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Estimation of Solar Radiation by Using ASHRAE Clear-Sky Model in Erzurum, Turkey

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Abstract *In this study, the solar radiation variation on horizontal surfaces calculated by the ASHRAE clear-sky model is compared with measurements for Erzurum, Turkey (latitude: 39.55; longitude: 41.15; altitude: 1,869 m). A daily total solar radiation is obtained by integrating the hourly distribution. The results show that the ASHRAE clear-sky model is suitable to estimate hourly solar radiation in Erzurum, Turkey. Also, correlations giving the monthly average clear sky solar radiation on horizontal surfaces are developed. In addition, mean bias error, root mean square error, and t-statistic methods are used to indicate model performance.*

Keywords clear sky radiation, correlation, estimation of solar radiation, solar energy

1. Introduction

In many applications of solar energy, the solar irradiance incident on the surface of the earth at the location of interest is an important input parameter. In order to derive the detailed solar radiation climatology of a region and to estimate its solar energy potential, extensive radiation measurements of high quality at a large number of stations covering all major climate zones of the region are necessary.

A comprehensive knowledge of the climatic data and solar radiation components, which are direct and diffuse, is an essential requirement for the evaluation and assessment of the performance and efficiency of any solar energy system. In most locations, only bright sunshine hours and global solar radiation are measured. Therefore, solar radiation components such as direct and diffuse were estimated and derived using an empirical formula. Estimations of the clear sky solar radiation for some locations were presented in various works (Parishwad et al., 1997; Al-Mohamad, 2004; Al-Sanea et al., 2004).

In this article, the ASHRAE clear-sky model is used to estimate the monthly average hourly global solar radiation on horizontal surfaces in Erzurum, Turkey. The basic idea of this article is to present the theoretical values of the estimation of hourly clear sky solar radiation for Erzurum based on the ASHRAE method. The results of the present study will enable us to predict how much solar radiation can be expected on average at Erzurum, hour by hour, during any given month of the year.

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The measurements of the global radiation on a horizontal surface have been concurrently measured by using Davis pyranometer and recorded at its datalogger (Davis Instruments, Hayward, CA, USA) connecting with a computer in the meteorological station of the Energy Laboratory at the Department of Mechanical Engineering, University of Atatürk in Erzurum.

2. Estimation Method

As recommended by ASHRAE (1985), hourly global radiation (I), hourly beam radiation in the direction of rays (I_{bn}), and hourly diffuse radiation (I_d) on the horizontal surface on a clear day are calculated using the following equations, respectively:

$$I = I_{bn} \cos\theta_z + I_d \tag{1}$$

$$I_{bn} = A \exp(-B/\cos\theta_z) \tag{2}$$

$$I_d = C I_{bn}, \tag{3}$$

where A is the apparent solar-radiation constant, B is the atmospheric extinction coefficient, and C is the diffuse sky factor.

The θ_z in those equations is the zenith angle and the cosine of the zenith angle is given by the equation:

$$\cos\theta_z = \cos\delta \cos\varphi \cos\omega + \sin\delta \sin\varphi, \tag{4}$$

where δ is the solar declination, φ is the latitude of the station, and ω is the hour angle. The solar declination (δ) is given as (Howell et al., 1982; Duffie and Beckman, 1991):

$$\delta = 23.45 \sin\left[\frac{360(D + 284)}{365}\right], \tag{5}$$

where D the number of days of the year starting from January 1. The hour angle (ω) is an angular measure of time and is equivalent to 15° per hour with morning (+) and afternoon (−). It is measured from noon-based local solar time (*ST*) from the equation given by

$$\omega = 15(12.0 - ST). \tag{6}$$

The local solar time (*ST*) is calculated from the local standard time (*LT*) and the equation of time (*ET*) is given later by

$$ST = LT + ET/60 - 4/60(L_S - L_L), \tag{7}$$

where L_S is the standard meridian (= 45°) for the local time zone (longitude of the time zone) and L_L is the longitude of the location in degrees west ($0° < L_L < 360°$). The equation of time (*ET*) is obtained from formulae given by Tasdemiroglu (1988) as:

