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Estimating daily global solar radiation by day of year in China

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ABSTRACT

In this study, a new empirical model is proposed for estimating daily global solar radiation on a horizontal surface by the day of the year. The performance of the proposed model is validated by comparing with three trigonometric correlations at nine representative stations of China using statistical error tests such as the mean absolute percentage error (MAPE), mean absolute bias error (MABE), root mean square error (RMSE) and correlation coefficients (*r*). The results show that the new model provides better estimation and has good adaptability to highly variable weather conditions. Then the application of the methodology is performed for the other 70 meteorological stations across China.

1. Introduction

Solar energy is one of the most important and promising renewable and sustainable energy. China has abundant solar energy resources and more than two-thirds of areas receive an annual total solar radiation that exceeds 5.9 GJ/m^2 with sunshine duration more than 2200 h [1]. It is meaningful to substitute solar energy for fossil energy with respect to solar energy resources.

An accurate knowledge of the solar radiation data at a particular geographical location is important for solar energy system design [2]. However, in most areas of the world, solar radiation measurements are not easily available due to cost and techniques involved. There are only 103 solar radiation observation stations until 2008 in Chinese mainland [3]. Long-term data on global solar radiation are not available for most areas in China, especially in remote rural and mountainous areas, where approximately 80% of the Chinese population is living [4]. Therefore, elaborating methods to estimate the solar radiation is of great significance.

Solar radiation can be estimated by means of empirical relations using other available meteorological observations [5–17], interpolating methods [18], geostationary satellite images [19], time series methods [20], stochastic weather models [21], physically radiative transfer models [22], and the artificial neural network method [23,24]. Among the numerous methods, those based on empirical correlations using commonly measured meteorological data are attractive due to lower data requirement and computation cost [10]. Recently, several empirical formulas using some available meteorological parameters have been tested around the world. The meteorological parameters include sunshine hours [5–8], ambient temperature [9–11], cloudiness [12–14], relative humidity [15], precipitation [16] and vapor pressure [17].

In general, although sophisticatedly empirical formulas try to simulate solar radiation with a good prediction, it is on the other hand, very useful to build reliable and easy models to estimate solar radiation.

Simple models to estimate solar radiation without meteorological data have been implemented by using the only one parameter, i.e., the day of the year [25–28]. Bulut [25] developed a model to estimate the daily global solar radiation for Istanbul using long-term measured data with a sine wave equation. Subsequently, Bulut and Büyükalaca [26] tested the model for 68 locations in Turkey and the results showed that the predictions from the model agree well with the long-term measured data. Al-Salaymeh [27] predicted the daily global solar radiation of Amman city in Jordan on a horizontal oriented surface using four models, including a sine wave model. Statistical results showed that the sine wave model gave best fit. Kaplanis and Kaplani [28] used a cosine wave model to calculate the daily global solar radiation in six climatic zones of Greece and the correlation coefficient for all cases is higher than 0.996.

The main advantage of these models is the readily usage of mathematical expressions even by a pocket calculator and thus, do not require tedious inputting work for the variables and database files for simulation [25]. However, there has been a lack of reports in literature about the evaluation of the applicability of these models for estimating daily global solar radiation.

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In the present study, a new trigonometric model in conjunction with a sine and cosine wave for estimating the daily global radiation is proposed. The performance of the proposed model is validated by comparing with three existing trigonometric correlations at nine representative stations of China using statistical error tests, and then the methodology is applied to the other 70 meteorological stations across China.

2. Data and methodology

2.1. Data

Daily measured global solar radiation data of 79 meteorological stations covering all over China are taken from the National Meteorological Information Centre (NMIC), China Meteorological Administration and then are averaged to obtain the annual mean values after processing. There are missing measurements in the data, and they are marked and coded as 32766 in the files. Fig. 1 shows the distribution of the selected stations. The daily global solar radiation data measured during at least 10 years between January 1 1994 and December 31 2008 are used in the calculations.

The quality control of the original solar radiation data is performed to eliminate spurious data and inaccurate measurements, with the clearness index K_t as an indicator. Data will be rejected if the daily global solar radiation were greater than the corresponding extraterrestrial radiation, i.e., $K_t > 1$, or the daily global solar radiation were less than a minimum value expected with continuous overcast conditions. The smallest acceptable value for K_t is set as 0.015, representing a heavy overcast sky for the whole day [29–31]. All excluded and missing data, accounting for approximately 0.58% of the whole data-base, are replaced with the values derived from those of preceding and subsequent days by interpolation.

