the empirical method was consistent (27.0% for winter and 16.3% for summer). R^2 , slope and IoA were more satisfactory for summer. Smaller RMSE values calculated for winter were attributed to the significantly lower ET_o values (95.5 mm for winter and 552.4 mm for summer). The ratio of the overestimation of the empirical method to the ASCE PM (2005) method is also a measure of the relative error of the empirical method and supports the better performance of the empirical method during the summer period for high-altitude climatic conditions, despite lower RMSE values for the winter period. The yearly values of the statistical indices are always within the range of the seasonal values. Summer is the most important part of the year because of the increased needs for water consumption. The performance of the empirical model is best during the summer period compared to the yearly and the winter periods, which is supported by the similar results of Chatzithomas and Alexandris (2015) for the summer period under the climatic conditions of Davis, California, and for the performance of the empirical method under the (similar to Davis) climatic conditions of Copais, Greece.

It can also be remarked that in all cases (yearly, winter and summer), the statistical indices tended to improve with decreasing altitude (Big Bear Lake to Camino). Ravazzani *et al.* (2012) suggested that the elevation of the station correlated with the observed error of estimation for the Hargreaves Samani (Hargreaves 1994) (HS) equation and corrected it by introducing a linear equation calibrated against FAO PM estimations.

3.1 Effects of high altitude on various climatic variables and adjustment for these effects

The effect of altitude is very important on a number of climatic parameters such as T , R_s , e_a , e_s , etc. These climatic parameters determine the climatic conditions of the locations considered. ET_o is a climatic parameter expressing the evaporating power of the atmosphere (Allen *et al.* 1998). The ASCE PM (2005) method calculates ET_o by recognising two components of the flux, namely the radiation term and the aerodynamic term (the first

and second terms, respectively, of the right-hand side of equation 1). The radiation term is a measure of the energy availability that, for high altitude, with adequate soil moisture, is a limiting factor (Isard and Belding 1989; Ma *et al.* 2015). The radiation or diabatic or energy term of the ASCE PM (2005) method is the amount of the available energy ($R_n - G$) weighed by a factor (w_{rad}) equal to $\Delta/(\Delta + \gamma(1 + C_d \times u_2))$, which depends on the temperature, altitude and wind speed (see equations 1, 2 and 4–7).

The empirical method, however, does not take into account the net radiation, temperature or wind speed. The incoming solar radiation is used instead as the only direct measure of the available energy. Therefore, high-altitude climate introduces additional sources of bias. It can be concluded that the empirical method would give higher hourly rates of ET_o with higher hourly values of the incoming solar radiation and smaller hourly rates of ET_o with smaller hourly values of the incoming solar radiation, all other factors being the same (see equation 8).

The aerodynamic term (the second term of the right-hand side of equation (1)) of the ASCE PM (2005) method depends mainly on the values of the vapour pressure deficit (VPD) of the atmosphere and the value of the wind speed (u_2). Similarly, the factor of the aerodynamic term (w_{aero}) is equal to $(\gamma(37/(273.16 + T_a)))/(\Delta + \gamma(1 + C_d u_2))$ and depends on the air temperature, altitude and wind speed (see equations 1, 2 and 4–7). The empirical method does not take into account the values of the temperature and wind speed and uses the relationship between the value of the VPD and the inverse of the natural logarithm of the RH (Chatzithomas and Alexandris 2015).

Therefore, the yearly average of the hourly values of R_n ($W\ m^{-2}$), w_{rad} , R_s ($W\ m^{-2}$), e_s (kPa), e_a (kPa), VPD (kPa), RH (%), T ($^{\circ}C$), u_2 ($m\ s^{-1}$) and w_{aero} for each one of the four high-altitude stations was calculated (see table 3). An increase in the values of these climatic variables produces an increase in the value of the ET_o rate, with the exception of e_a and RH. An increase in RH value is associated with the decreases in the ET_o rate. e_s and e_a values are combined in the VPD value. Therefore, they were examined together in order for the behaviour of the VPD values with altitude to be interpreted. Additionally, the same values of Davis station for year 2000 (calibration year of the empirical method) were calculated. The altitude of Davis station is 18 m, and thus, this enabled the

