Chapter 72
New Models for Separating Hourly Diffuse and Direct Components of Global Solar Radiation

Wanxiang Yao, Zhengrong Li, Yuan Lu, Fujian Jiang and Cui Li

Abstract Due to the lack of domestic hourly solar radiation measured data, models which are used to separate hourly diffuse and direct components of global solar radiation on horizontal surface are always referencing foreign models. However, because of different geographical factors (such as latitude and longitude) and meteorological conditions (such as atmospheric transparency, temperature, and humidity), it is difficult to have broad application. This study uses hourly solar radiation measured data from Shanghai to evaluate and compare models in the published literature which were used to separate hourly diffuse and direct components of global solar radiation on horizontal surface, and several relatively accurate available models are chosen. Then, new improved models are consequently proposed and compared with these existing models for calculating hourly diffuse solar radiation based on statistical parametric analysis, residual histogram analysis, and fitted curve analysis. It is found that these new improved models are in better agreement with the measured data, and they are more suitable for calculating diffuse and direct solar radiation under complicated weather conditions.

Keywords Solar radiation · Clearness index · Diffuse fraction · New models

Nomenclature

H_0	Hourly extraterrestrial global solar radiation on a horizontal surface (kJ/m^2)
H	Hourly global solar radiation on a horizontal surface (kJ/m^2)
H_d	Hourly diffuse solar radiation on a horizontal surface (kJ/m^2)
H_b	Hourly beam solar radiation on a horizontal surface (kJ/m^2)
H_{bc}	Hourly beam solar radiation on a horizontal surface under clear-sky conditions (kJ/m^2)

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K_T	Daily clearness index (dimensionless)
K_t	Hourly clearness index (H/H_0)(dimensionless)
K_{t+1}	Hourly clearness index at hour h + 1(dimensionless)
K_{t-1}	Hourly clearness index at hour h-1(dimensionless)
K_d	Hourly diffuse solar radiation fraction (H_d/H)(dimensionless)
K_b	Hourly beam solar radiation fraction (H_b/H)(dimensionless)
ΔK_b	Hourly direct beam atmospheric transmittance changes (dimensionless)
K_{nc}	Hourly direct beam atmospheric transmittance under clear-sky conditions $(H_{bc}/(H_0/\sinh))$(dimensionless)
ϕ	Latitude of site (degrees)
H	Solar altitude (degrees)
K_1	Intermediate variable (dimensionless)
K_2	Intermediate variable (dimensionless)
m	Air mass (dimensionless)
t	Ambient temperature (°)
φ	Relative humidity (%)
S_0	Apparent solar time (h)
ψ	Persistence index (dimensionless)

72.1 Introduction

Knowledge of the solar radiation incident at a specific location is necessary for the design and assessment of solar energy conversion systems [1]. Solar system and building design as well as thermal performance analysis require irradiation values on inclined surfaces. However, for most areas, these data are not available and must be estimated generally through models that use input of daily and hourly global irradiation data on the horizontal surface [2]. Our stations always measure only global radiation and for which an estimated model of diffuse radiation is desired. Even when data on both global and diffuse radiation are available, it is often necessary to compile long, unbroken sequences of data to estimate missing values of diffuse radiation [3].

