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Simple model for the generation of daily global solar-radiation data in Turkey

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Abstract

Modelling, performance analysis, and designing of solar energy systems depend on solar radiation data. In this study, a simple model for estimating the daily global radiation is developed. The model is based on a trigonometric function, which has only one independent parameter, namely the day of the year. The model is tested for 68 locations in Turkey using the data measured during at least 10 years. It is seen that predictions from the model agree well with the long-term measured data. The predictions are also compared with the data available in literature for Turkey. It is expected that the model developed for daily global solar radiation will be useful to the designers of energy-related systems as well as to those who need to estimates of yearly variation of global solar-radiation for any specific location in Turkey.

Keywords: Global solar radiation; Solar radiation model; Turkey

1. Introduction

Solar radiation data are a fundamental input for solar energy applications such as photovoltaics, solar thermal systems, and passive solar design. The data should be contemporary, reliable and readily available for design, optimization and performance evaluation of solar technologies for any particular geographical location. Unfortunately, for many developing countries, solar-radiation measurements are not easily available

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Nomenclature

d	number of the day, starting from the first of January
I	daily global solar-radiation on a horizontal surface (MJ/m^2 day)
I_1, I_2	coefficients (Eq. (1))
n	number of measured data
r	correlation coefficient
S_t	standard deviation
S_r	deviation from calculated values
$\bar{I}_m$	average of measured values
Abbreviations	
DMİ	The Turkish State Meteorological Service
MAE	mean absolute error
MRE	mean relative error
RMSE	root-mean-square error
Subscripts	
c	calculated value
m	measured value

because of the expensive measuring equipment and techniques required. Therefore, it is necessary to develop methods to estimate the solar radiation on the basis of the more readily available meteorological data [1]. Wong and Chow [2] reviewed the available solar-radiation models in detail. The majority of the models developed for the prediction of solar radiation are based on existing climatic-parameters, such as sunshine duration, cloud cover, relative humidity, and minimum and maximum temperatures [3–11].

Solar energy is accepted as a key alternative energy source for the future. Therefore, solar energy is being seriously considered for satisfying significant part of the energy demand in Turkey, and the world. In this respect, the importance of solar-radiation data for design and efficient operation of solar-energy systems has been acknowledged [12]. Many individual studies have been carried out in recent years on this subject for different locations of Turkey [6–19]. In the present study, a simple model for simulating daily global solar radiation was developed. The model was implemented for 68 provinces of Turkey.

2. Modelling of daily global solar radiation

The weather variables such as temperature and solar radiation are neither completely random nor deterministic; hence it is very difficult to present all variances mathematically. On the other hand, it is necessary to know the changes of weather data as well as possible throughout the year. Therefore, many attempts have been made to develop models for generating typical weather variables such as solar radiation, temperature and relative humidity, both daily and hourly [20]. Solar-radiation models range from simple empirical relations [3,4,9,13,15,22–24] to complex models [21,25–30]. Time series, Fourier series, stochastic modelling and regression analysis are the mostly used techniques for synthetic

Table 1
Solar-radiation database and basic information for weather stations

Province	Longitude (°E)	Latitude (°N)	Elevation (m)	Period	Total years
Adana	35.18	36.59	20	1986–2001	16
Adapazarı	30.25	40.47	30	1984–1998	15
Adıyaman	38.17	37.45	678	1981–2001	19
Afyon	30.32	38.45	1034	1984–1998	15
Ağrı	43.08	39.31	1585	1986–1998	13
Aksaray	34.03	38.23	980	1981–1998	17
Amasya	35.51	40.39	412	1984–1998	15
Ankara	32.53	39.57	894	1983–2001	19
Antakya	36.07	36.15	100	1984–1998	14
Antalya	30.42	36.53	42	1983–2001	19
Artvin	41.49	41.10	597	1985–1998	14
Aydın	27.50	37.51	57	1983–1998	16
Balıkesir	27.52	39.39	147	1983–1997	15
Bartın	32.21	41.38	30	1985–1998	14
Batman	41.10	37.52	540	1986–2001	16
Bilecik	29.58	40.09	526	1984–1998	15
Bingöl	40.30	38.52	1177	1987–1998	12
Bitlis	42.06	38.22	1559	1985–1998	11
Bursa	29.04	40.11	100	1983–1998	16
Çanakkale	26.24	40.08	3	1981–1998	17
Çankırı	33.37	40.36	751	1981–1995	14
Çorum	34.58	40.33	798	1984–1998	15
Denizli	29.05	37.47	428	1984–1998	15
Diyarbakır	40.12	37.55	660	1983–2001	18
Edirne	26.34	41.40	48	1983–1998	14
Elazığ	39.13	38.40	1105	1981–1998	18
Erzincan	39.30	39.44	1215	1981–1998	18
Erzurum	41.16	39.55	1869	1984–2001	17
Gaziantep	37.22	37.05	855	1985–2001	17
Gümüşhane	39.27	40.27	1219	1986–1998	13
Hakkari	43.46	37.34	1720	1981–1998	16
Iğdır	44.02	39.56	858	1981–1998	16
İskenderun	36.07	36.37	3	1983–1998	16
Isparta	30.33	37.45	997	1981–1998	18
İstanbul	29.05	40.58	39	1983–2001	19
İzmir	27.10	38.24	25	1983–2001	19
K.Maraş	36.56	37.36	549	1985–2001	17
Karaman	33.14	37.11	1025	1985–1998	14
Kars	43.05	40.36	1775	1984–1998	15
Kastamonu	33.46	41.22	791	1983–1998	16
Kayseri	35.29	38.43	1068	1984–2001	16
Kilis	37.05	36.44	638	1985–1998	14
Kırıkkale	33.30	39.50	725	1986–1995	10
Kırşehir	34.10	39.08	985	1983–1995	13
Kocaeli	29.54	40.46	76	1986–1998	13
Konya	32.30	37.52	1028	1983–2001	19
Kütahya	29.58	39.24	969	1985–1998	14
Malatya	38.18	38.21	998	1983–2001	17
Mersin	34.36	36.49	5	1984–1998	15
Muğla	28.21	37.12	646	1983–1998	15
Muş	41.31	38.44	1283	1986–1998	13