Table 3. Average values of R_n ($W m^{-2}$), w_{rad} (weighing factor of the radiation term of the ASCE PM (2005) method), R_s ($W m^{-2}$), e_s (kPa), e_a (kPa), VPD (kPa), T ($^{\circ}C$), RH (%), u_2 ($m s^{-1}$) and w_{aero} , calculated from the hourly records of each station located at a high altitude.

Station name	R_n ($W m^{-2}$)	w_{rad}	R_s ($W m^{-2}$)	VPD (kPa)	e_s (kPa)	e_a (kPa)	T ($^{\circ}C$)	u_2 ($m s^{-1}$)	w_{aero}	RH (%)	Remarks
Big Bear Lake	93.3	0.41	226	0.7	1.2	0.5	7.5	2.0	0.038	51	Overestimation
Tulelake FS	88.8	0.39	197	0.5	1.3	0.8	8.2	2.2	0.039	72	Overestimation
McArthur	97.0	0.41	208	0.6	1.5	0.9	10.1	2.1	0.038	72	Overestimation
Camino	99.1	0.44	218	0.9	1.8	0.9	14.3	2.4	0.032	61	Overestimation
Average	94.6	0.41	212	0.7	1.5	0.8	10.0	2.2	0.037	64	Overestimation
Davis	93.8	0.43	202	0.8	1.9	1.1	15.2	2.5	0.033	70	

The weighing factor of the radiation term and aerodynamic term of the ASCE PM (2005) method (w_{rad} and w_{aero}) were calculated for each hourly record of each station according to equations (1–7). The average hourly values were then calculated for each station. Using the same equations and the same averaging procedure, we calculated the same values for Davis station (altitude 18 m) for year 2000 (calibration year of the empirical method).

altitudinal effects on the calculated values to be demonstrated and analysed.

3.1.1 Effects of high-altitude climate on the radiation term of the ASCE PM (2005) method

The average of all the hourly values of the net radiation of the four high-altitude stations was calculated and was found to be equal to $94.6 W m^{-2}$. The average of the hourly values of the net radiation for Davis stations for year 2000 was also calculated and was found to be equal to $93.8 W m^{-2}$. The coefficient of determination between the averages of the hourly values of R_n of each station and the altitude of the station was calculated and found to be equal to 0.04. The almost identical values of the two averages, which are evident in the very low coefficient of determination, do not indicate any altitudinal effects on the amount of the net radiation. Garcia *et al.* (2004) investigated the dependence of R_n on the altitude for the Bolivian Altiplano (high plateau between 3600 and 4000 m) and found that R_n levels between sea level and the plateau were similar. Marty *et al.* (2002) investigated the dependence of R_n on the altitude using data from 11 stations in the Swiss Alps, with altitudes from 370 to 3580 m. They reported decreasing annual and winter R_n values with increasing altitude and almost constant R_n values during summer regardless of the altitude of the station. Rosset *et al.* (1997) noted that during the growing season, R_n should vary little with altitude. Budyko (1974) comments that almost constant R_n rates below the snow line can be attributed to the balance between

shortwave and net long-wave radiation trends. Barry (2008) attributed the decreasing trend of the annual and winter R_n values to the presence of snow, which increases the albedo of the surface and reduces the net shortwave radiation. Similarly, he also remarks that in summer, the net radiation stays almost constant with altitude. In a reference environment, albedo is by definition constant and equal to 0.23, and therefore, the findings of this research (same R_n levels for low and high altitudes) are in line with the findings of previous researchers.