$$ET = 9.87 \sin 2B - 7.53 \cos B - 1.50 \sin B, \tag{8}$$

Table 1
Constants for ASHRAE equations for the 21st day of each month

Months	A, Wm^{-2}	B, dimensionless	C, dimensionless
January 21	1,229.475	0.142	0.058
February 21	1,213.713	0.144	0.060
March 21	1,185.340	0.156	0.071
April 21	1,134.900	0.180	0.097
May 21	1,103.375	0.196	0.121
June 21	1,087.613	0.205	0.134
July 21	1,084.460	0.207	0.136
August 21	1,106.528	0.201	0.122
September 21	1,150.663	0.177	0.092
October 21	1,191.645	0.160	0.073
November 21	1,220.018	0.149	0.063
December 21	1,232.628	0.142	0.057

where B is given as:

$$B = \frac{360(D-81)}{365}. \tag{9}$$

The input to the ASHRAE clear-sky model is, thus, complete by specifying values for nine parameters, namely: A, B, C, ET, δ, φ, L_S, L_L, and local standard time (LT). The model solar data given by ASHRAE (1985) for each month are given in Table 1 for the first three parameters. The following other parameters are specific to the location of interest; their values for Erzurum are given in the article. The final parameter; namely the local standard time (LT) is now the only varying parameter which is input for calculations at any required time in the day.

It is interesting to note that the solar parameters given in Table 1 are for the 21st day of each month. In the present investigation, the ASHRAE clear-sky model is run for every day in the year. Therefore, the values of the solar parameters (A, B, and C) for days other than the 21st day in each month are obtained by linear interpolation. Constants for ASHRAE equations for the average values of each month are given in Table 2.

3. Methods of Statistical Comparison

In the literature, to compare solar radiation estimation models, the most widely used statistical indicators are mean bias error (MBE), root mean square error (RMSE), and t-statistic (Ma and Iqbal, 1983; Akınoglu and Ecevit, 1990; Stone, 1993; Tiris et al., 1996; Kaygusuz, 1999; Togrul et al., 2000; Ulgen and Hepbasli, 2003). In the present study, MBE, RMSE, and t-statistic are calculated. The MBE provides information on the long-term performance of an equation. A positive value gives the average amount of overestimation in the estimated values and vice versa. RMSE provides information on the short-term performance of an equation. The smaller the value is, the better the

Table 2
Constants for ASHRAE equations for the average values of each month

Months	A, Wm^{-2}	B, dimensionless	C, dimensionless
January 17	1,229.882	0.142	0.058
February 16	1,216.255	0.144	0.060
March 16	1,190.407	0.153	0.068
April 15	1,144.663	0.175	0.092
May 15	1,109.680	0.192	0.116
June 11	1,092.697	0.202	0.130
July 17	1,084.880	0.207	0.136
August 16	1,102.968	0.202	0.124
September 15	1,142.120	0.182	0.098
October 15	1,183.449	0.164	0.077
November 14	1,213.611	0.151	0.065
December 10	1,228.004	0.145	0.059

equation's performance. The MBE and RMSE are

$$\mathrm{MBE} = \frac{1}{k}\sum_{i=1}^{k}(H_{i,c} - H_{i,m}), \tag{10}$$

$$\mathrm{RMSE} = \left[\frac{1}{k}\sum_{i=1}^{k}(H_{i,c} - H_{i,m})^2\right]^{1/2}, \tag{11}$$

where $H_{i,c}$ is the ith calculated value, $H_{i,m}$ is the ith measured value, and k is the total number of observation (Ma and Iqbal, 1983).

The t-statistic is defined as the following (Stone, 1993):

$$t = \left(\frac{(k-1)\mathrm{MBE}^2}{\mathrm{RMSE}^2 - \mathrm{MBE}^2}\right)^{1/2}. \tag{12}$$

The smaller the value of t is, the better the performance of the model. In order to determine whether a model's estimates are statistically significant, one simply has to determine a critical t value obtainable from standard statistical tables, i.e., $t_{\alpha/2}$ at the α level of significance and $(k-1)$ degrees-of-freedom. For the model's estimates to be judged statistically significant at the $1-\alpha$ confidence level, the calculated t value must be less than the critical t value (Stone, 1993).

