Wind-adjusted Turc equation for estimating reference evapotranspiration at humid European locations

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ABSTRACT

The Turc equation is one of the simplest empirical equations used for estimating reference evapotranspiration (ET_0) under humid conditions. However, this equation generally overestimates ET_0 values at windless humid locations and underestimates ET_0 at windy humid locations. The main objective of this study is to develop a new adjusted Turc equation through introduction of the wind adjustment factor. In this study, data from CLIMWAT database have been divided into two groups in order to verify the model on half of the dataset. As the mean monthly data from CLIMWAT refer to the long-term average year, the detailed Western Balkans (WB) dataset with the monthly data from real years has been used for additional verification of the wind adjustment factor. For each verification station, ET_0 estimates from the original and adjusted Turc equations have been statistically compared with FAO-56 Penman–Monteith (PM) ET_0 estimates. The adjusted Turc equation provides good agreement with the evapotranspiration, and produces a reliable estimation at all locations. These results support the use of the adjusted Turc equation for estimating reference evapotranspiration at European humid locations where humidity data are not available.

Key words | adjustment factor, FAO-56 Penman–Monteith equation, reference evapotranspiration, Turc equation, wind speed

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NOMENCLATURE

ASEE	adjusted standard error of estimation
C_u	wind speed adjustment factor
$e_a - e_d$	vapour pressure deficit
ET	evapotranspiration
ET_0	reference evapotranspiration
$ET_{0,PM}$	ET_0 estimated by FAO-56 PM equation
$ET_{0,Turc}$	ET_0 estimated by original Turc equation
$ET_{0,cTurc}$	ET_0 estimated by adjusted Turc equation
G	soil heat flux density
k	total number of observations
R_n	net radiation
R_s	solar radiation
SEE	standard error of estimation
T	mean air temperature
T_{max}	average annual maximum temperature
T_{min}	average annual minimum temperature
U_2	average 24-hour wind speed at height 2 m above ground
$\bar{U}_2$	long-term average U_2
γ	psychometric constant
Δ	slope of saturation vapour pressure function

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INTRODUCTION

Evapotranspiration (ET) is one of the major components in the hydrological cycle, and its reliable estimation is essential for water resources planning and management. A common procedure for estimating evapotranspiration is to first estimate reference evapotranspiration (ET_0), and then apply an appropriate crop coefficient. Reference evapotranspiration is defined in Allen *et al.* (1998) as "the rate of evapotranspiration from hypothetical crop with an assumed crop height (0.12 m) and a fixed canopy resistance ($70\,\mathrm{s\,m^{-1}}$) and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water". Crop coefficients, which depend on the crop characteristics and local conditions, are then used to convert ET_0 to ET. This paper only addresses the estimation of ET_0.

The FAO-56 Penman–Monteith combination equation (FAO-56 PM) has been recommended by the Food and Agriculture Organization of the United Nations (FAO) as the sole equation for estimating reference evapotranspiration (ET_0).

The FAO-56 Penman–Monteith (FAO-56 PM) equation is (Allen *et al.* 1998):

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_\mathrm{n} - G) + \gamma\frac{900}{T+273}U_2(e_\mathrm{a} - e_\mathrm{d})}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where $\mathrm{ET}_0 =$ reference evapotranspiration ($\mathrm{mm\,d^{-1}}$), Δ is slope of the saturation vapour pressure function ($\mathrm{k\,Pa\,°C^{-1}}$), R_n is net radiation ($\mathrm{MJ\,m^{-2}\,day^{-1}}$), G is soil heat flux density ($\mathrm{MJ\,m^{-2}\,day^{-1}}$), γ is a psychometric constant ($\mathrm{k\,Pa\,°C^{-1}}$), T is mean air temperature (°C), U_2 is average 24-hour wind speed at two metres height ($\mathrm{m\,s^{-1}}$) and $e_\mathrm{a} - e_\mathrm{d} =$ vapour pressure deficit (kPa).