Most existed works on diffuse irradiation have been based on data from North American, Canadian, Australian, or North European stations as well as from Liu and Jordan [4]. After that, a lot of models have been proposed to establish a relationship between diffuse and total global horizontal irradiation. Orgill and Hollands [5] analyzed the hourly diffuse radiation and recommended an equation to determine hourly ratio of diffuse to total radiation received on horizontal surfaces. Collares-Pereira and Rabl [6] proposed a new correlation for the daily total ratio of diffuse over hemispherical insolation, which agreed with results reported in India, Israel, and Canada which included the shade-ring correction. This model suggested that latitude independence was a good approximation, and it implied that the diffuse component was significantly larger than that predicted by the original formulas of Liu and Jordan. Erbs et al. [7] used a new database (from four US weather stations) composed with hourly direct, normal radiation and global radiation to develop an estimated model of the diffuse fraction of hourly, daily, and monthly average global radiation. Spencer [3] compared four models of estimating hourly diffuse irradiation from global radiation and then suggested a new method for deriving suitable values of the constants for places situated between 20° and 45° Reindl et al. [8] studied the influence of climatic and geometric variables on the hourly diffuse fraction and concluded that the diffuse correlations are season and location dependent. Chandrasekaran and Kumar [1] used five-year data of hourly global and diffuse radiation on a horizontal surface at a tropical location (Madras, India) to establish the relationship between the hourly diffuse fraction and hourly clearness index. Lam and Li model [9] analyzed the data for diffuse, global horizontal radiation measured at the City University of Hong Kong for the period 1991–1994 and proposed a hybrid correlation model for the prediction of hourly direct and diffuse components from the global solar radiation for Hong Kong. Boland et al. [10] developed two models: one model used hourly data from a weather station setup at Deakin University, Geelong. Another model was developed for 15-min data values. These two models show that apparent solar time is a better predictor than solar altitude. Miguel et al. [2] examined the performance of daily and hourly diffuse horizontal solar irradiation models and correlations using an assembled data set of multivariate meteorological time series from countries in the North Mediterranean Belt area. Oliveira et al. [11] developed correlation models to estimate hourly, daily, and monthly values of diffuse solar radiation on horizontal surfaces using global and diffuse solar radiation data measured from May 1994 to June 1999 in São Paulo City, Brazil. Karatasou et al. [12] presented an analysis of hourly diffuse radiation on a horizontal surface. Soares et al. [13] applied a perceptron neural network technique to estimate hourly values of the diffuse solar radiation at the surface in São Paulo City, Brazil, using as input the global solar radiation and other meteorological parameters measured from 1998 to 2001. Boland et al. [14] used the logistic function instead of piecewise linear or simple nonlinear functions to estimate hourly diffuse solar radiation.

We choose some models from the literature. The criteria for selection in this study are as follows: (1) full availability of algorithms and numerical coefficients, (2) use of input data either generally available or obtainable from available model cascades, and (3) the results reported by the original literature as well as those published in reviews were considered [2]. This paper presents a comparison of these 19 models of estimating hourly diffuse from global solar radiation using data from Shanghai. For comparative analysis, models are divided into five groups according to the performance characteristics. After analyzing the existing models, five new improved correlations are proposed and compared with these existing models.

72.2 Data and Methodology

72.2.1 Meteorological Data Collection

The data of hourly diffuse, direct, and global solar radiation on a horizontal surface were measured by Tongji University (31°17′N, 121°31′E) from July 2012 to November 2012.

In order to investigate the relationship between hourly diffuse and global radiation, we have to control the quality of records. The quality control procedures used are based on Miguel et al. (2001) [2] and referred to the physical and climatic extremes found in our measured data. About three percent of the data are discarded which have incomplete or unreasonable records. Application of above criteria does not have any significant effect on our results. The final data set contains 1,155 pairs of data points.

72.2.2 Statistical Analysis Methods

In the literature, there are several statistical test methods used to statistically evaluate the performance of the solar radiation models. Among those, the coefficient of correlation (R), the relative standard error (RSE), the mean bias error (MBE), the root mean square error (RMSE), Nash–Sutcliffe Equation (NSE), and the t-statistic (t-stat) are the most commonly used methods to compare the results statistically [2, 11–13, 15].

72.3 Performance Results and Discussion

These models are evaluated by three indexes: statistical parametric, fitted curve, and residual histogram.