(continued on next page)

Table 1 (*continued*)

Province	Longitude (°E)	Latitude (°N)	Elevation (m)	Period	Total years
Niğde	34.40	37.59	1208	1985–1998	14
Ordu	37.52	40.59	4	1985–1998	13
Rize	40.30	41.02	4	1987–1998	12
Samsun	36.20	41.17	44	1983–1998	16
Siirt	41.56	37.56	875	1981–1998	17
Sinop	35.10	42.02	32	1985–1998	14
Sivas	37.01	39.49	1285	1983–1998	14
Şanlıurfa	38.46	37.08	547	1983–2001	18
Tekirdağ	27.29	40.59	4	1984–1998	15
Tokat	36.54	40.18	608	1984–1998	14
Trabzon	39.43	41.00	30	1983–2001	19
Tunceli	39.32	39.06	979	1988–1998	11
Uşak	29.29	38.40	919	1981–1995	13
Van	43.41	38.28	1725	1983–2001	18
Yalova	29.16	40.39	2	1984–1998	15
Yozgat	34.49	39.50	1298	1983–1998	16
Zonguldak	31.48	41.27	136	1985–1998	13

Table 2
The coefficients and statistical values for Eq. (1) for 68 provinces of Turkey

Province	I_1	I_2	±MAE (MJ/m^2 day)	MRE (%)	RMSE (MJ/m^2 day)	r
Adana	22.56	5.81	2.57	20	3.36	0.86
Adapazarı	21.10	3.02	3.96	36	4.96	0.78
Adıyaman	19.72	4.47	2.36	24	3.08	0.86
Afyon	24.05	5.16	2.91	22	3.80	0.86
Ağrı	21.18	4.51	2.56	22	3.34	0.86
Aksaray	22.84	6.07	2.62	20	3.37	0.86
Amasya	22.04	3.25	2.87	25	3.75	0.86
Ankara	22.71	3.86	2.78	23	3.62	0.87
Antakya	21.38	3.97	2.19	21	2.91	0.90
Antalya	26.12	6.86	2.79	20	3.74	0.87
Artvin	20.77	4.06	3.87	30	4.81	0.76
Aydın	25.34	5.69	2.71	20	3.65	0.88
Balıkesir	20.23	2.75	2.84	29	3.71	0.85
Bartın	20.38	2.68	3.50	34	4.47	0.80
Batman	19.88	4.00	2.67	25	3.33	0.85
Bilecik	21.31	3.95	3.36	29	4.20	0.81
Bingöl	24.55	4.23	3.03	25	3.98	0.87
Bitlis	22.85	5.00	2.87	23	3.77	0.85
Bursa	19.82	3.74	3.31	31	4.24	0.79
Çanakkale	23.19	3.96	2.92	26	3.84	0.86
Çankırı	22.79	4.35	2.99	24	3.79	0.86
Çorum	22.11	4.29	3.08	25	3.91	0.84
Denizli	19.96	3.87	2.13	20	2.90	0.88
Diyarbakır	26.43	5.26	3.07	23	3.94	0.88
Edirne	14.23	2.41	3.28	39	3.97	0.71
Elazığ	23.38	4.06	2.58	22	3.39	0.89
Erzincan	21.60	5.02	2.67	22	3.48	0.85
Erzurum	23.89	6.91	3.12	21	4.03	0.82
Gaziantep	22.47	4.39	2.49	23	3.22	0.89
Gümüşhane	24.00	3.97	2.92	21	3.88	0.87

Table 2 (*continued*)