The yearly averages of the hourly values of w_{rad} ($\Delta/(\Delta + \gamma(1 + C_d \times u_2))$), weighing factor of the radiation term of the ASCE PM (2005) method, which represent the fraction of the available energy allocated to latent heat, were calculated for all the four high-altitude stations and for Davis station (see table 3 and figure 3b). The average of all the four high-altitude stations was found to be equal to 0.41. The range of the w_{rad} values was 0.05 (0.39–0.44). The yearly average for Davis station was found to be equal to 0.43. The coefficient of determination and the slope of the regression line between the values of w_{rad} (dependent variable, see figure 3b) of each station and the altitude of the station (independent variable) were calculated. The calculated slope of the regression line between the values of the yearly average of w_{rad} factor and the altitude of each station was negative (-1.25×10^{-5}) and shows a slight decreasing trend of the weighing factor with altitude. The coefficient of determination was found to be equal to 0.23.

Similar net radiation values and the decreasing values of the weighing factor (w_{rad}) with altitude

Figure 3. Plots of the yearly averages of the hourly values of (a) R_n ; (b) the weighing factor, w_{rad} ($\Delta/(\Delta + \gamma(1 + C_d \times u_2))$), of the radiation term of the ASCE PM (2005) method; (c) the incoming solar radiation R_s ; (d) the VPD; (e) the actual and the saturated vapour pressures of the atmosphere; (f) the temperature; (g) the wind speed; (h) w_{aero} ; and (i) the relative humidity RH as the dependent variable against the altitude of each station as the independent variable. Regression lines indicate the increasing or decreasing trend of each variable with respect to altitude.

for all the four high-altitude stations suggest that lower amounts of the net radiation are received from the radiation term of the ASCE PM (2005) method due to altitudinal effects. Lower radiation terms of the ASCE PM (2005) method, for higher altitudes, have also been reported by Garcia *et al.* (2004). The small value of the coefficient of determination, however, combined with the range of the average w_{rad} values suggests that further examination of the incoming solar radiation is necessary.

The average of all the hourly values of R_s was calculated and was found to be equal to $212 W m^{-2}$. The same average was calculated for Davis station, year 2000 ($202 W m^{-2}$). The highest value of the yearly average of the hourly values of R_s was calculated for Big Bear Lake station (station with the highest altitude 2106 m) and was found to be equal to $226 W m^{-2}$. The lower value of R_s was calculated for Tululake station (altitude 1230 m) and was found to be equal to $197 W m^{-2}$. The

coefficient of determination between the average of the hourly values of the incoming solar radiation and the altitude of each station was calculated and was found to be equal to 0.38 (see figure 3c). Bosch *et al.* (2008) suggested that altitude is the most important geographic variable in estimating daily global radiation. Budyko (1974) comments that the variations in the shortwave radiation are due to both changes in terrain altitude and the regime of cloudiness. Altitude and cloud cover are considered to be important factors in R_s estimation procedures (Allen *et al.* 1998). The solar radiation models as a function of altitude have been reported in the literature (Lacis and Hansen 1974). Increases in the incoming solar radiation have been reported with increasing altitude (Müller 1985; Barry 2008; Ye *et al.* 2009). This trend is attributed to higher transmissivities and lower levels of turbidity which occur at high altitudes (Hottel 1976). This general trend observed in the selected stations supports

previous research findings. Radiation-based estimates of ET will, therefore, be distorted by this trend, and this distortion is systematic as far as the increase in altitude is concerned and the subsequent microclimate that is associated with it.

The increased values of the incoming solar radiation can account for the increased estimations of the hourly values of ET_o from the radiation-based empirical method (see equation 9). Higher estimations of the empirical method for higher values of the incoming solar radiation, as the altitude of the station increases, contribute to the overestimation of the empirical method compared with the estimations of the ASCE PM (2005) method. Equally influenced radiation methods should, therefore, give similar overestimations in high-altitude climatic conditions.

3.1.2 Effects of high-altitude climate on the aerodynamic term of the ASCE PM (2005) method

VPD, u_2 and w_{aero} ($(\gamma(37/(237,16 + T_a)))/(\Delta + \gamma(1 + C_d u_2))$), i.e., the second term of the right-hand side of equation (1), are part of the aerodynamic term of the ASCE PM (2005) method. The average of all the hourly values of the VPD and u_2 for all the four high-altitude stations was calculated.