72.3.1 Statistical Parametric Analysis

For the five groups of models studied, the following statistical parameters are obtained from the evaluation of the values presented in Table 72.1:

The measured data are compared with the values calculated from the correlations tabulated in Table 72.1 which shows the following results:

Table 72.1 The *R*, MBE, RMSE, NSE, and t-stat values of the models

Models	*R*	MBE	RMSE	NSE	t-stat
Orgill and Hollands model [5]	0.917	0.091	0.164	0.722	22.706
Spencer model [3]	0.913	0.190	0.232	0.440	47.898
Reindl et al. model 1 [8]	0.916	0.094	0.170	0.701	22.427
Louche et al. model [17]	0.911	0.122	0.192	0.620	28.186
Oliveira et al. model [11]	0.861	0.077	0.185	0.645	15.488
Soares et al. model [13]	0.877	0.122	0.198	0.593	26.383
Collares-Pereira and Rabl model [6]	0.792	0.020	0.191	0.623	3.658
Erbs et al. model [7]	0.916	0.088	0.169	0.704	20.730
Hawlader model [18]	0.906	0.122	0.180	0.665	31.330
Chandrasekaran and Kumar model [1]	0.912	0.081	0.161	0.731	19.658
CLIMED hourly model [2]	0.915	0.088	0.165	0.718	21.277
Karatasou et al. model [12]	0.896	0.117	0.183	0.654	28.353
Boland et al. model 1 [10]	0.920	0.097	0.168	0.707	24.132
Boland et al. model 2 [14]	0.921	0.103	0.176	0.679	24.527
Skartveit and Olseth Model [19]	0.558	0.090	0.292	0.116	10.976
DISC model [20]	0.642	0.087	0.432	0.939	6.980
Reindl et al. model 2 [8]	0.894	0.063	0.161	0.730	14.478
Reindl et al. model 3 [8]	0.881	0.076	0.174	0.687	16.595
Boland-Ridley-Lauret (BRL) model [21]	0.926	0.099	0.172	0.693	24.048

(a) Among Group I (piecewise linear models), coefficient of correlation (R) of these models are greater than or equal to 0.913. Reindl et al. model 1 gives the best results of t-stat value, while Orgill and Hollands model gives the best results of R, MBE, RMSE, and NSE. So in this group, Orgill and Hollands model is the most accurate model, and the optimal statistical parameters of this model are as follows: $R = 0.917$, MBE $= -0.091$, RMSE $= 0.164$, and t-stat $= 22.427$.

(b) Among Group II (polynomial models), coefficient of correlation (R) of these models are greater than or equal to 0.861. Louche et al. model gives the best results of R, while Oliveira et al. model gives the best results of MBE, RMSE, NSE, and t-stat. So in this group, Oliveira et al. model is the most accurate model, and the optimal statistical parameters of this model are as follows: $R = 0.911$, RSE $= -0.077$, MBE $= 0.185$, RMSE $= 0.645$, and t-stat $= 15.488$.

(c) Among Group III (piecewise polynomial models), coefficient of correlation (R) of most models are greater than or equal to 0.896 except Karatasou et al. model equal to 0.792. Collares-Pereira and Rabl model gives the best results of RSE and t-stat, while Erbs et al. model gives the best results of R and MBE. So in this group, Erbs et al. model is the most accurate model, and the optimal statistical parameters of this model are as follows: $R = 0.916$, RSE $= -0.020$, MBE $= 0.169$, RMSE $= 0.731$, and t-stat $= 3.658$.

(d) Among Group IV (nonlinear models), coefficient of correlation (R) of models are greater than or equal to 0.920. Boland et al. model 2 gives the best results of R, while Boland et al. model 1 gives the best results of RSE, MSE, RMSE, and t-stat. So in this group, Boland et al. model 1 are the most accurate models, and the optimal statistical parameters of these models are as follows: $R = 0.921$, RSE $= -0.097$, MBE $= 0.168$, RMSE $= 0.707$, and t-stat $= 24.132$.

(e) Among Group V (multi-parameters models), coefficient of correlation (R) of most models are greater than or equal to 0.881 except Skartveit and Olseth Model and DISC model. Reindl et al. model 2 gives the best results of MBE and RMSE. However, Boland-Ridley-Lauret (BRL) model gives the best results of R. So in this group, BRL model is the most accurate model, and the optimal statistical parameters of these models are as follows: $R = 0.926$, RSE $= -0.090$, MBE $= 0.161$, RMSE $= 0.730$, and t-stat $= 6.980$.