Many studies have indicated the superiority of this equation (Todorovic 1999; Pereira & Pruitt 2004; Lopez-Urrea *et al.* 2006; Gavilan *et al.* 2007). The FAO-56 Penman–Monteith equation requires maximum and minimum air temperature, maximum and minimum relative air humidity (or the actual vapour pressure), wind speed at 2 metres height and solar radiation (or sunshine hours). However, the application of the FAO-56 PM approach is limited in many regions due to the lack of required weather data. In such circumstances, equations based on either radiation or temperature are often used to estimate reference evapotranspiration.

Jensen *et al.* (1990) analysed the properties of twenty different equations against carefully selected lysimeter data from eleven stations located worldwide in different climates. The Turc equation compared very favourably with combination equations at the humid lysimeter locations. The Turc equation was ranked second when only humid locations were considered. Only the Penman–Monteith equation performed better than this equation. For this reason, the Turc equation is often used to estimate ET_0 under humid conditions (Xu & Singh 1998; Kashyap & Panda 2001; Irmak *et al.* 2003; Nandagiri & Kovoor 2006).

There are a number of Turc versions (with and without a radiation term for annual, monthly and 10-day time steps) (Turc 1954, 1961). Turc (1961) simplified earlier versions of this equation for general climatic conditions of Western Europe. Turc (1961) computed reference evapotranspiration in millimetres per day at humid locations as:

$$\mathrm{ET}_0 = 0.013 \times (R_\mathrm{s} + 50) \times T \times (T + 15)^{-1} \quad (2)$$

where R_s is solar radiation ($\mathrm{cal\ cm^{-2}\,day^{-1}}$).

Several studies have indicated that this equation overestimated FAO-56 PM ET_0 estimates at windless locations and underestimated ET_0 at windy locations (Xu & Singh 2000; George *et al.* 2002). Xu & Singh (2000) attempted to improve the accuracy of the Turc equation through recalibration of the coefficient. They concluded that the new coefficient (0.015 instead of 0.013) did not improve Turc estimates substantially. Up until now, there have been no attempts to solve the problem of influence of wind speed on the reliability of the Turc equation. The main objective of this study has been to develop a new adjusted Turc equation through introduction of a wind adjustment factor.

METHODS AND MATERIALS

Weather datasets

CLIMWAT dataset

In this study, two datasets have been used. The first dataset has been obtained from United Nations Food and Agricultural Organization database and is known as the CLIMWAT database (Smith 1993). This database was originally compiled by the Agrometeorological Group of the FAO Research. CLIMWAT is the largest global climatic database which was developed primarily for use in providing weather data inputs for the estimation of reference evapotranspiration (Temesgen *et al.* 1999; Droogers & Allen 2002; Valiantzas 2006). The weather data that have been included are long-term monthly average values for maximum air temperature, minimum air temperature, mean relative humidity, sunshine hours, wind speed and ET_0 estimated with the FAO-56 PM equation.

The CLIMWAT database includes data from 3,262 meteorological stations in 144 countries divided over five continents. This database comprises data from several European countries such as Spain, Greece, Cyprus, Belgium, France, Italy and ex-Yugoslavia (Slovenia, Croatia, Serbia, Bosnia and Herzegovina, Montenegro and Macedonia).

All European humid stations from the CLIMWAT database have been selected for this study. Humid stations were classified as those locations at which the long-term monthly average value for mean relative humidity of the peak month (July) was greater than 60% (Jensen *et al.* 1990). According to this criterion, eighty stations have been used and divided into two subsets.

CLIMWAT subset I (40 stations) has been used for establishing the wind speed adjustment factor and CLIMWAT subset II (the remaining 40 stations) has been used for verification of the developed equation. The list of countries selected and number of stations in each are given in Table 1.

A wide range of weather parameters, latitudes and altitudes was observed at these locations. The average annual temperature ranged from 6.0 to 16.6°C. The average annual wind speed varied from 0.53 to 3.66 $\mathrm{m\,s^{-1}}$. The average annual relative humidity ranged between 68 and 91%. Latitude varied from 43°N to 52°N. Altitude ranged from 1 to 871 m. The description of the weather stations from CLIMWAT subset I along with average annual weather data is given in Table 2.