The average value of the VPD was found to be equal to 0.7 kPa. The average of the hourly values of the VPD for Davis station, year 2000 (altitude 18 m), was also calculated and found to be equal to 0.8 kPa. The average of the hourly values of the VPD for all the four high-altitude stations was calculated. Camino station (altitude 874 m) was the station with the highest average of the hourly values of the VPD (0.92 kPa), and Tulelake station (altitude 1230 m) was the station with the lowest average of the hourly values of the VPD (0.53 kPa). The coefficient of determination between the averages of the hourly values of the VPD of each station and the altitude of the station was found to be equal to 0.08 (see figure 3d). The small R^2 and slope values suggest that the correlation of VPD with altitude is negligible. VPD is defined as the difference between the saturation vapour pressure (temperature dependent) and actual vapour pressure. Therefore, we calculated the averages of the hourly values of T ($^{\circ}\text{C}$), e_s and e_a , (kPa) for the four high-altitude stations and for Davis station, year 2000, as shown in figure 3(e and f), respectively.

The averages of the hourly values of the temperature of each station (dependent variable) were plotted against the altitude of each station (independent variable, figure 3f). The slope of the regression line between these values was found to be equal to $-0.004^{\circ}\text{C m}^{-1}$. The coefficient of determination for the same data has been calculated and found to be equal to 0.74. The decreasing air temperatures with altitude are well known (Harding 1979; Rolland 2003; Goulden *et al.* 2012) and are studied for a variety of scientific fields (Trumbore *et al.* 1996). A direct consequence of the above in conjunction with equation (2) is a reduction, due to elevation, in saturation vapour pressure of the atmosphere, which is an exponential function of air temperature. Similarly, minimum temperatures of the atmosphere are also reduced. Kimball *et al.* (1997) suggested that minimum air temperature can be used as a surrogate for the estimation of dew temperature, i.e., the actual vapour content of the atmosphere. It was also suggested that in arid climatic conditions, the difference between minimum and dew temperatures would insert deviations between estimated and actual vapour contents of the atmosphere. The measurements of the actual vapour pressure at both weather stations and the free air have shown decreasing values with altitude (Prohaska 1970; Feld *et al.* 2013). Various models of estimating the actual vapour pressure as a function of altitude have been proposed. In figure 3(e), the least squares line between the averages of the hourly values of the actual and saturated vapour pressures of the four high-altitude stations and the altitude of the station (independent variable) was plotted. Both the saturation vapour pressure and the actual vapour pressure were decreasing with respect to altitude (see figure 3e). The slope of the regression lines of e_a and e_s (dependent variables, y -axis) against altitude (independent variable, x -axis) was negative and (both) equal to $-0.0004 \text{ kPa m}^{-1}$. The coefficient of determination was equal to 0.89 for the actual vapour pressure and 0.66 for the saturation vapour pressure. The findings of this paper were in agreement with the findings of the previous research.

The average of the hourly values of the wind speed was calculated and found to be equal to 2.2 m s^{-1} . The average of the hourly values of the wind speed for Davis station, year 2000 (altitude 18 m), was also calculated and was found to be equal to 2.5 m s^{-1} . The average of the hourly values of the wind speed was calculated for each

station separately. Camino station was the station with the highest average of the hourly values of the wind speed (2.40 m s^{-1}), and McArthur station (altitude 1008 m) had the lowest average of the hourly values of the wind speed (2.1 m s^{-1}). The coefficient of determination between the average of the hourly values of the wind speed of each station and the altitude of the station was calculated and was found to be equal to 0.78. The slope of the regression line for the same data was found to be equal to -0.0003 , indicating slightly smaller values of the wind speed (u_2) as altitude increases. Barry (2008) suggested that the most important properties of wind velocity over mountainous regions are related to their topographic rather than to their altitudinal effects. Körner (2007) also notes that the wind is not an altitude-specific characteristic. In fact, according to the same author, mountains, as a whole, are among the less windy places on the Earth mainly because of their topography. With these remarks and the fact that areas of concern for the estimation of ET_o , such as the areas covered by the CIMIS network, are mainly agricultural areas, into account, we can either restrict the validity of the observations to similar (agricultural use) high-altitude areas or extend them to areas other than high-altitude locations, topographically exposed to high winds. The findings of this paper are in agreement with the findings of previous research. They are also important for areas of agricultural uses.