2.2. Methods

Daily solar radiation is a quasi-periodic phenomenon on a yearly cycle due to seasonal effects [32]. It is convenient to model daily global solar radiation by the day of the year. Among the models estimating daily global solar radiation by the day of the year, trigonometric correlations give excellent fitting. A brief description of the trigonometric models examined is given below.

Bulut [25] proposed a sine wave model:

$$H = a_0 + a_1 \times \left|\sin\left[\frac{\pi}{365}(n+5)\right]\right|^{1.5} \tag{1}$$

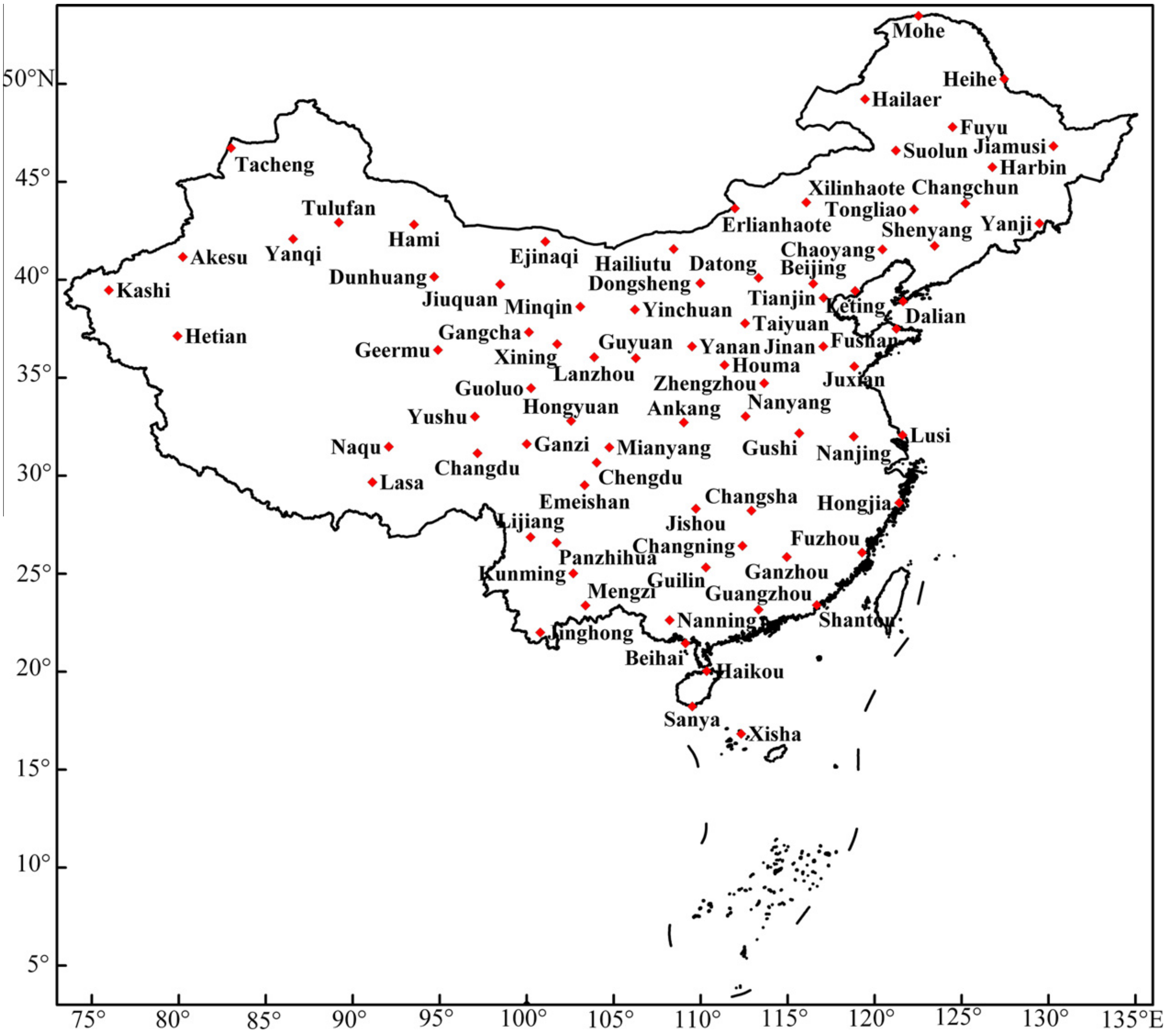

Fig. 1. Distribution of the selected stations in China.