Province	I_1	I_2	±MAE (MJ/m^2 day)	MRE (%)	RMSE (MJ/m^2 day)	r
Hakkari	22.94	6.75	2.66	19	3.59	0.84
Iğdır	20.45	4.47	2.53	22	3.27	0.86
İskenderun	21.50	5.55	2.74	22	3.56	0.84
Isparta	19.24	5.19	2.22	20	2.89	0.85
İstanbul	21.41	2.57	3.24	33	4.20	0.84
İzmir	24.15	5.27	2.81	21	3.67	0.87
Kahramanmaraş	25.36	4.50	2.89	24	3.83	0.88
Karaman	25.88	6.17	2.76	19	3.64	0.88
Kars	22.05	6.28	2.94	21	3.82	0.81
Kastamonu	18.00	3.33	2.82	28	3.58	0.81
Kayseri	21.99	4.95	2.88	22	3.72	0.84
Kilis	25.78	6.09	2.72	21	3.55	0.88
Kırıkkale	22.84	3.95	2.78	24	3.57	0.87
Kırşehir	23.77	5.86	2.69	20	3.50	0.87
Kocaeli	17.25	2.74	3.23	36	4.04	0.77
Konya	25.12	5.89	2.82	20	3.60	0.88
Kütahya	23.19	3.78	3.11	24	4.08	0.85
Malatya	24.68	4.56	2.66	22	3.48	0.89
Mersin	25.00	7.01	2.57	18	3.49	0.87
Muğla	21.15	5.04	2.69	24	3.54	0.84
Muş	22.49	4.93	3.28	26	4.08	0.82
Niğde	28.16	7.60	3.03	19	3.98	0.87
Ordu	18.75	3.19	4.30	39	5.27	0.71
Rize	16.20	3.57	4.45	43	5.45	0.62
Samsun	20.85	3.30	3.96	35	4.87	0.77
Siirt	23.95	5.56	3.27	25	4.12	0.83
Sinop	19.86	2.47	3.18	33	4.01	0.83
Sivas	20.82	3.58	2.80	25	3.64	0.85
Şanlıurfa	25.07	5.43	2.80	22	3.57	0.88
Tekirdağ	20.46	2.88	3.14	32	3.99	0.83
Tokat	21.94	4.50	3.75	29	4.65	0.79
Trabzon	16.97	3.73	3.92	37	4.78	0.69
Tunceli	24.79	4.94	3.19	25	4.14	0.85
Uşak	22.60	5.36	3.14	24	3.97	0.83
Van	26.45	7.22	2.80	18	3.72	0.87
Yalova	21.89	2.16	3.53	36	4.56	0.83
Yozgat	21.15	4.49	2.62	23	3.37	0.86
Zonguldak	21.68	2.31	3.86	38	4.84	0.80

generation of weather variables [4,21–23,26,27,30]. The main advantage of the synthetic generation of weather variable is the readily usage of mathematical expressions in the computer programs and thus, do not require tedious inputting work for the variables and database files for simulation [18].

Some researchers showed that the variations of solar radiation throughout the year could be well-represented using harmonic equations [18,23,31].

In the present study, a simple mathematical model for daily global solar-radiation based on a trigonometric function was developed to simulate the long-term measured data. The function has only one independent parameter, namely the day of the year. The daily global solar radiation on a horizontal surface (I) in MJ/m^2 day can be estimated using the following equation;

$$I = I_2 + (I_1 - I_2)\left|\sin\left[\frac{\pi}{365}(d+5)\right]\right|^{1.5} \tag{1}$$

where d is the number of the day starting from January 1. For the 1st January, $d = 1$, and for 31st December $d = 365$. I_1 and I_2 are the coefficients and they should be determined for each location separately by means of statistical-error tests, for which the details are given below.

For better data modelling, mean absolute error (MAE), mean relative error (MRE), and root-mean-square error (RMSE) should be minima, and the correlation coefficient r should approach unity as closely as possible. MAE, MRE, RMSE, and r are defined as:

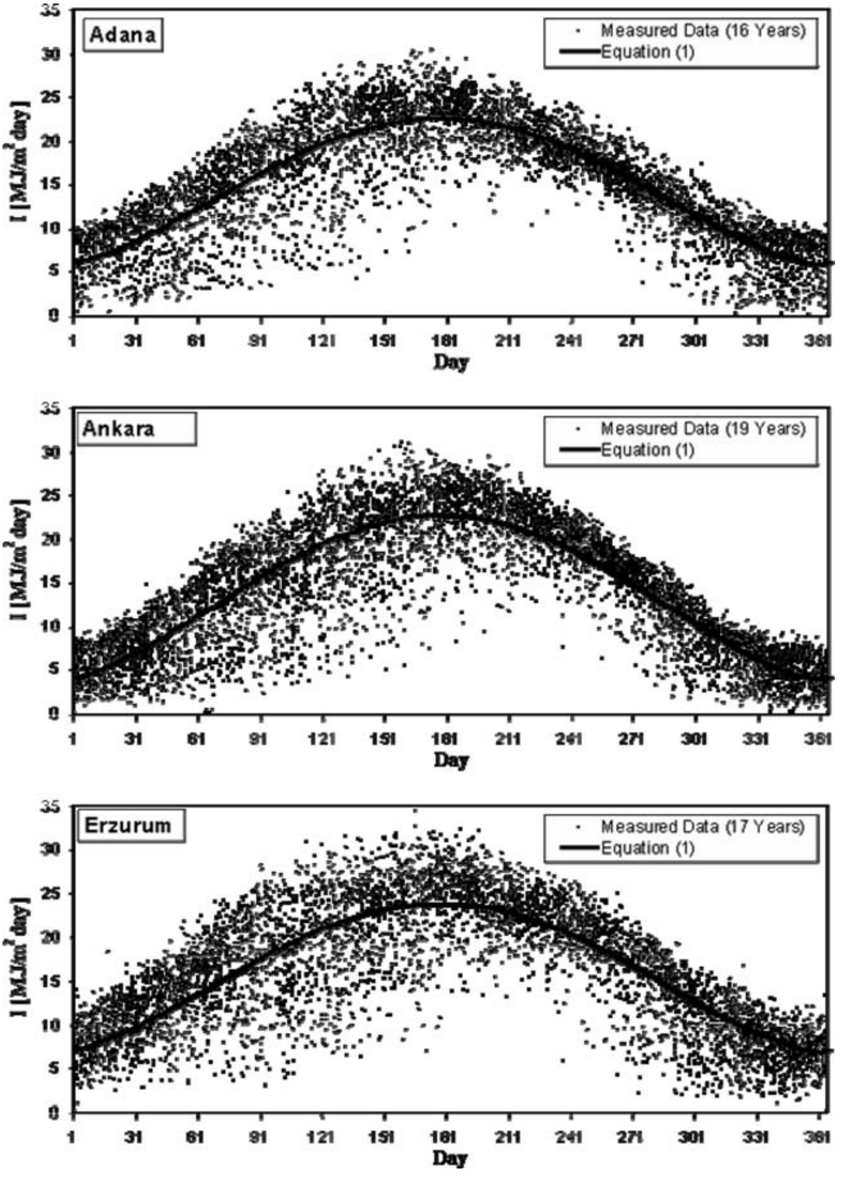

Fig. 1. Variation of daily global solar-radiation throughout the year for the main provinces of Turkey.

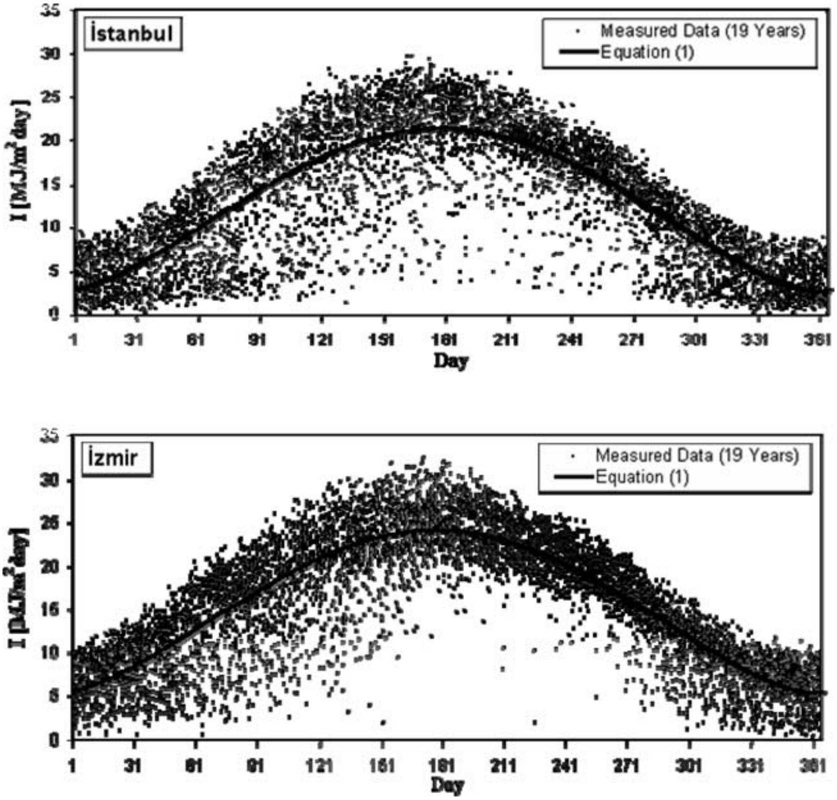

Fig. 1 (*continued*)

Mean absolute error (MAE):

$$\mathrm{MAE} = \sum_{i=1}^{n} \left| \frac{I_{\mathrm{c},i} - I_{\mathrm{m},i}}{n} \right| \tag{2}$$

where I_c and I_m are the calculated and the measured daily global solar-radiation, respectively; n represents the number of the measured data. Mean relative error (MRE):

$$\mathrm{MRE} = \frac{\sum_{i=1}^{n} \left| \frac{I_{\mathrm{c},i} - I_{\mathrm{m},i}}{I_{\mathrm{m},i}} \right|}{n} \tag{3}$$

Root-mean-square error (RMSE):

$$\mathrm{RMSE} = \left(\frac{\sum_{i=1}^{n} (I_{\mathrm{c},i} - I_{\mathrm{m},i})^2}{n-2} \right)^{1/2} \tag{4}$$

Correlation coefficient (r):