The average of the 33,383 hourly values of the w_{aero} part of the aerodynamic term of the ASCE PM (2005) method ($(\gamma(37/(237.16 + T_a))/(\Delta + \gamma(1 + u_2 C_d)))$) was calculated and was found to be equal to 0.037. The same value was calculated for Davis station, year 2000 (altitude 18 m), and was found to be equal to 0.033. The same averages were calculated for each station, and the maximum value was calculated for Tullake station (0.039), and the minimum value was calculated for Camino station (0.032). The values of the four stations and Davis station were plotted against the altitude of each station (independent variable, x -axis). The slope of the regression line between them was found to be equal to 3×10^{-6} . The coefficient of determination was found to be equal to 0.37.

In the case of the four high-altitude stations, the small values of the coefficient of determination ($R^2=0.08$) between the VPD (dependent variables) and the value of the altitude (independent variable) of each station and the opposite trends of wind speed (decreasing) and w_{aero} (increasing) with

altitude do not support any hypothesis regarding any positive or negative influence of the altitude on the aerodynamic term of the ASCE PM (2005) method.

Although the VPD values show no appreciable trend (see figure 3d), e.g., the values of Big Bear Lake and Davis stations were very close, Big Bear Lake had much lower e_s and e_a values which gave the similar VPD value compared with the VPD value of the Davis station. Their ratio, however, i.e., RH, was not the same. It was higher for Davis and lower for Big Bear Lake station. The aerodynamic part of the ASCE PM (2005) method uses VPD for the estimation of the aerodynamic term, i.e., the drying power of the atmosphere, while the empirical method uses the RH variable for the same purpose. Therefore, the average of the hourly values of the RH for all the 33,383 values was calculated and found to be equal to 64%. The average of the hourly values for the Davis station was also calculated and found to be equal to 70%. We calculated the averages of the hourly values of the relative humidity (RH, dependent variable, y -axis) for each one of the four high-altitude stations and for Davis station, and we plotted these values against the altitude (independent variable, x -axis) of each station (see figure 3i). The slope of the regression line and the coefficient of determination between the averages of the hourly values of the RH and the altitude of each station were calculated and found to be equal to -0.008 (slope) and 0.44 (R^2). The lower temperatures in high-altitude climatic conditions determine the upper limit of the vapour pressure known as saturation vapour pressure, and since the saturation vapour pressure in high altitudes is low, the actual vapour pressure is also low. When the gradient of VPD is negligible with altitude, the RH values tend to decrease. Manabe and Wetherald (1967), Peixoto and Oort (1996) and Sakai *et al.* (2000) have also reported decreasing RH values with altitude. Smaller values of the RH produce higher values of the hourly rate of ET_o when calculated with the empirical method, all other factors being the same (see equation 9), which contribute to its overestimation for the high-altitude climatic conditions in the State of California.