Table 1
Regression coefficients of Eqs. (1)–(4) and errors at nine representative stations.

#	Location	Model #	a_0	a_1	a_2	a_3	a_4	a_5	a_6	MAPE	MABE	RMSE	r
1	Minqin	1	8.644	15.372	–	–	–	–	–	6.616	1.163	1.566	0.958
		2	16.847	−7.640	−382.281	1.978	–	–	–	5.545	0.980	1.314	0.970
		3	17.217	−7.449	−6.047	–	–	–	–	5.932	1.018	1.330	0.970
		4	16.440	−7.889	0.909	8.360	0.519	1.946	7.915	5.254	0.936	1.273	0.972
2	Shantou	1	10.463	6.845	–	–	–	–	–	12.892	1.720	2.100	0.741
		2	14.329	−3.798	359.014	1.065	–	–	–	8.845	1.205	1.582	0.863
		3	14.282	−3.813	−0.456	–	–	–	–	8.852	1.206	1.583	0.863
		4	14.273	−3.835	1.002	1.115	−0.603	4.353	0.597	8.594	1.168	1.526	0.873
3	Leting	1	6.743	13.081	–	–	–	–	–	9.625	1.344	1.795	0.927
		2	12.816	−7.119	−431.305	0.847	–	–	–	8.156	1.136	1.558	0.945
		3	14.038	−6.341	0.294	–	–	–	–	9.512	1.263	1.65	0.939
		4	13.755	−1.037	2.257	0.270	−6.327	0.943	0.482	7.630	1.069	1.418	0.955
4	Harbin	1	4.021	15.973	–	–	–	–	–	9.095	1.152	1.550	0.961
		2	11.886	−8.315	411.802	2.119	–	–	–	7.857	0.994	1.388	0.969
		3	12.929	−7.678	0.214	–	–	–	–	9.267	1.098	1.466	0.965
		4	11.607	8.509	0.861	5.337	0.739	3.877	−4.615	7.003	0.913	1.286	0.974
5	Ganzhou	1	6.411	10.938	–	–	–	–	–	19.393	2.033	2.481	0.831
		2	12.782	−5.699	−345.566	2.087	–	–	–	12.983	1.394	1.751	0.920
		3	12.512	−5.787	−0.336	–	–	–	–	13.053	1.411	1.763	0.919
		4	12.844	−5.680	1.068	1.009	0.836	4.610	−3.693	11.999	1.286	1.647	0.929
6	Lasa	1	14.888	10.043	–	–	–	–	–	4.938	1.054	1.394	0.925
		2	19.672	−5.352	422.923	2.210	–	–	–	4.882	1.014	1.289	0.937
		3	20.489	−4.840	0.262	–	–	–	–	5.274	1.072	1.334	0.932
		4	19.733	1.016	−2.076	−0.146	−5.290	0.868	6.940	4.003	0.824	1.083	0.956
7	Kashi	1	5.232	18.197	–	–	–	–	–	6.947	1.004	1.320	0.978
		2	15.141	−8.867	−373.907	20.295	–	–	–	6.354	0.919	1.201	0.982
		3	15.381	−8.740	0.042	–	–	–	–	6.661	0.938	1.207	0.982
		4	15.343	−0.608	2.951	2.570	−8.771	0.999	6.337	5.618	0.844	1.126	0.984
8	Tulufan	1	4.286	19.412	–	–	–	–	–	6.392	0.905	1.208	0.984
		2	13.813	−10.094	−412.644	1.063	–	–	–	5.273	0.785	1.094	0.987
		3	15.112	−9.286	0.158	–	–	–	–	7.513	0.956	1.226	0.983
		4	13.696	10.180	0.876	17.811	0.481	3.653	2.703	5.108	0.752	1.039	0.988
9	Mengzi	1	12.799	4.564	–	–	–	–	–	11.466	1.709	2.127	0.588
		2	14.911	−2.862	−435.726	0.431	–	–	–	9.627	1.437	1.789	0.733
		3	15.343	−2.676	0.742	–	–	–	–	9.894	1.471	1.827	0.719
		4	15.332	2.497	0.942	5.678	1.005	2.260	2.492	9.103	1.348	1.660	0.776

Another sine wave correlation used by Al-Salaymeh [27]:

$$H = a_0 + a_1 \times \sin\left(\frac{2\pi}{a_2}n + a_3\right) \tag{2}$$

Kaplanis and Kaplani [28] suggested a cosine wave correlation:

$$H = a_0 + a_1 \times \cos\left(\frac{2\pi}{364}n + a_2\right) \tag{3}$$

In addition, a new model in conjunction with a sine and cosine wave correlation is proposed and defined as follows:

$$H = a_0 + a_1 \times \sin\left(\frac{2\pi a_2}{365}n + a_3\right) + a_4 \times \cos\left(\frac{2\pi a_5}{365}n + a_6\right) \tag{4}$$

Where H is the daily global solar radiation and n is the number of the day of year starting from January 1. For the 1st January, $n = 1$, and for 31st December $n = 365$. a_0, a_1, a_2, a_3, a_4, a_5 and a_6 are the empirical coefficients.