Table 1 | List of countries selected and number of stations in each country

Country	Total number of stations	Number of humid stations	CLIMWAT subset I	CLIMWAT subset II
Belgium	3	3	2	1
France	44	40	20	20
Italy	60	24	12	12
Ex-Yugoslavia	21	13	6	7
Total	128	80	40	40

Table 2 | List of humid European stations used for establishing the adjustment factor

Station	State	Latitude (°N)	Altitude (m)	T (°C)	RH (%)	U_2 ($\mathrm{m\,s^{-1}}$)
Ostende	Belgium	51.25	10	10.0	90	3.3
Botrange	Belgium	50.50	694	6.0	91	2.9
Cherbourg	France	49.65	8	11.4	82	3.0
Rouen	France	49.42	68	10.4	84	1.5
Nancy Essey	France	48.70	212	9.7	85	1.7
Dinard	France	48.60	63	11.0	84	2.7
Alencon	France	48.45	140	10.2	86	2.0
Brest Guipavas	France	48.45	98	10.8	87	3.5
Rennes	France	48.07	35	11.3	85	2.2
Le Mans	France	47.93	52	11.1	83	2.0
Nantes	France	47.25	41	11.6	85	2.6
Maribor	Slovenia	46.53	275	9.7	83	1.2
Tarvisio	Italy	46.50	751	6.6	82	1.1
La Rochelle	France	46.15	1	12.7	82	2.4
Trento	Italy	46.07	200	12.7	70	0.7
Clermont Ferrand	France	45.80	329	11.0	76	2.2
Trieste	Italy	45.65	11	14.4	69	1.7
Venezia	Italy	45.45	1	13.5	80	1.3
Verona	Italy	45.42	60	13.4	77	0.7
Crikvenica	Croatia	45.17	4	14.4	71	1.7
Torino	Italy	45.08	238	12.9	79	0.5
Le Puy Chadrac	France	45.05	714	9.3	78	1.9
Bordeaux	France	44.83	46	12.5	85	2.2
Beograd	Serbia	44.80	132	12.1	71	1.7
Montelimar	France	44.58	73	12.9	73	3.5
Gospic	Croatia	44.53	566	8.8	83	0.7
Genova	Italy	44.42	21	15.6	68	2.6
Rimini	Italy	44.05	2	14.2	81	1.6
Sarajevo	Bosnia	43.87	630	10.2	75	1.2
San Remo	Italy	43.82	9	16.6	76	2.6
Firenze	Italy	43.77	51	14.6	76	1.0
Kraljevo	Serbia	43.73	219	11.3	81	1.0
Nice	France	43.65	5	15.0	74	2.6
Ancona	Italy	43.62	105	14.8	73	2.1
Montpellier	France	43.58	5	13.8	72	2.4
Cannes	France	43.55	3	14.3	74	3.0
Biarritz	France	43.47	69	13.6	80	2.7
Pisa	Italy	43.42	6	14.8	76	1.6
Carcassone	France	43.22	123	13.4	68	2.6
Toulon	France	43.10	28	15.4	72	3.6

Western Balkans dataset

As the mean monthly data from CLIMWAT stations refer to the long-term average year, the detailed Western Balkans (WB) dataset with monthly data from real years has been used for verification of the wind adjustment factor. Twelve humid locations selected for the WB dataset were: Palic, Zagreb, Belje, Karlovac, Novi Sad, Bihac, Tuzla, Valjevo, Negotin, Kragujevac, Nis and Vranje. The records were procured from the Federal Meteorological Service. Each station is equipped with mercury and alcohol thermometers, a Campbell–Stokes sunshine recorder, an anemometer at 10 m and a psychrometer. Climate data included daily values of the following parameters averaged over each month: maximum air temperature; minimum air temperature; actual vapour pressure, wind speed and sunshine hours.

Differences in the weather data for these locations are not very significant. The average annual maximum and minimum temperatures (T_{max} and T_{min}) for all locations varied between 15.4–17.0°C and 5.1–6.3°C, respectively. The average annual wind speed (U_2) was the lowest at Tuzla ($0.5\,m\,s^{-1}$), Valjevo ($0.5\,m\,s^{-1}$) and Karlovac ($0.6\,m\,s^{-1}$); it varied for all other locations between 1.0 and $1.9\,m\,s^{-1}$. The average annual relative humidity (RH) varied from 71–80% and the average annual ET_0 computed by FAO-56 PM equation ranged from $1.8–2.3\,mm\,day^{-1}$.