From the above analysis, it can be concluded that Orgill and Hollands model, Oliveira et al. model, Erbs et al. model, Boland et al. model 1, and BRL model are more accurate than other models in each group, and BRL model is the most accurate one.

72.3.2 Residual Histogram Analysis

Graphical residual analysis of typical models (residuals are estimations of experimental error obtained by subtracting the observed hourly diffuse solar fraction from the estimated one) for the horizontal surface is shown in Fig. 72.1.

The residual distribution of hourly diffuse solar fraction shows four tendencies, wide and left-skewed, wide and centered, concentrated and left-skewed, and concentrated and centered. Most of them are concentrated and left-skewed, only Collares-Pereira and Rabl model is concentrated and centered.

The above histograms show that the values of residuals of Orgill and Hollands model, Reindl et al. model 1, Spencer model, Oliveira et al. model, Chandrasekaran and Kumar model, CLIMED hourly model, Collares-Pereira and Rabl model, Erbs et al. model, Boland et al. model 1, BRL model, Reindl et al. model 2, and Reindl et al. model 3 exhibit generally small difference and are very close to zero. The average errors of these models are from −0.099 to 0.020. This suggests that these models' estimation of irradiation agree well with measured data [16]. On the contrary, the values of residuals for DISC model and Skartveit and Olseth Model exhibit generally large differences and are far away from zero, and these models are therefore not recommended.

72.3.3 Fitted Curve Analysis

The correlation between diffuse fraction and clearness index is displayed via $K_t - K_d$ scatter diagrams. The scatter diagrams of hourly values of $K_t - K_d$ are based

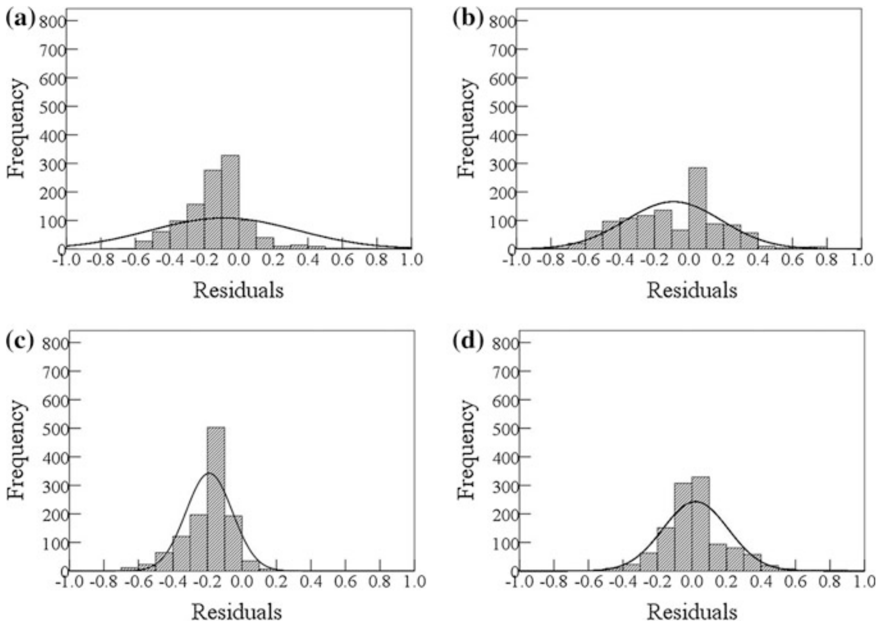

Fig. 72.1 Frequency of the residuals of the hourly diffuse solar fraction on a horizontal surface, calculated by models using the experimental data (**a**) wide and left-skewed (DISC model), (**b**) wide and centered (Skartveit and Olseth Model), (**c**) concentrated and left-skewed (Soares et al. model), and (**d**) concentrated and centered (Collares-Pereira and Rabl model)

on 1,155 pairs of points. The K_t–K_d diagrams displayed in Fig. 72.2 show 4 group correlations between diffuse fraction and clearness index in Shanghai.