$$r \equiv \sqrt{\frac{S_\mathrm{t} - S_\mathrm{r}}{S_\mathrm{t}}} \tag{5}$$

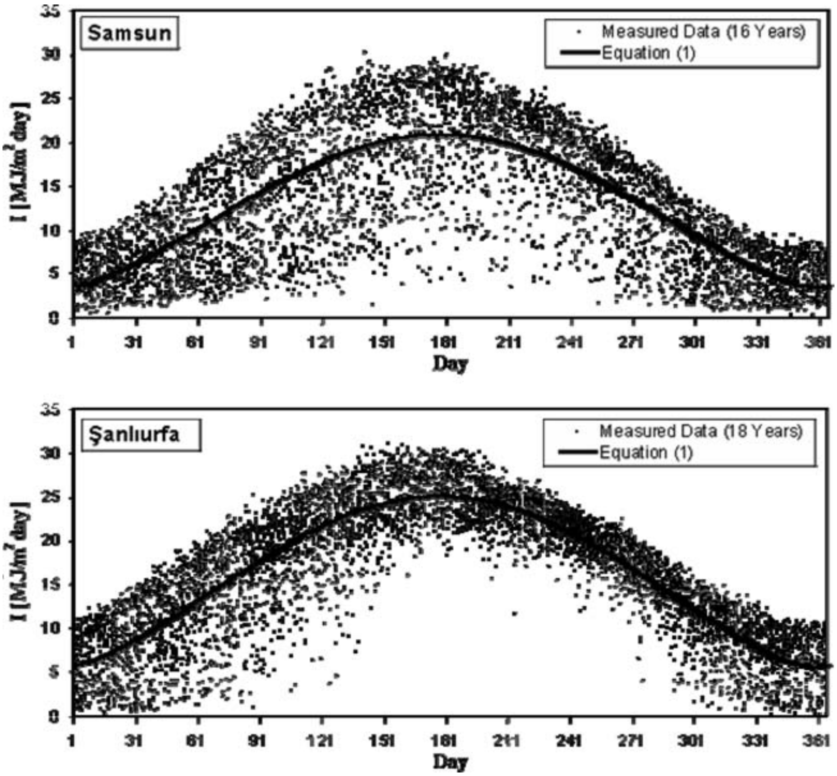

Fig. 1 (*continued*)

where S_t is the standard deviation and S_r is the deviation of the calculated value from the measured one. S_t and S_r are defined as follow:

$$S_t = \sum_{i=1}^{n} (\overline{I}_m - I_{m,i})^2 \tag{6}$$

$$S_r = \sum_{i=1}^{n} (I_{m,i} - I_{c,i})^2 \tag{7}$$

where $\overline{I}_m$ is the average of the measured values and it is given by:

$$\overline{I}_m = \frac{\sum_{i=1}^{n} I_{m,i}}{n} \tag{8}$$

3. Implementation of the model for Turkey

The new simple model for daily global solar-radiation was implemented for 68 provinces of Turkey; they cover almost all parts of the country (total number of the provinces in Turkey is 81). In Turkey, meteorological measurements are taken and the related records are kept by the Turkish State Meteorological Service (Turkish initials "DMİ"). Meteorological stations are located in city centres and there is generally only one station in each city. In this study, the global solar-radiation data were taken from the Turkish State Meteorological Service in computer files for each location. There were missing and invalid measurements in the data and they were marked and coded as 99999 in the files. The missing and invalid measurements, accounting for approximately 0.46% of the whole data-base, were replaced with the values derived from those of preceding and subsequent days by interpolation. In the calculations, if more than 15 days-measurements

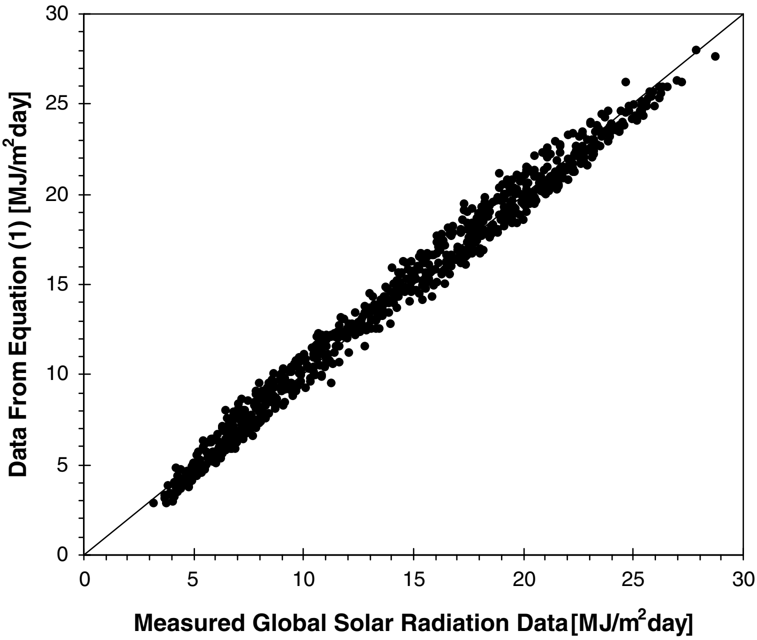

Fig. 2. Comparison of the monthly mean values of long-term measured data with the data obtained from Eq. (1) for all provinces of Turkey.

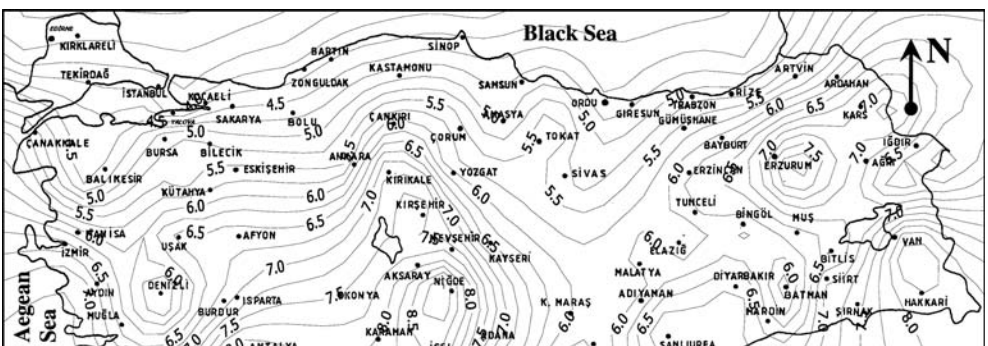

Fig. 3. Contour map of daily global solar-radiation (MJ/m^2 day) calculated from Eq. (1) for 17 January for Turkey.