3.1.3 Adjustment of the empirical method for altitudinal effects

High-altitude climatic conditions for the four stations located above 800 m gave overestimations

Figure 4. Plot of the adjusted cumulative values of the estimations of the empirical method and the values of the estimations of the ASCE PM (2005) method. The estimations of the empirical method were adjusted using the ratio of the atmospheric pressure of the station's altitude to the atmospheric pressure at sea level (101.3 kPa).

of the total sum of ET_o . However, the calculated values of the coefficient of determination between the values of the hourly estimation of the empirical method and the values of for the hourly estimations of the ASCE PM (2005) method ranged from 0.95 to 0.97. The coefficient of determination is a correlation-based measure of goodness of fit which is insensitive to proportional differences (Legates and McCabe 1999), i.e., the coefficient of determination between a set of observations and a set of model predictions would not change for any set of products of the model predictions and any non-zero value. The adjustments of empirical formulas for error in ET_o estimation in high-altitude climatic conditions have been proposed by Ravazzani *et al.* (2012). Therefore, we investigated a proportional adjustment for the hourly estimations of the radiation-based empirical method.

Increasing values of R_s with altitude, which contribute to the overestimation of the yearly sums of ET_o by the empirical method, are related with the mass of the atmosphere through which the solar radiation passes to reach the surface. Higher altitudes correspond to smaller masses of atmosphere through which the incoming solar radiation passes compared with lower altitudes, all other factors being the same. Barry (2008) suggests that the ratio of the atmospheric pressure at altitude A to the atmospheric pressure at sea level can be used for comparative radiation calculations at different altitudes.

Therefore, we adjusted the hourly estimations of the empirical method, by multiplying the value by the ratio of the atmospheric pressure of the altitude of the station, calculated by equation (6), to the atmospheric pressure at sea level, equal to 101.3 kPa (see table 4, figures 4 and 5), i.e., for Big Bear Lake station, the ratio of the atmospheric pressure of the station (altitude 2106 m) to the atmospheric pressure at sea level is equal to 0.777; therefore, for an hourly estimation of the empirical method equal to 0.49 mm h^{-1} , the adjusted value of the empirical method would be equal to $0.49 \times 0.777 = 0.38 \text{ mm h}^{-1}$.

3.1.4 Performance of the empirical method for high-altitude climatic conditions

The adjusted hourly estimations of ET_o with the empirical method were summed for the four stations and compared with the yearly sums of the hourly estimations of the ASCE PM (2005) method for the same stations.

The sum of the adjusted values for all the four stations (above 800 m) overestimated the sum of the ASCE PM (2005) method by 168.0 mm or 3.4%. The overestimation of the yearly sum of the hourly values of ET_o with the adjusted empirical method is small but consistent (see figure 4). The decreasing trend of the average of the hourly values of the RH with altitude yields higher estimations with the empirical method (see equation 9), which contributes to this consistent overestimation. The adjustment of the estimations based on considerations of the trends of radiation influx for climatic conditions occurring at higher altitudes and for hourly time step of the empirical method is satisfactory.

The adjusted empirical method was least accurate for Big Bear Lake station (altitude 2106 m) with RMSE value equal to 0.054 mm h^{-1} , slope of the regression line between the adjusted hourly estimations of the empirical method and the hourly estimations of the ASCE PM (2005) method equal to 0.83 (see figure 5) and the value of the IoA equal to 0.980. The yearly sum of the adjusted hourly ET_o estimations of the empirical method was 120.0 mm or 9.1% greater than the ASCE PM (2005) yearly sum. All the statistical indices for Big Bear Lake station were acceptable, and we concluded that the empirical method estimations were satisfactory for this station. The most accurate adjusted hourly estimations of the empirical method in comparison with the hourly estimation

Figure 5. Plot of the values of the hourly ET_o estimations with the ASCE PM (2005) method (independent value, x -axis) against the adjusted values of the hourly ET_o estimations with the empirical method (dependent variable, y -axis) for the four high-altitude stations. The estimations of the empirical method were adjusted with the ratio of the atmospheric pressure at the altitude of the station to the atmospheric pressure at sea level (101.3 kPa).

Table 4. Annual sums of the hourly estimations of ET_o by the adjusted empirical method, by the ASCE PM (2005) method, their difference, their difference as a percentage, the coefficient of determination between the hourly estimations of the two methods, the RMSE, the slope and the IoA, after the adjustment of the hourly values of the empirical method with the ratio of the atmospheric pressure at the altitude of the station to the atmospheric pressure at sea level.