It can be seen from Fig. 72.2 that the main differences among these models are the following two aspects. One is whether hourly diffuse solar fraction is close to 1 when clearness index is close to 0. Another one is what value hourly diffuse solar fraction is equal to when clearness index is greater than 0.75. The hourly diffuse solar fraction of most models is close to 1 when clearness index is close to 0 except for Spencer model ($K_d = 0.85$ when $K_t = 0$), Soares et al. model ($K_d = 0.9$ when $K_t = 0$), and Hawlader model ($K_d = 0.915$ when $K_t = 0$), and this is supported by the observed data shown in black square scatters in Fig. 72.2. However, hourly diffuse solar fraction is diverged when clearness index is greater than 0.75. It could hardly draw a conclusion from Fig. 72.2 that hourly diffuse solar fraction value is more accurate, because of deficient observed data in this interval.

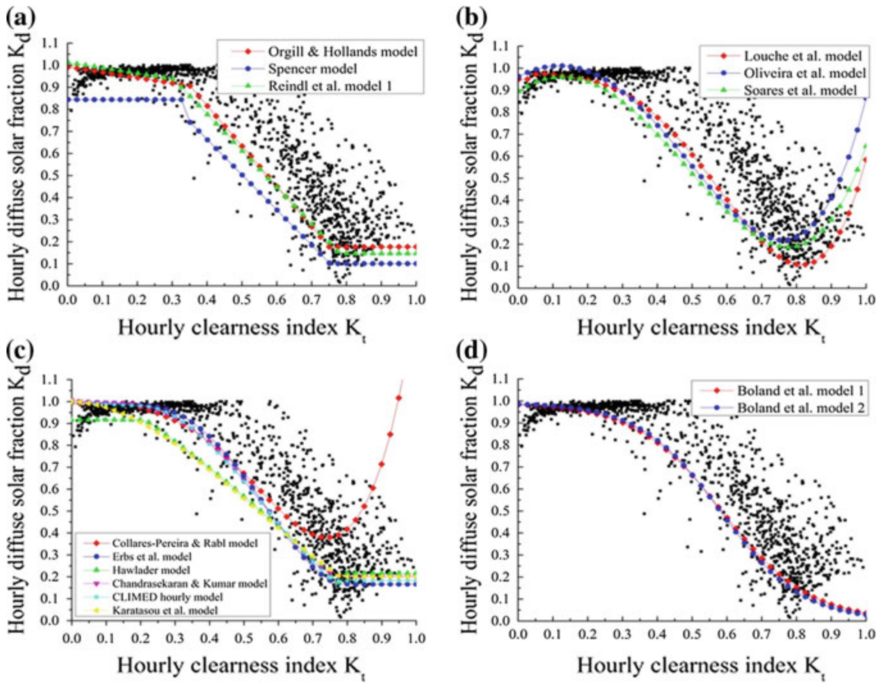

Fig. 72.2 Correlation of hourly diffuse solar fraction with clearness index. (**a**) Group I (piecewise linear models), (**b**) Group II (polynomial models), (**c**) Group III (piecewise polynomial models), and (**d**) Group IV (nonlinear models)

72.4 Improved Hourly Diffuse Solar Fraction Model

Five new improved correlations are proposed based on hourly diffuse, direct, and global solar radiation data from June 2012 to November 2012.

(1) Hourly measured data fitting model 1(HMDF model 1)

$$K_d = 0.9381 + 0.1481\, K_t, 0 \le K_t \le 0.3 \tag{72.1}$$

$$K_d = 1.5197 - 1.534 K_t, 0.3 < K_t \le 0.8 \tag{72.2}$$

$$K_d = 0.27, K_t > 0.8 \tag{72.3}$$

(2) Hourly measured data fitting model 2(HMDF model 2)

$$K_d = 0.8142 + 2.0792 K_t - 6.1439 K_t^2 + 3.4707 K_t^3 \tag{72.4}$$

(3) Hourly measured data fitting model 3(HMDF model 3)

$$K_d = 0.8775 + 1.3991\,K_t - 4.9285\,K_t^2, K_t \leq 0.2 \tag{72.5}$$

$$K_d = 1.1209 - 2.1699K_t + 11.06K_t^2 - 22.355K_t^3 + 12.863K_t^4, K_t > 0.2 \tag{72.6}$$