4. Results and Discussion

Using calculated values for Erzurum, possible correlations of monthly average daily radiation to clear day radiation (H_c) due to extraterrestrial radiation (H_o), the maximum possible sunshine duration (N), the solar declination (δ), and Angstrom-type first- and second-order polynomial equations are derived and given below:

$$H_c = -1.0244 + 0.7533(H_o), \tag{13}$$

$$H_c = -2.3352 + 0.8612(H_o) - 0.0019(H_o)^2, \tag{14}$$

$$H_c = -26.0436 + 3.8499(N), \tag{15}$$

$$H_c = -48.4922 + 7.6846(N) - 0.1596(N)^2, \tag{16}$$

$$H_c = 20.1735 + 0.4489(\delta), \tag{17}$$

$$H_c = 20.7792 + 0.4491(\delta) - 0.0023(\delta)^2, \tag{18}$$

$$H_c = H_o[0.6716 + 0.0760(n/N)], \tag{19}$$

$$H_c = H_o[0.5622 + 0.5444(n/N) - 0.4490(n/N)^2], \tag{20}$$

where H_o is the monthly average daily extraterrestrial radiation, n is the monthly average daily measured sunshine duration (h) (the values of n are taken from measured data at the Turkish State Meteorological Service), and N is the monthly average maximum possible daily sunshine duration. In this study, the values of H_o and N are calculated with equations given by Duffie and Beckman (1991).

The values of the model and measures of the hourly clear sky solar radiation (I) on the horizontal surface are given in Table 3 and Figure 1. The corresponding monthly averaged hourly solar radiation results using the ASHRAE clear-sky model with the original set of coefficients are presented in Figures 2a and 2b. The values of the monthly averaged daily global, diffuse, beam, and extraterrestrial radiation on horizontal surfaces in Erzurum are presented in Figure 3. Also, the values of the clear day monthly average daily radiation (H_c) calculated from Eqs. (13)–(20) are given in Table 4. The values of

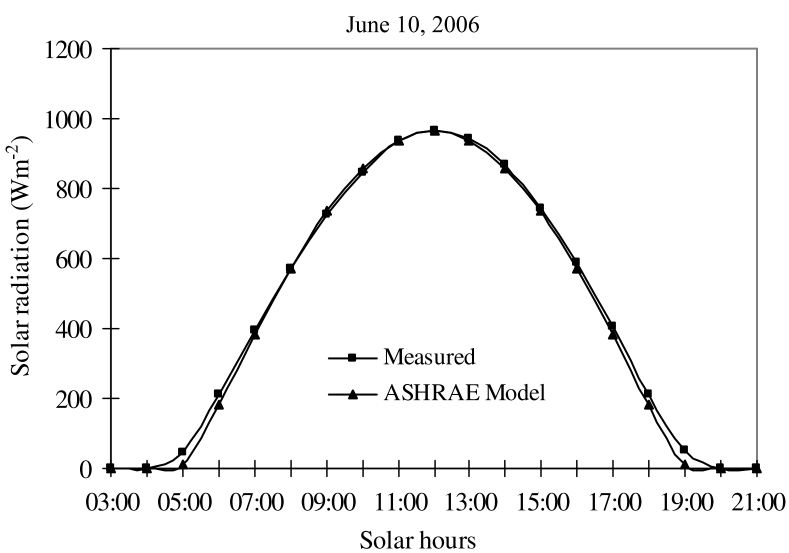

Figure 1. The values of the model and measured of the hourly clear sky solar radiation (I, Wm^{-2}) on the horizontal surface.