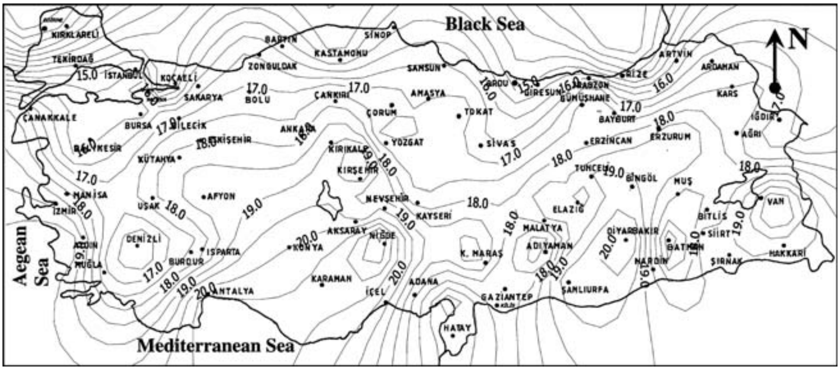

Fig. 4. Contour map of daily global solar-radiation (MJ/m^2 day) calculated from Eq. (1) for 15 April for Turkey.

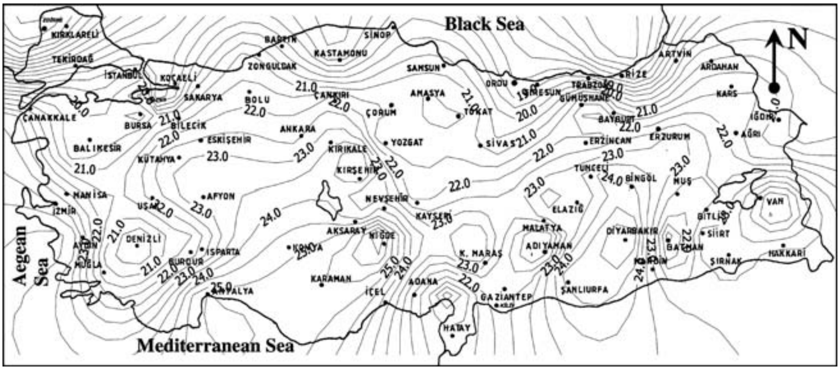

Fig. 5. Contour map of daily global solar-radiation (MJ/m^2 day) calculated from Eq. (1) for 17 July for Turkey.

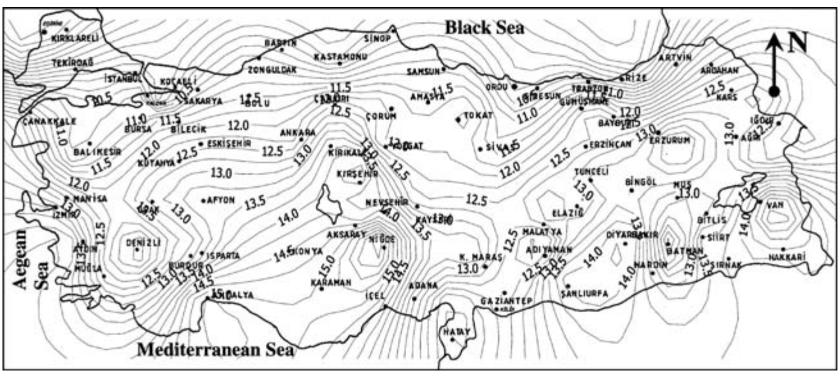

Fig. 6. Contour map of daily global solar-radiation (MJ/m^2 day) calculated from Eq. (1) for 15 October for Turkey.

were not available in a month, the year was excluded from the database. For example, the data for the year 1984 for Diyarbakır was not considered in the calculations due to missing values. Table 1 provides information for locations and, the period and total year of the daily global solar-radiation data considered in this study. As can be seen from Table 1, the daily global solar-radiation data measured during at least 10 years between 1981 and 2001 were used in the calculations.