3. Performance evaluations

In this study, the performance of the models is evaluated in terms of the mean absolute percentage error (MAPE), mean absolute bias error (MABE), root mean square error (RMSE) and correlation coefficients (r). These error terms can be calculated using the following equations:

$$\mathrm{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{H_{ci} - H_{mi}}{H_{mi}} \times 100\right| \tag{5}$$

$$\mathrm{MABE} = \frac{1}{n}\sum_{i=1}^{n}|H_{ci} - H_{mi}| \tag{6}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_{ci} - H_{mi})^2} \tag{7}$$

$$r = \frac{\sum_{i=1}^{n}(H_{ci} - H_{ca}) \cdot (H_{mi} - H_{ma})}{\sqrt{\left[\sum_{i=1}^{n}(H_{ci} - H_{ca})^2\right] \cdot \left[\sum_{i=1}^{n}(H_{mi} - H_{ma})^2\right]}} \tag{8}$$

where H_{ci} and H_{mi} are the ith calculated value and measured value, respectively; H_{ca} and H_{ma} are the average of the calculated and measured values, respectively.

4. Results and discussion

The performance of the above four models, Eqs. (1)–(4), are evaluated at nine meteorological stations over China, namely Minqin, Shantou, Leting, Harbin, Ganzhou, Lasa, Kashi, Tulufan and Mengzi, which represent geographical and climatic conditions of their regions suggested by Lam et al. [31].

According to MAPE, MABE, RMSE and r as shown in Table 1, the proposed model, Eq. (4), has the best accuracy based on the measured data at nine stations, with the MAPE, MABE, RMSE and r in