	Adjusted empirical (mm yr ⁻¹)	PM (mm yr ⁻¹)	Adjusted empirical- PM	Adjusted empirical- PM (%)	R^2	RMSE	Slope	IoA
Big Bear Lake	1436.5	1316.2	120.2	9.1	0.95	0.054	0.83	0.980
Tulelake	1145.4	1108.9	36.5	3.3	0.96	0.038	1.01	0.991
McArthur	1148.9	1129.8	19.1	1.7	0.96	0.045	0.92	0.988
Camino	1371.8	1360.8	11.0	0.8	0.97	0.044	0.92	0.990
Average	1280.0	1228.9	51.1		0.96	0.045	0.92	0.987
Total	5102.6	4934.5	168.0	3.4				

of the ASCE PM (2005) method were for Tulelake station (altitude 1230 m) with RMSE equal to 0.038 mm h⁻¹, slope of the regression line between the adjusted estimations of the empirical method and the estimations of the ASCE PM (2005) method equal to 1.01 and a value of the IoA equal to 0.991. The empirical method overestimation of the yearly sum of the adjusted hourly estimations of the ET_o was equal to 36.5 mm or 3.3% of

the yearly sum of the hourly values of the ET_o estimations of the ASCE PM (2005) method.

The estimations of the adjusted empirical method were improved in all cases (see tables 2 and 5), and they were all satisfactory in terms of the statistical indices examined. The value of the RMSE was always below the limit set by Ventura *et al.* (1999), equal to 0.073 mm h⁻¹. The influence of the high-altitude climatic conditions can,

Table 5. *RMSE of the adjusted values of the empirical method, calculated according to the values of the wind speed, VPD and the percentage of the estimations of the empirical method that yielded the RMSE values.*

From	To	RMSE	Data (%)	Data % (cumulative)
Wind speed (ms^{-1})				
0	1	0.036	11.1	11.1
1	2	0.040	42.9	54.0
2	3	0.049	23.6	77.6
3	4	0.053	13.4	91.1
4	5	0.056	4.9	96.0
5	6	0.065	2.4	98.4
6	13	0.060	1.6	100.0
VPD (kPa)				
0	1	0.037	72.0	72.0
1	2	0.055	20.1	92.8
2	2.5	0.073	3.4	96.1
2.5	3	0.079	2.2	98.4
3	4	0.091	1.4	99.8
4	6	0.113	0.2	100.0

RMSE values $\leq 0.073 \text{ mm h}^{-1}$ were considered satisfactory. All the hourly records (33,383) of the four high-altitude stations downloaded from the CIMIS database were used for this paper. We used the adjusted estimations of the empirical method for the high-altitude stations.

therefore, be accounted for by an easy and straightforward manner, in terms of its accuracy against the benchmark method. The performance of the adjusted empirical method for the high-altitude climatic conditions ($>800 \text{ m}$) was considered to be satisfactory, according to the statistical indices shown in table 5.

3.2 Investigation of the RMSE based on the values of u_2 and VPD

The two parameters of the high-altitude climate, namely, wind speed and VPD, are of particular interest because the empirical method does not involve them. Instead of VPD values, the empirical method utilises the relationship between VPD and the inverse of the natural logarithm of relative humidity (Chatzithomas and Alexandris 2015). The values of the RMSE of the empirical method against the ASCE PM (2005) method were investigated with respect to the values of the wind speed and VPD. The range of the observed values was equal to $0.4\text{--}12.4 \text{ m s}^{-1}$ for the wind speed and $0\text{--}5.1 \text{ kPa}$ for the VPD. The range of the values of the wind speed and of VPD was divided into intervals of 1 m s^{-1} for the wind speed and of 1 kPa

for the VPD, and the RMSE of the estimations of the two methods was calculated for each interval. The intervals different from 1 m s^{-1} or 1 kPa were introduced when the RMSE was approaching the limit of 0.073 mm h^{-1} set by Ventura *et al.* (1999). The 550 pairs (1.6% of the total 33,383 pairs) of the estimations of the two methods with the wind speed values between 6 and 12.4 m s^{-1} were considered as a single interval. The intervals included their starting points (closed at the beginning) and did not include their end points (open at the end). The adjusted hourly values of the four high-altitude stations were used for the investigation. Finally, the number of data of each interval was calculated as a percentage of the total number of the estimations (see table 5).