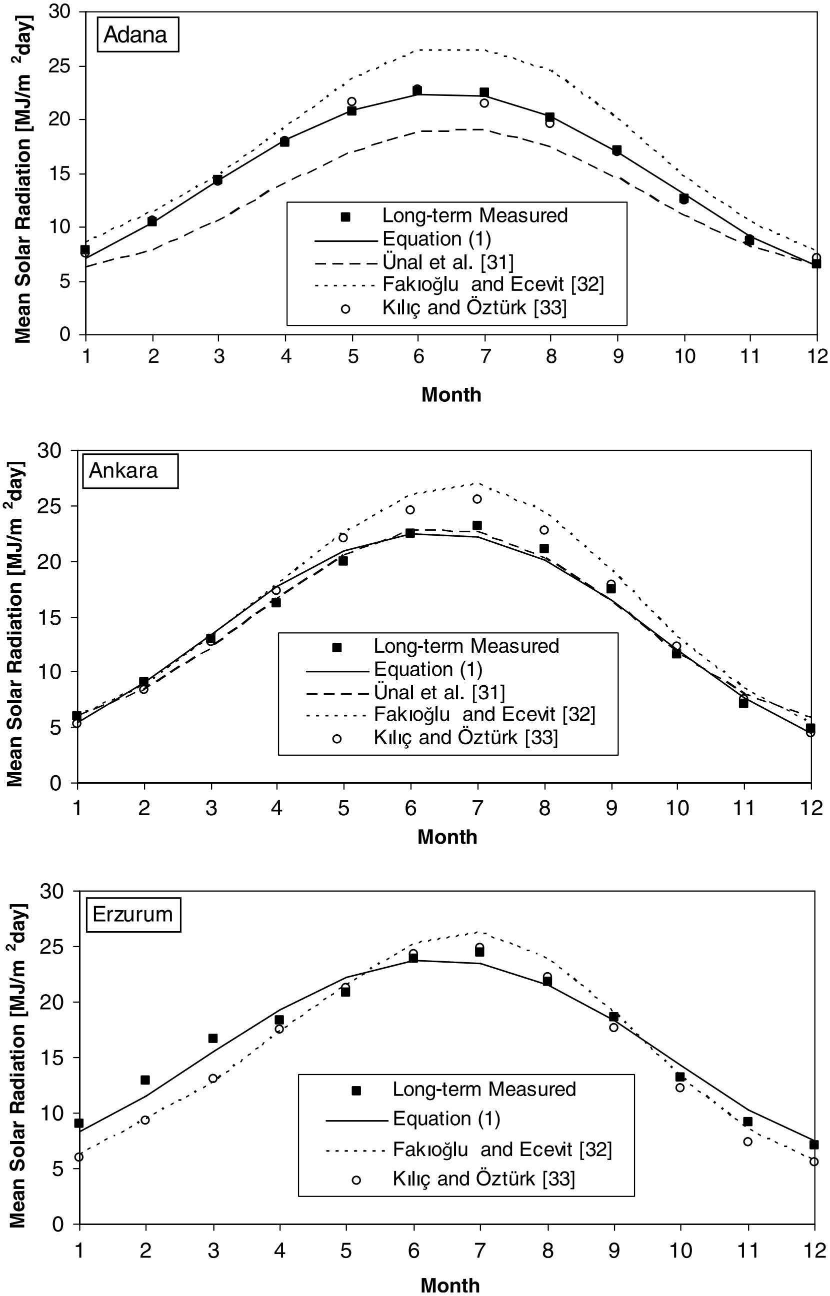

Fig. 7. Comparison of the data obtained from Eq. (1) with the published data for main locations in Turkey.

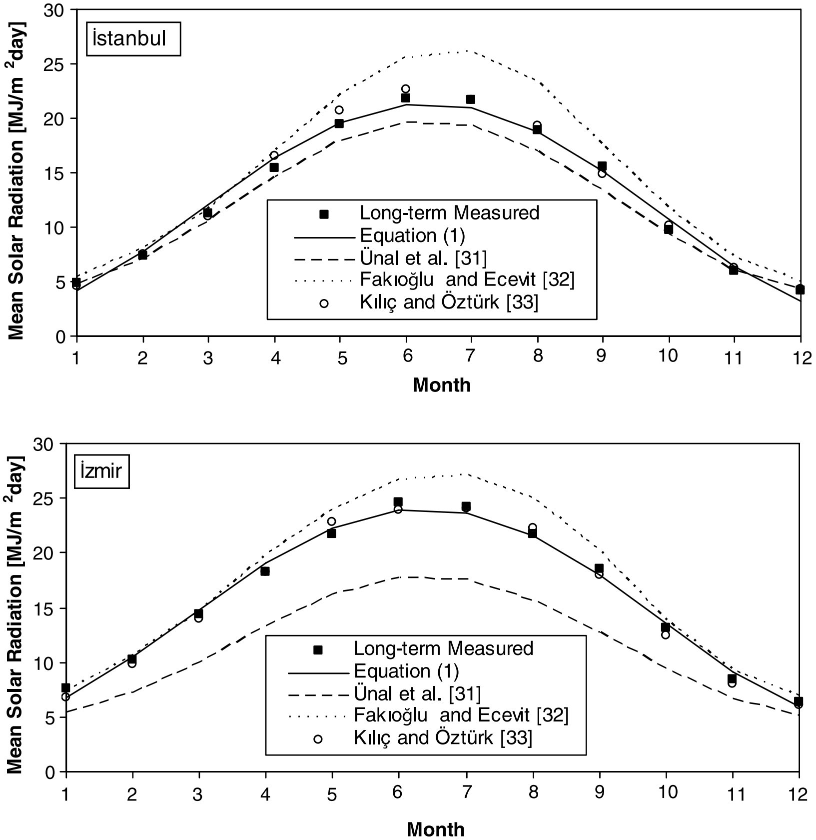

Fig. 7 (*continued*)

In the current study, the coefficients of Eq. (1) were determined for 68 locations in Turkey by considering mean absolute error (MAE), mean relative error (MRE), root-mean-square error (RMSE), and correlation coefficient (r). The coefficients and the values for MAE, MRE, RMSE and r of the equations obtained are given in Table 2. It can be seen from Table 2 that correlation coefficient is in the range of 0.62 and 0.90. This means that the equation obtained represent the measured data satisfactorily. The provinces located in the coastal Black Sea, such as Rize, Trabzon, Samsun and Ordu have relatively low r values. This is mainly due to highly-variable weather conditions and high rainfall in this region. For some locations, the correlation is very good such as for Antakya, Elazığ, Gaziantep, Konya, Kahramanmaraş, Malatya, Kilis and Şanlıurfa. MAE is between 2.13 and 4.45, whilst MRE is in the range of 18% to 43% throughout Turkey. It can also be seen from the table that RMSE values vary between 2.89 and 5.45, indicating that the proposed model accounts well for the variability in the daily global solar-radiation.