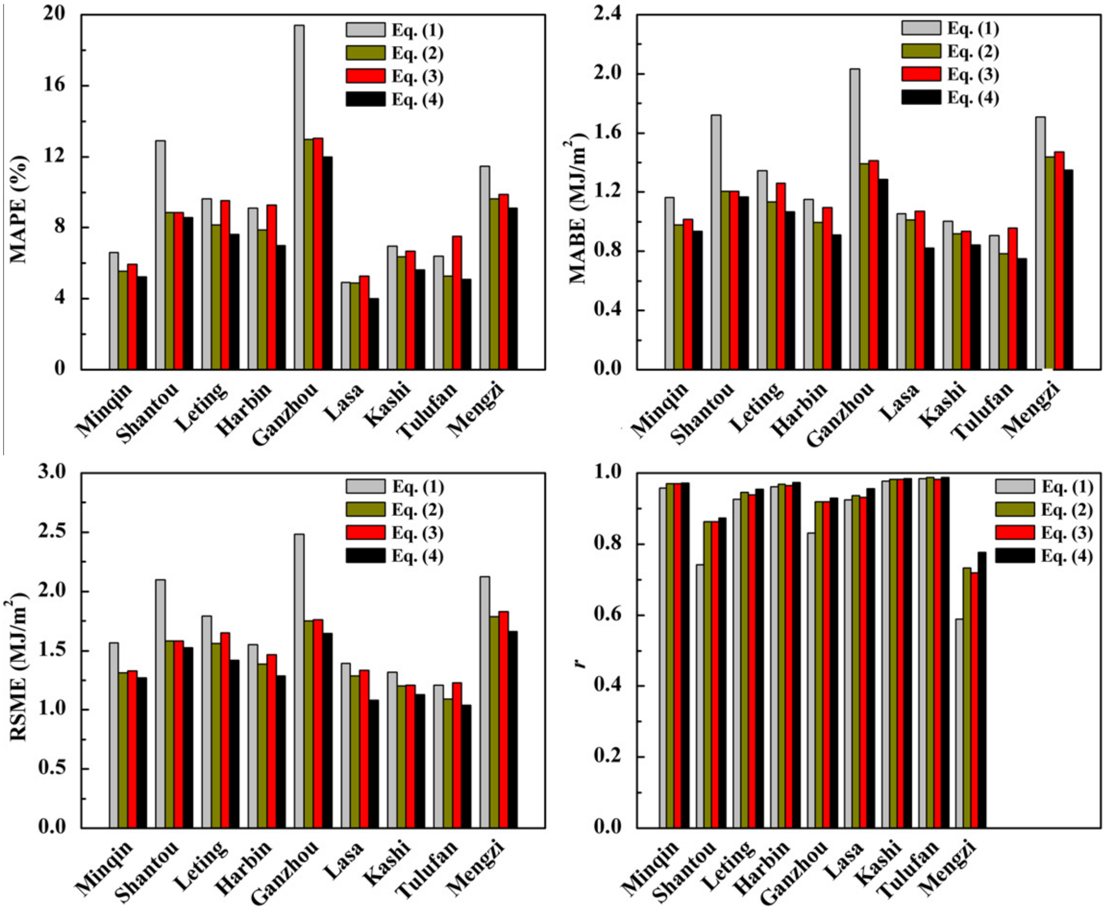

Fig. 2. Comparison between the MAPE, MABE, RSME and *r* of Eqs. (1)–(4) at nine stations in China.

the range of 4.004–11.999%, 0.752–1.348 MJ/m^2, 1.039–1.660 MJ/m^2 and 0.776–0.988, respectively. This indicates that we can obtain reasonably accurate data of daily global solar radiation from the proposed model. Eqs. (2) and (3) yield sound estimations, and the estimation differences among them are very slight, but their performance is second to Eq. (4); Eq. (1) yields relatively large errors with maximum MAPE value of 19.393% at Ganzhou and minimum *r* value below 0.6 at Mengzi. To be obvious, the MAPE, MABE, RMSE and *r* of the four models for the nine typical stations are shown in Fig. 2.

In terms of *r*, the stations with the best and worst value, i.e., Tulufan and Mengzi station are selected for further comparative investigation. Fig. 3 shows apparently that the performance of Eqs. (1)–(4) following the variation of the daily global solar radiation throughout the year at Tulufan station (Fig. 3a) is better than that at Mengzi station (Fig. 3b), mainly due to different weather conditions in these two regions, which can be seen apparently from the solar radiation variation in Fig. 3. The interest we focus is that the performance degradation of the four models according to the weather conditions is much different, and the minimum degradation of *r*, 0.2 (Table 1), is obtained by Eq. (4). This illustrates that Eq. (4) has better adaptability to the complicated weather conditions than the other models.

Overall evaluation, the relative performance of the four models at nine stations is that the Eq. (4) is best, followed by Eqs. (2) and (3), and Eq. (1) shows poor performance. So, for China, the daily global solar radiation can be estimated by the proposed model with better accuracy.

Based on the data at the other 70 stations, the regression coefficients of Eq. (4) and corresponding errors have been generated for each station, as shown in Table 2. The results showed that the regression coefficients of Eq. (4) are site dependent. For most of the stations, the best performance, based on MAPE, MABE, RMSE and *r* is achieved by Eq. (4). The errors resulting from Eq. (4) for the 70 stations are such that the MAPE at about 77% of the stations does not go beyond 10% and has an average value of 7.960%, the MABE lies between 0.737 and 1.417 MJ/m^2, the RMSE stays well below 1.832 MJ/m^2 and the mean value of *r* at all stations is up to 0.937. This result is considered acceptable.

5. Conclusions

Empirical modeling is an essential and economical tool for estimating solar radiation. A trigonometric model in conjunction with a sine and cosine wave for estimating daily global solar radiation is proposed in this study.

The model is compared with three existing models at nine representative stations of China by using statistical indicators such as the mean absolute percentage error (MAPE), mean absolute bias error (MABE), root mean square error (RMSE) and correlation coefficients (*r*). It is found that the new model can be used for estimating daily values of global solar radiation with a higher accuracy and has good adaptability to highly variable weather conditions. Then the regression coefficients and errors of the proposed model are generated at the other 70 meteorological stations of China, and the statistical indicators are at acceptable levels.