Adjustment procedure

The adjusted Turc equation can be written as:

$$ET_0 = C_u \times 0.013 \times (23.88 \times R_s + 50) \times T \times (T + 15)^{-1} \qquad (3)$$

where C_u is the wind speed adjustment factor.

The data from 40 European humid stations from CLIMWAT subset I have been used for establishing the wind speed adjustment factor. The following regression types have been used to compute the wind adjustment factor: linear, logarithmic, second- and third-order polynomial, power and exponential. The second-order polynomial equation produced the lowest RMSE (0.072). The wind speed adjustment factor used here has the form:

$$C_u = -0.0211 \times \bar{U}_2^2 + 0.1109 \times \bar{U}_2 + 0.9004 \qquad (4)$$

where $\bar{U}_2$ is the long-term average annual wind speed at two metres height ($m\,s^{-1}$) which has been obtained at each location as an average of twelve long-term monthly average values for wind speed.

Evaluation parameter

In this study, the standard error of estimate was used for the evaluation of the ET_0 estimates. This statistical criterion was calculated as:

$$SEE = \left[\frac{\sum_{i=1}^{k}(ET_{0,PM,i} - ET_{0,Turc,i})^2}{k-1}\right]^{0.5} \qquad (5)$$

or

$$ASEE = \left[\frac{\sum_{i=1}^{k}(ET_{0,PM,i} - ET_{0,cTurc,i})^2}{k-1}\right]^{0.5} \qquad (6)$$

where SEE is the standard error of estimate ($mm\,day^{-1}$), ASEE is the adjusted standard error of estimate ($mm\,day^{-1}$), $ET_{0,PM}$ is ET_0 estimated by the standard (FAO-56 PM) equation ($mm\,day^{-1}$), $ET_{0,Turc}$ is the corresponding ET_0 estimated by the original Turc equation ($mm\,day^{-1}$), $ET_{0,cTurc}$ is the corresponding ET_0 estimated by the adjusted Turc equation ($mm\,day^{-1}$) and k is the total number of observations ($k = 12$ for CLIMWAT stations; $k = 48$ for WB stations except Palic where $k = 84$ and Nis where $k = 96$). The standard error of estimate indicates how well each equation estimates reference evapotranspiration over all months of the record.

RESULTS AND DISCUSSION

Estimating ET_0 using CLIMWAT verification subset

The CLIMWAT subset II has been used for verification of the adjusted Turc equation. The ET_0 values estimated by the original and adjusted Turc equations were compared with FAO-56 PM estimates for 40 humid locations across Europe. These data have not been used for the development of the wind adjustment factor. The list of the CLIMWAT verification stations with average annual weather data and evaluation parameters is presented in Table 3. The SEE

Table 3 | List of CLIMWAT verification stations with average annual weather data and evaluation parameters