Table 3
Values of the model and measures of the hourly clear sky solar radiation (I, $\mathrm{Wm^{-2}}$) on the horizontal surface

Solar hours	ASHRAE model (May 25, 2006)	I (measured) (May 25, 2006)	ASHRAE model (June 10, 2006)	I (measured) (June 10, 2006)
04–05	0	0	0	0
05–06	64	100	86	128
06–07	265	272	285	303
07–08	466	449	482	482
08–09	646	630	658	648
09–10	793	789	802	790
10–11	897	893	904	900
11–12	951	946	956	953
12–13	951	946	956	956
13–14	897	903	904	914
14–15	793	805	802	810
15–16	646	655	658	667
16–17	466	486	482	503
17–18	265	292	285	307
18–19	64	120	86	134
19–20	0	0	0	0
Total ($\mathrm{MJm^{-2}}$)	29.398	29.830	30.043	30.582

Table 4
Values of the clear day monthly average daily radiation (H_c, $\mathrm{MJm^{-2}}$)

Months	ASHRAE model	Eq. (13)	Eq. (14)	Eq. (15)	Eq. (16)	Eq. (17)	Eq. (18)	Eq. (19)	Eq. (20)
January	10.403	10.523	10.420	10.711	10.325	10.784	10.379	10.664	10.569
February	14.703	14.480	14.585	14.534	14.773	14.358	14.575	14.340	14.264
March	19.942	19.586	19.805	19.130	19.702	19.088	19.680	19.120	19.140
April	25.099	24.882	25.035	24.195	24.609	24.400	24.804	24.199	24.483
May	28.662	28.598	28.592	28.532	28.372	28.609	28.406	27.969	28.471
June	30.095	30.102	30.005	30.734	30.127	30.537	29.921	29.790	30.014
July	29.091	29.304	29.257	29.736	29.344	29.683	29.261	29.214	29.080
August	25.957	26.277	26.381	26.005	26.228	26.213	26.405	26.429	25.981
September	21.417	21.468	21.685	21.096	21.673	21.169	21.764	21.535	21.684
October	16.209	15.954	16.110	16.034	16.432	15.864	16.256	16.013	16.300
November	11.265	11.437	11.391	11.719	11.528	11.684	11.463	11.657	11.813
December	9.217	9.441	9.262	9.595	8.968	9.827	9.206	9.581	9.255

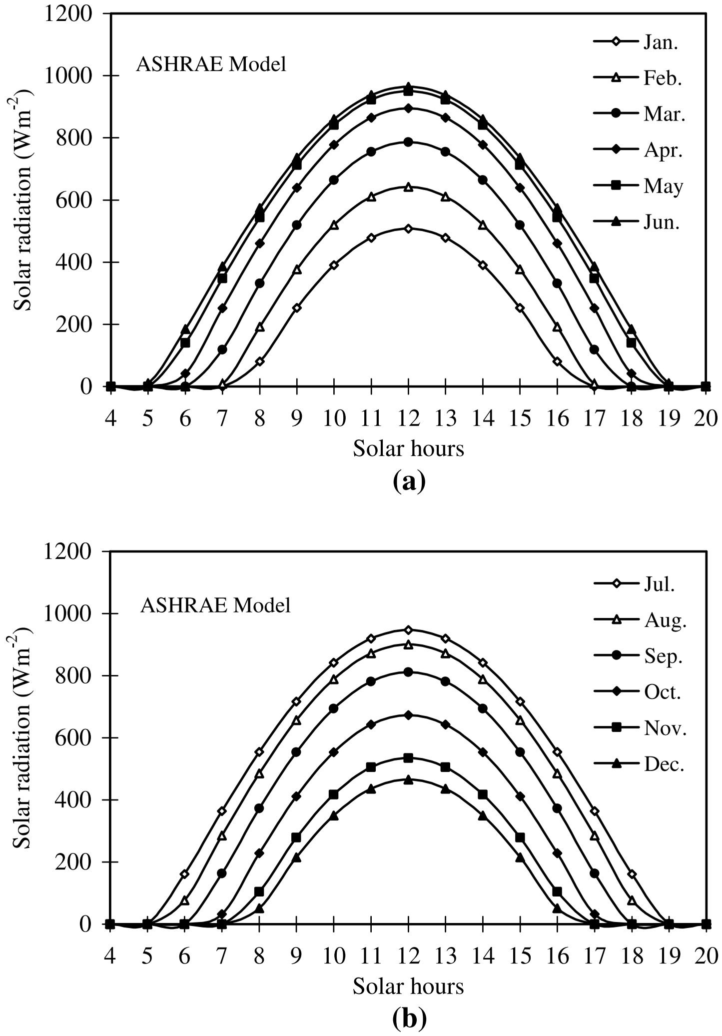

Figure 2. Monthly averaged hourly global solar radiation variations on horizontal surfaces in Erzurum; calculations by the ASHRAE clear-sky model using original set of coefficients: (a) January–June, (b) July–December.

the clear day monthly average daily radiation (H_c) are calculated for days giving the average of each month offered by Klein (1977).