The model is very simple, fast, effective and reliable, and estimations can be derived even by a pocket calculator without tedious inputting work for meteorological measurements. There-

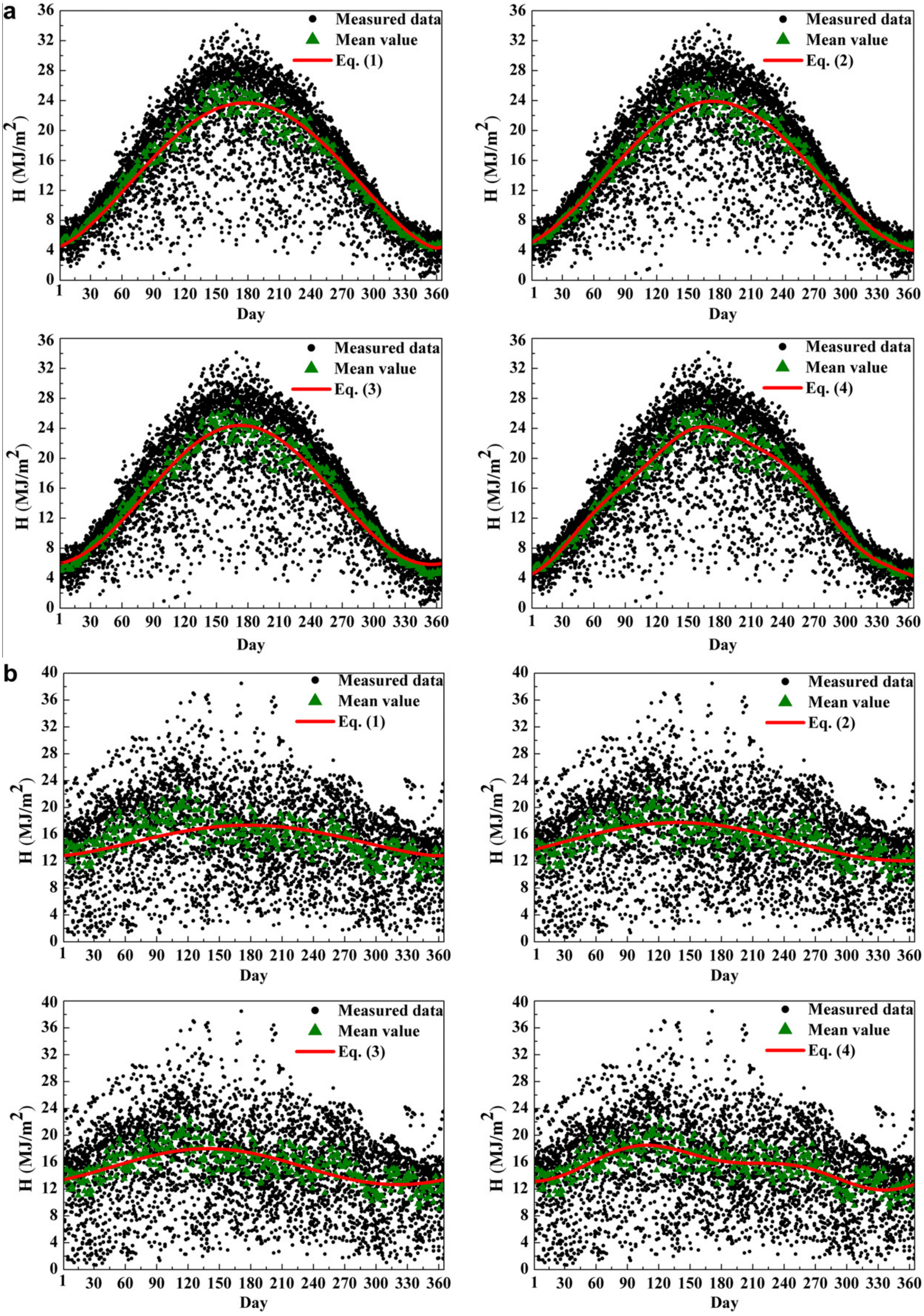

Fig. 3. Comparison between daily measured global solar radiation data and estimated values from Eqs. (1)–(4) at (a) Tulufan and (b) Mengzi station.

Table 2
Regression coefficients of Eq. (4) and errors for the other 70 stations.