Station	State	Latitude (°N)	Altitude (m)	RH (%)	U_2 (m s^{-1})	SEE (mm d^{-1})	ASEE (mm d^{-1})
Uccle/Bruxelles	Belgium	50.80	100	84	2.8	0.20	0.15
Boulogne Sur Mer	France	50.73	70	86	3.7	0.18	0.21
Lille	France	50.57	44	85	3.2	0.21	0.17
Reims	France	49.30	94	84	2.6	0.26	0.21
Caen	France	49.17	66	84	3.1	0.10	0.13
Paris Montsouris	France	48.82	75	79	2.4	0.21	0.16
Strasbourg	France	48.55	149	82	1.6	0.23	0.23
Orleans	France	47.98	125	83	3.1	0.30	0.22
Auxerre	France	47.80	207	81	2.4	0.23	0.19
Belfort	France	47.63	422	84	2.6	0.29	0.28
Tours St Symph.	France	47.42	96	79	2.6	0.27	0.22
Dijon	France	47.27	220	80	2.2	0.26	0.22
Nevers	France	47.00	176	83	2.3	0.21	0.20
Poitiers	France	46.58	118	84	2.6	0.18	0.15
Bolzano	Italy	46.50	271	75	0.7	0.24	0.22
Sondrio	Italy	46.17	300	72	0.7	0.24	0.23
Udine	Italy	46.08	116	75	1.2	0.22	0.23
Ljubjana-Bezigrad	Slovenia	46.07	299	82	0.8	0.27	0.26
Limoges	France	45.82	282	79	1.8	0.31	0.30
Zagreb/Gric	Croatia	45.82	157	75	1.4	0.26	0.26
Lyon /Bron	France	45.72	200	79	2.1	0.26	0.20
Bergamo	Italy	45.67	238	79	1.1	0.19	0.19
Osijek	Croatia	45.55	90	82	1.0	0.27	0.26
Milano	Italy	45.47	121	80	0.8	0.27	0.22
Padova	Italy	45.40	14	77	0.8	0.24	0.21
Novi Sad/R San	Serbia	45.33	84	81	1.9	0.27	0.24
Grenoble	France	45.17	223	82	1.9	0.23	0.24
Slavonski Brod	Croatia	45.15	95	83	1.1	0.22	0.22
Gourdon	France	44.92	205	82	1.2	0.21	0.21
Piacenza	Italy	44.82	138	76	1.0	0.24	0.23
Ferrara	Italy	44.80	9	77	1.6	0.20	0.19
Parma	Italy	44.80	57	77	0.8	0.26	0.23
Govone	Italy	44.78	300	82	1.0	0.24	0.22
Banja Luka	Bosnia	44.75	153	80	0.8	0.30	0.28
Bologna	Italy	44.50	60	76	1.1	0.21	0.21
Agen	France	44.18	59	86	2.4	0.15	0.13
Millau	France	44.10	409	74	1.4	0.21	0.20
Toulose	France	43.62	225	83	2.6	0.19	0.13
Nis	Serbia	43.33	201	74	1.0	0.26	0.25
Perugia	Italy	43.12	493	71	0.9	0.24	0.21

varied from 0.10 (Caen) to 0.31 mm day^{-1} (Limoges), averaging 0.23 mm day^{-1}.

The long-term average annual ratios of Turc ET_0 estimates to FAO-56 PM ET_0 ($ET_{0,Turc}/ET_{0,PM}$) were plotted against corresponding long-term average annual values of wind speed in Figure 1. From this figure, it may be observed that the Turc equation overestimates FAO-56 PM ET_0 estimates at windless locations and underestimates ET_0 at windy locations. The long-term average annual ratio of Turc ET_0 to FAO-56 PM ($ET_{0,Turc}/ET_{0,PM}$) varied from 0.88 (Orleans) to 1.09 (Milano). The relative difference between the two equations was higher than 5% in fifteen locations. Based on other studies (Irmak *et al.* 2003), 5% difference between the FAO-56 PM and Turc estimated ET_0 would be in the acceptable range.

The adjusted Turc equation yielded lower SEE in comparison to the Turc equation at almost all locations. This equation had the greatest advantage at locations with long-term average annual wind speed less than 1.0 m s^{-1} and at locations with wind speed between 2.0 and 3.0 m s^{-1}. The only two stations where the adjusted Turc equation yielded slightly higher SEE than the Turc equation are located in the north of France (Caen, 49°N and Boulogne, 51°N) with long-term average annual wind speed higher than 3.0 m s^{-1}. The long-term average annual ratio of the adjusted Turc ET_0 to FAO-56 PM ET_0 ($ET_{0,cTurc}/ET_{0,PM}$) ranged from 0.92 (Orleans) to 1.06 (Milano). The relative difference between these equations only exceeded 5% at these two locations.

Figure 2 depicts a plot of long-term average annual ET_0 values estimated by Turc and adjusted Turc equations versus corresponding FAO-56 PM ET_0 estimates. From this figure, it may be observed that the adjusted Turc equation performed better than the Turc equation for the majority of stations.