As shown in Table 4, all the radiation values calculated from the equations are maximal in June. As an example, the maximum value of the monthly average daily clear sky global radiation is about 30 MJm^{-2} calculated in June for the Erzurum location in Turkey. This value is nearly the same with a measured value for June 10, as shown in Table 3.

The value of calculated MBE, RMSE, and t-statistic are given in Table 5. Eqs. (13)–(20) produce results very close to each other. As can be understood from Table 5, in the equations with H_c, each of the equations yield better results in the terms of MBE,

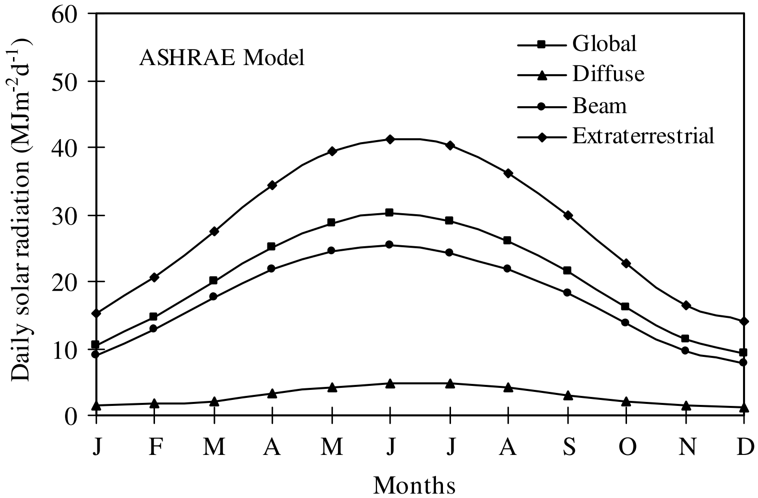

Figure 3. Monthly averaged daily global, diffuse, beam, and extraterrestrial radiation on horizontal surfaces in Erzurum; calculations by the ASHRAE clear-sky model using original set of coefficients.

Table 5
Values of calculated MBE, RMSE, and t-statistic
(t-critic $= 3.106$ for $\alpha = 0.01$ and $k = 12$)

Models	MBE	RMSE	t-statistic
Eq. (13)	−0.001	0.211	0.010
Eq. (14)	0.039	0.172	0.774
Eq. (15)	−0.003	0.494	0.021
Eq. (16)	0.002	0.254	0.024
Eq. (17)	0.013	0.485	0.089
Eq. (18)	0.005	0.235	0.072
Eq. (19)	−0.129	0.766	0.913
Eq. (20)	−0.084	0.373	0.486

RMSE, and t-statistic. According to t-statistic, among models, Eqs. (13), (15), (16), (18), (17), (20), (14) and (19), respectively.

It is recommended that the ASHRAE clear-sky model be used for solar radiation calculations in Erzurum, Turkey. Instantaneous and daily solar radiation on different surfaces, such as building walls and solar collectors, can be conveniently calculated using the ASHRAE model. The model also allows the beam and diffuse solar radiation component to be determined separately.

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Nomenclature

H_c	monthly average daily radiation to clear day radiation ($\mathrm{MJm^{-2}}$)
H_o	monthly average daily extraterrestrial radiation on a horizontal surface ($\mathrm{MJm^{-2}}$)
I	hourly clear sky global radiation ($\mathrm{Wm^{-2}}$)
I_b	hourly clear sky beam radiation ($\mathrm{Wm^{-2}}$)
I_d	hourly clear sky diffuse radiation ($\mathrm{Wm^{-2}}$)
θ_z	Zenith angle, the between the vertical and the line to the sun (°)
φ	latitude of site (°)
δ	declination angle (°)