#	Location	a_0	a_1	a_2	a_3	a_4	a_5	a_6	MAPE	MABE	RMSE	r
1	Beijing	13.363	−5.885	0.962	2.045	−1.035	2.177	−0.874	7.909	1.068	1.422	0.949
2	Fuzhou	12.596	−4.928	1.059	1.128	0.700	2.409	3.511	12.209	1.375	1.761	0.896
3	Dunhuang	16.318	−0.589	2.528	−0.583	8.827	0.873	9.967	4.970	0.853	1.131	0.982
4	Jiuquan	16.439	−0.586	2.297	−0.042	8.136	0.952	−2.807	5.052	0.865	1.182	0.979
5	Lanzhou	13.495	−0.348	12.383	−2.566	−7.158	0.938	0.422	8.665	1.236	1.677	0.946
6	Guangzhou	11.526	−3.175	1.018	0.737	−0.646	4.758	−0.893	10.330	1.095	1.357	0.860
7	Beihai	14.362	1.269	2.150	9.313	−4.461	1.030	−0.516	10.513	1.395	1.727	0.889
8	Guilin	11.719	−0.874	4.835	0.755	5.520	1.008	2.569	13.165	1.315	1.656	0.922
9	Nanning	11.863	−0.784	2.780	−1.589	−5.193	−0.895	0.110	11.098	1.200	1.495	0.924
10	Haikou	13.500	−0.607	6.006	−1.253	−5.465	0.921	0.204	10.224	1.277	1.612	0.917
11	Sanya	16.607	−3.086	−1.035	7.722	0.820	2.250	1.651	6.741	1.087	1.415	0.859
12	Xisha	17.391	−5.315	0.813	2.588	−0.911	2.011	−0.195	7.133	1.259	1.599	0.909
13	Gushi	11.860	−0.604	6.830	5.535	5.785	0.888	−2.637	10.076	1.179	1.480	0.933
14	Nanyang	11.427	−5.820	0.883	−4.174	0.396	−13.448	20.051	9.321	1.101	1.441	0.935
15	Zhengzhou	12.865	5.718	0.973	−1.182	−0.637	2.134	−1.083	8.785	1.079	1.395	0.946
16	Fuyu	12.844	−8.946	−0.869	0.955	0.596	3.746	−3.723	6.261	0.911	1.306	0.975
17	Heihe	11.883	0.643	3.930	−3.289	8.540	0.905	3.677	6.747	0.864	1.235	0.978
18	Jiamusi	11.342	−0.613	−3.854	2.920	7.899	0.878	3.708	6.924	0.888	1.257	0.972
19	Mohe	11.247	−9.066	0.910	2.106	−0.623	4.104	4.191	9.115	1.063	1.510	0.971
20	Changsha	10.963	0.715	−4.550	−1.109	5.555	1.045	9.033	13.629	1.270	1.622	0.928
21	Changning	11.033	−0.875	4.784	0.617	5.599	−1.078	3.738	14.821	1.329	1.696	0.924
22	Jishou	10.280	5.190	1.067	−2.036	1.035	−2.422	3.462	13.952	1.217	1.565	0.928
23	Changchun	11.714	8.179	0.799	−7.021	0.826	3.678	−3.666	7.847	1.086	1.476	0.958
24	Yanji	10.861	7.892	0.757	5.639	0.572	3.871	1.562	7.682	0.984	1.318	0.959
25	Lusi	10.926	−0.980	4.700	−6.236	−6.979	0.688	7.311	10.553	1.371	1.747	0.900
26	Nanjing	10.669	−6.172	0.766	8.674	−0.632	6.937	−2.320	9.994	1.194	1.550	0.916
27	Chaoyang	13.687	−0.932	2.265	6.930	6.727	0.938	−2.697	7.134	0.992	1.342	0.963
28	Dalian	13.808	1.206	−2.301	5.943	6.326	0.964	−2.719	8.830	1.198	1.607	0.946
29	Shenyang	12.961	0.940	2.255	9.979	6.509	0.921	9.914	8.999	1.172	1.530	0.949
30	Dongsheng	15.655	0.706	2.112	−2.603	−7.337	0.960	0.411	5.699	0.921	1.264	0.971
31	Ejinaqi	17.371	0.607	2.241	3.466	−9.194	0.949	0.340	4.000	0.737	1.025	0.988
32	Erlianhaote	16.835	8.652	0.978	−1.258	0.852	2.118	−3.565	4.282	0.765	1.070	0.985
33	Hailaer	12.433	−8.725	−0.904	−5.251	0.549	3.991	1.690	6.439	0.849	1.220	0.979
34	Hailiutu	16.474	−0.721	2.122	6.865	8.343	0.965	3.465	5.558	0.937	1.216	0.979
35	Suolun	14.358	1.158	2.090	−1.441	−7.467	0.975	0.299	5.556	0.860	1.276	0.973
36	Tongliao	13.791	−0.792	2.173	0.878	7.127	0.938	3.602	5.880	0.856	1.195	0.973
37	Xilinhaote	14.887	0.589	2.277	−2.340	7.882	0.936	−2.759	5.200	0.825	1.193	0.977