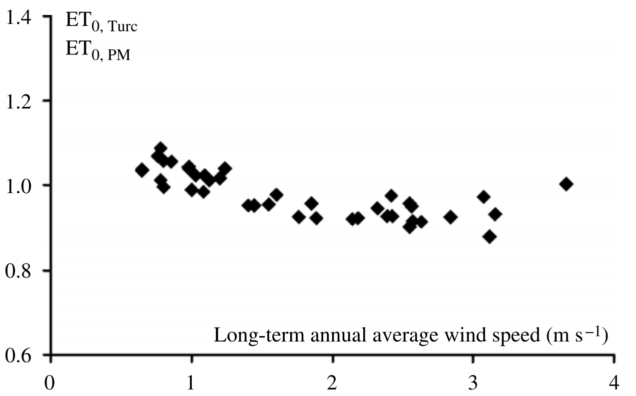

Figure 1 | Long-term average annual ratios of Turc ET_0 estimates to FAO-56 PM ET_0 against corresponding long-term average annual values of wind speed.

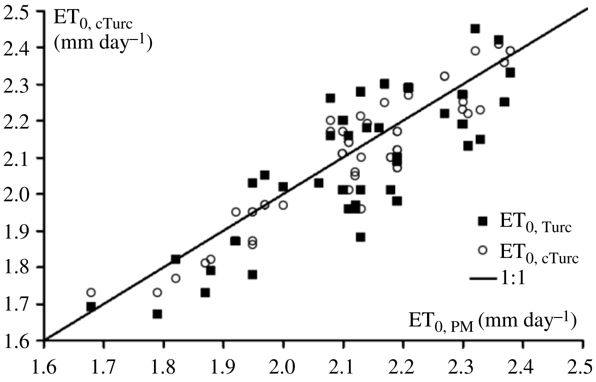

Figure 2 | Long-term average annual ET_0 values estimated by Turc and adjusted Turc equations versus corresponding FAO-56 PM ET_0 estimates.

The mean monthly ET_0 values for Toulouse, France as estimated by the FAO-56 PM Equation ($ET_{0,PM}$), Turc equation ($ET_{0,Turc}$) and adjusted Turc equation ($ET_{0,cTurc}$) are plotted in Figure 3. Toulouse, with a long-term wind speed of 2.57 m s^{-1}, was selected as a representative of windy locations. At this location, the Turc equation consistently underestimated ET_0 obtained by the FAO-56 PM equation over the entire year. The adjusted Turc equation followed ET_0 very well.

Estimating ET_0 using Western Balkans dataset

The Western Balkans (WB) dataset has been used for additional verification of the adjusted Turc equation by using the data from the real years. The ET_0 values estimated

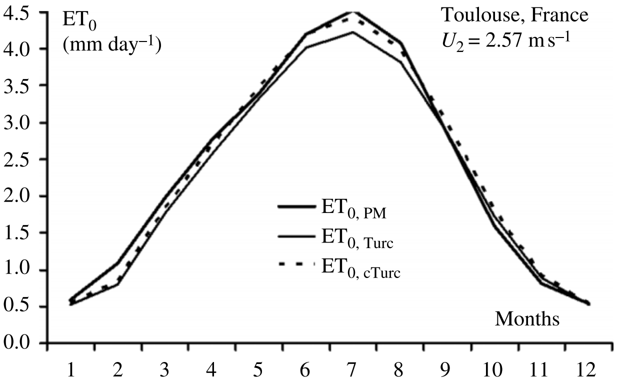

Figure 3 | Comparison of mean monthly ET_0 calculated at Toulouse, France using FAO-56 PM equation ($ET_{0,PM}$), Turc equation ($ET_{0,Turc}$) and adjusted Turc equation ($ET_{0,cTurc}$).

Table 4 | List of WB verification stations with average annual weather data and evaluation parameters