Fig. 1 shows variation of the measured daily global solar-radiation and the data obtained from Eq. (1) for seven main provinces of Turkey, which represent geographical and climatic conditions of their regions. Although the long-term measured data fluctuate and are very random, the values obtained from Eq. (1) follow the variation of the daily global solar-radiation throughout the year.

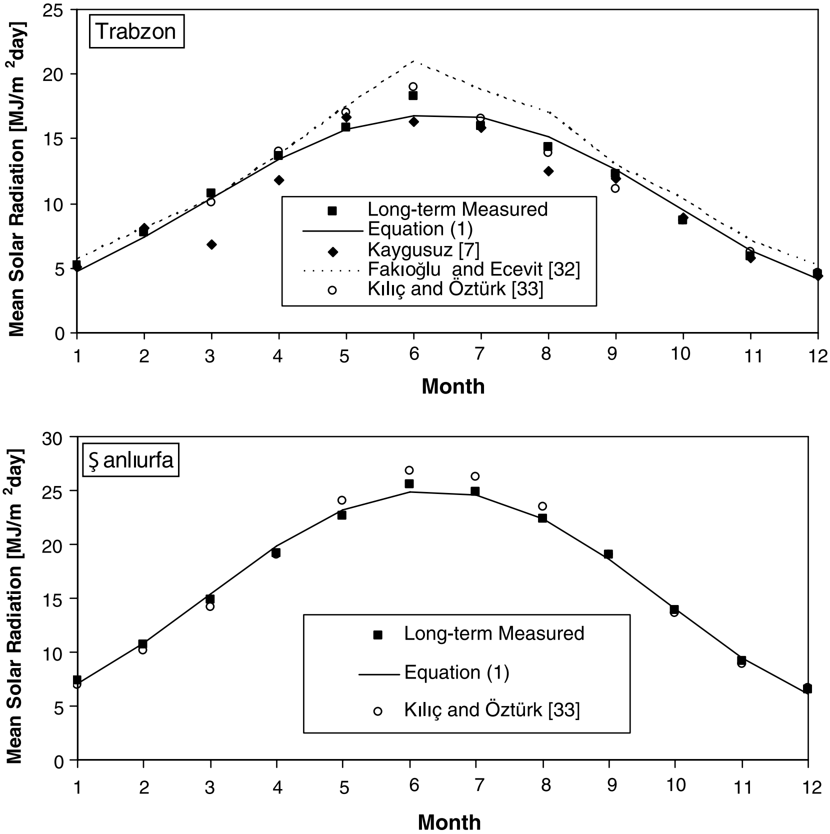

Fig. 7 (*continued*)

The monthly mean values of the daily global-radiation calculated from the model (Eq. (1)) were compared with the corresponding measured values. The results are illustrated in Fig. 2 for all locations considered in this study. It is clear from the figure that the deviation between the measured and calculated values is very small.

Contour maps of the daily global solar radiation calculated from Eq. (1) for four different days that represent four seasons in a year are shown in Figs. 3→6. As can be seen from these figures, daily global solar-radiation is lower during the year in the locations near to Black Sea coast, where rainfall is quite high, compared with the other regions of the country. Daily global solar-radiation varies between 4 and 9 MJ/m^2 day on 17 January (Fig. 3), between 15 and 20 MJ/m^2 day on 15 April (Fig. 4), between 19 and 25 MJ/m^2 day on 17 July (Fig. 5) and between 10 and 15 MJ/m^2 day on 15 October (Fig. 6).

In Fig. 7, the monthly mean values of the daily global solar-radiation, obtained from Eq. (1), are compared with the data available in literature [7,31–33] for the main locations in Turkey. As can be seen from the figure, agreement between the values obtained from Eq. (1) and the long-term measurements is very good. Among the data given in the literature, those given by Kılıç and Öztürk [33] generally exhibit the best agreement with the long-term measured data. The data given by Fakıoğlu and Ecevit [32] overestimate the monthly mean values of daily global solar radiation, while the model of Ünal et al. [31] underestimates generally.

4. Conclusions

A simple model for simulating daily global solar-radiation was suggested in this study. The proposed model can be used for predicting accurately daily global solar-radiation, which helps in the estimation of the long-term performances of solar-energy systems.

The model is tested for 68 provinces of Turkey. It was seen that the statistical indicators for the model such as mean absolute error, root-mean-square error and correlation coefficient are at acceptable levels. It was found that the model can be used for estimating monthly values of global solar-radiation with a high accuracy. Comparison of the model with the measured data and the data available in the literature revealed that the model provides predictions in good agreement with both the measured data and the data available in the literature. It is expected that the model developed for daily global solar-radiation will be useful to the engineers of solar-energy related systems as well as those who need to have fairly good estimates of yearly variations of daily global solar-radiation for specific location.

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