The RMSE between the estimations of the adjusted empirical method and the estimations of the ASCE PM (2005) method for the stations above 800 m is below 0.073 mm h^{-1} for all the intervals of the range of the values of the wind speed. The values of the RMSE tended to increase with an increase in wind speed but remained below 0.073 mm h^{-1} in all cases examined. In total, 96.1% of the 33,383 hourly values of the estimations of the empirical method gave RMSE values below the 0.073 mm h^{-1} limit when we used the intervals of the VPD values. For values of VPD $> 2.5 \text{ kPa}$ (3.9% of the estimations), the RMSE of the estimations of the empirical method in comparison with the estimations of the ASCE PM (2005) method is $>0.073 \text{ mm h}^{-1}$, and it is not satisfactory.

4. Conclusions

The influence of high-altitude climatic conditions observed in the State of California on the radiation-based empirical method (Chatzithomas and Alexandris 2015) against the hourly ET_o estimations of the ASCE PM (2005) method using the four statistical indices (RMSE, R^2 , slope and IoA) was examined. The hourly records (33,383 hourly records) for all the four stations, in arid, semiarid and subhumid climatic zones, were downloaded from the database of the CIMIS network. The RMSE value of 0.073 mm h^{-1} was set as the upper limit for a satisfactory performance of the method.

For high-altitude (above 800 m) climatic conditions, the empirical method despite the good values of the statistical indices consistently overestimated (yearly, winter and summer periods). The values of the statistical indices tended to worsen

with increasing altitude. The summer periods tend to have better statistical indices compared with the winter or yearly periods. The meteorological variables of the energy term and aerodynamic term of the ASCE PM (2005) method were investigated. A decreasing trend between the energy term and the altitude of the stations was observed. Based on the findings of this research, no correlation between the aerodynamic term of the ASCE PM (2005) method and altitude could be confirmed. The increasing trend of the incoming solar radiation and the decreasing trend of the relative humidity, with respect to altitude, which contributed to the overestimation of the empirical method, were also investigated. To account for the increasing trend of the incoming solar radiation due to higher altitude and the decreasing trend of the relative humidity, the hourly ET_o estimations of the empirical method were adjusted by multiplying the values by the ratio of the atmospheric pressure at the altitude of the station to the atmospheric pressure at sea level (101.3 kPa). The adjusted empirical method performed satisfactorily for all the stations examined (above 800 m) when compared with the ASCE PM (2005) method. The overestimation of the empirical method for all the values of the four stations was 3.6%, and the RMSE values ranged from 0.038 to 0.054 mm h⁻¹.

The range of the observed values of the wind speed and VPD was divided into intervals, and the RMSE of the adjusted estimations of the empirical method against the estimations of the ASCE PM (2005) method for each interval was calculated. All the wind speed intervals gave satisfactory RMSE values between the estimations of the empirical method and the estimations of the ASCE PM (2005). When the VPD intervals were examined, 96.3% of the data (VPD < 2.5 kPa) gave satisfactory RMSE values between the estimations of the empirical method and the estimations of the ASCE PM (2005) method.

The high-altitude climatic conditions represented by the stations in arid, semiarid and subhumid climatic zones introduced systematic overestimations for the radiation-based empirical formula. These overestimations were satisfactorily accounted for, when estimating ET_o at an hourly time step, with a radiation-based empirical method using the altitude of the stations for most of the data of this research. The adjusted empirical method is satisfactory for the locations with altitude >800 m in the State of California. The

evaluation of the method for other high-altitude locations is recommended.

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