Station	Country	Latitude (°N)	Altitude (m)	Period	RH (%)	U_2 (m s^{-1})	SEE (mm d^{-1})	ASEE (mm d^{-1})
Palic	Serbia	46.1	102	1977–1983	74	1.7	0.24	0.23
Zagreb	Croatia	45.8	123	1971–1974	76	1.3	0.28	0.28
Belje	Croatia	45.7	91	1981–1984	79	1.0	0.31	0.30
Karlovac	Croatia	45.5	122	1979–1982	74	0.6	0.30	0.24
Novi Sad	Serbia	45.3	84	1981–1984	74	1.9	0.34	0.32
Bihac	Bosnia	44.8	48	1981–1984	71	1.5	0.36	0.35
Tuzla	Bosnia	44.5	305	1977–1980	80	0.5	0.27	0.20
Valjevo	Serbia	44.3	174	1981–1984	72	0.5	0.36	0.29
Negotin	Serbia	44.2	42	1971–1974	74	1.7	0.27	0.26
Kragujevac	Serbia	44	190	1981–1984	75	1.1	0.25	0.25
Nis	Serbia	43.3	201	1977–1984	71	1.0	0.29	0.29
Vranje	Serbia	42.6	433	1971–1974	72	1.5	0.31	0.29

with the original and adjusted Turc equations have been compared with FAO-56 PM estimates for 12 humid locations across the Western Balkans. The WB test dataset had a total of 660 monthly data. These data had not been used for the development of the wind adjustment factor. The list of the WB stations with average annual weather data and evaluation parameters has been presented in Table 4. The wind speeds listed in Table 4 have been used for long-term average annual wind speeds.

In the Western Balkans, the Turc equation also overestimated FAO-56 PM ET_0 estimates at windless locations. The SEE varied from 0.24 (Palic) to 0.36 mm day^{-1} (Bihac), averaging 0.30 mm day^{-1}. The adjusted Turc equation performed better than the Turc equation for the Western Balkans dataset. The adjusted SEE varied from 0.19 (Tuzla) to 0.35 mm day^{-1} (Bihac), averaging 0.27 mm day^{-1}. As with the CLIMWAT verification subset, the advantage of the adjusted Turc equation is greatest for locations with average annual wind speed less than 1 m s^{-1}.

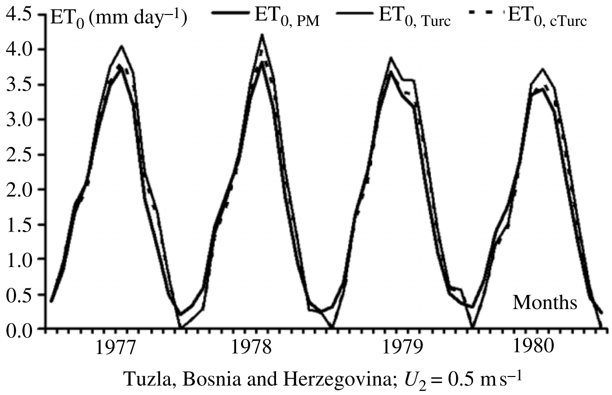

Figure 4 | Comparison of monthly ET_0 calculated for four years at Tuzla, Bosnia and Herzegovina using FAO-56 PM equation ($ET_{0,PM}$), Turc equation ($ET_{0,Turc}$) and adjusted Turc equation ($ET_{0,cTurc}$).

The monthly ET_0 calculated for four years at Tuzla using the FAO-56 PM equation ($ET_{0,PM}$), Turc equation ($ET_{0,Turc}$) and adjusted Turc equation ($ET_{0,cTurc}$) have been plotted in Figure 4. Tuzla, with a long-term wind speed of 0.5 m s^{-1}, was selected as a representative of windless locations. At this location, the Turc equation overestimated ET_0 obtained by the FAO-56 PM equation for May–November. The adjusted Turc equation followed ET_0 very well, except during the winter months.

CONCLUSIONS

The FAO-56 PM equation has been recommended as the standard for computing reference evapotranspiration. The use of this equation is limited due to the lack of required weather data. In such circumstances, the Turc equation is often used to estimate ET_0 under humid conditions. However, this equation overestimates FAO-56 PM ET_0 estimates at windless locations and underestimates ET_0 at windy locations.

The wind speed adjusted factor developed in this study improves the accuracy of the Turc equation. The results provide support for the use of the adjusted Turc equation for estimating reference evapotranspiration at humid European locations. The temperature and sunshine hours data and long-term average annual wind speed value are the minimum data requirements necessary to successfully use this equation in a humid climate.

Further research is required in order to assess the adjusted Turc equation, proposed in this paper, in other humid areas. The approach presented in this study could be applied in other regions for obtaining suitable regional calibrations of this equation.

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