38	Guyuan	15.585	5.993	1.003	−1.236	0.425	6.983	1.937	7.079	1.098	1.447	0.947
39	Yinchuan	15.112	−0.623	1.848	0.565	−7.820	−0.903	5.733	5.975	0.966	1.309	0.970
40	Gangcha	17.716	1.465	1.779	−0.896	6.074	1.020	−2.905	5.624	1.038	1.449	0.943
41	Geermu	18.553	7.834	0.958	−1.264	0.928	2.076	2.725	4.351	0.846	1.132	0.980
42	Guoluo	15.783	0.999	3.082	2.754	6.163	−0.747	2.126	6.286	1.087	1.397	0.929
43	Xining	14.147	6.856	0.811	−0.787	−0.947	1.322	0.275	6.363	1.012	1.396	0.954
44	Yushu	14.503	−0.720	2.958	−0.153	−7.465	0.721	1.028	5.614	0.957	1.230	0.956
45	Fushan	14.077	6.240	0.956	−1.107	1.228	2.202	2.136	8.060	1.115	1.449	0.953
46	Jinan	13.091	1.166	2.204	−9.065	−5.781	0.992	0.340	8.322	1.052	1.338	0.955
47	Juxian	13.713	−5.633	0.983	1.951	−1.108	2.191	−0.983	8.452	1.120	1.422	0.946
48	Datong	14.471	0.933	2.018	4.374	−7.348	0.985	0.310	5.873	0.879	1.232	0.973
49	Houma	12.504	−0.419	−18.143	−19.406	6.490	0.955	3.563	8.014	1.003	1.320	0.959
50	Taiyuan	13.043	6.262	−0.980	−8.225	0.681	1.966	−3.240	7.069	0.923	1.263	0.961
51	Ankang	11.576	0.928	2.160	−0.491	6.237	1.007	3.228	11.604	1.236	1.568	0.944
52	Yanan	12.828	−6.816	0.832	2.327	−1.020	1.587	−0.816	7.804	1.089	1.440	0.953
53	Chengdu	8.273	−0.691	3.357	−1.969	5.398	0.910	9.877	15.427	1.177	1.498	0.922
54	Emeishan	13.409	−2.431	1.003	2.416	−0.749	2.253	−0.194	10.132	1.315	1.663	0.751
55	Ganzi	18.298	−5.323	1.060	1.641	1.406	1.694	−2.085	6.250	1.148	1.517	0.915
56	Hongyuan	15.561	4.532	0.783	−0.615	1.060	2.973	1.530	7.600	1.274	1.662	0.857
57	Mianyang	9.227	5.708	−0.910	4.263	−0.796	3.299	−3.119	12.141	1.077	1.353	0.942
58	Panzhihua	15.416	1.302	1.866	5.286	3.992	0.986	−2.446	6.532	1.004	1.346	0.902
59	Tianjin	13.111	−0.834	2.220	0.641	−6.062	0.963	6.708	8.788	1.128	1.505	0.946
60	Changdu	16.248	−0.420	6.825	−7.125	−4.753	0.881	6.818	5.509	0.930	1.209	0.933
61	Naqu	17.598	0.878	1.851	4.207	5.521	0.760	4.089	4.888	0.941	1.244	0.930
62	Akesu	14.606	8.605	0.952	−1.336	−0.443	2.909	1.408	5.288	0.791	1.077	0.984
63	Hami	16.390	−0.592	−2.341	3.102	−9.615	0.938	12.972	4.485	0.772	1.073	0.987
64	Hetian	14.254	−7.968	0.814	2.263	−0.758	2.208	4.346	5.715	0.866	1.136	0.974
65	Tacheng	14.691	−0.669	3.476	8.532	10.313	0.945	3.477	6.347	0.891	1.209	0.986
66	Yanqi	14.292	−0.565	2.353	6.144	−9.477	0.889	0.480	5.303	0.798	1.079	0.986
67	Jinghong	15.106	−1.203	2.297	6.715	2.022	0.784	−1.852	7.350	1.104	1.399	0.778
68	Kunming	14.436	2.927	0.976	−0.183	1.439	2.308	−3.984	9.191	1.227	1.588	0.835
69	Lijiang	16.813	−2.878	0.979	2.546	−1.015	1.787	0.232	6.358	1.068	1.412	0.826
70	Hongjia	12.783	−0.991	4.325	2.025	5.174	0.952	3.088	12.104	1.417	1.832	0.893

fore, the proposed model is recommended for estimating the daily global solar radiation in areas where the radiation data is missing or not available and predicting yearly variations of daily global solar radiation for a specific location, which helps in evaluating the long-term performances of solar energy systems.

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