(4) Hourly measured data fitting model 4(HMDF model 4)

$$K_d = 0.2421 + \frac{0.7202}{1 + e^{(K_t - 0.6203)/0.0749}} \tag{72.7}$$

(5) Hourly measured data fitting model 5(HMDF model 5)

$$K_d = 1/\left[\begin{array}{r} 1 + \exp(-2.1839 - 20.745K_t + 58.29927K_t^2 - 36.6937K_t^3 - 0.97868S_0 \\ + 1.52939S_0^2 - 0.00701h + 1.14911K_T + 0.006486\psi) \end{array}\right] \tag{72.8}$$

72.5 Comparison and Verification of Models

Five more accurate models in the literature and 5 measured data fitting models are compared using solar radiation data measured in 2012 December, and the results are shown in Table 72.2.

According to Table 3, it can be seen that the hourly measured data fitting model (HMDF model 1 $\sim$ 5) is more consistent with the measured values than models in the literature of each group, and model 5 is the most accurate ($R = 0.935$). So, they are more suitable for calculating diffuse and direct solar radiation under complicated weather conditions in Shanghai.

Table 72.2 The R, MBE, RMSE, NSE, and t-stat values of the models

Models	R	MBE	RMSE	NSE	t-stat
Orgill and Hollands model	0.906	−0.064	0.135	0.743	9.995
HMDF model 1	0.924	−0.011	0.103	0.850	1.984
Oliveira et al. model	0.884	−0.141	0.204	0.410	17.851
HMDF model 2	0.924	−0.013	0.102	0.854	2.349
Erbs et al. model	0.916	−0.119	0.182	0.533	16.200
HMDF model 3	0.928	−0.006	0.099	0.861	1.072
Boland et al. model 1	0.919	−0.114	0.168	0.603	17.233
HMDF model 4	0.925	−0.004	0.101	0.854	0.663
Boland-Ridley-Lauret (BRL) model	0.926	−0.125	0.180	0.542	18.130
HMDF model 5	0.935	0.026	0.098	0.863	5.055

72.6 Conclusions

Measurements of global and diffuse solar radiations at the Earth's surface in Shanghai (31°24′N, 121°29′E) between July 2012 and December 2012 are used to develop models to estimate the diffuse solar radiation from values of global solar radiation. Comparison of these models based on the correlation between the hourly diffuse solar fraction and clearness index can come to the following conclusions:

(1) From statistical parametric analysis, the most accurate models in the previous literature are as follows: Orgill and Hollands model, Oliveira et al. model, Erbs et al. model, Boland et al. model 1, and BRL model are the most accurate models.
(2) Residual histogram analysis found that the residuals of Orgill and Hollands model, Reindl et al. model 1, Spencer model, Oliveira et al. model, Chandrasekaran and Kumar model, CLIMED hourly model, Collares-Pereira and Rabl model, Erbs et al. model, Boland et al. model 1, BRL model, Reindl et al. model 2, and Reindl et al. model 3 are very close to zero, and these models' estimation of hourly diffuse radiation on a horizontal surface are fitted well with measured data. On the contrary, the residuals of DISC model and Skartveit and Olseth Model are far away from zero, and these models are therefore not recommended.
(3) From fitted curve analysis, the hourly diffuse solar fraction of most models is close to 1 when clearness index is close to 0 except for Spencer model, Soares et al. model, and Hawlader model, and this is supported by the observed data shown in black square scatters in Fig. 72.2. However, hourly diffuse solar fraction is diverged when clearness index is greater than 0.75.
(4) Measured data fitting model (HMDF model 1 $\sim$ 5) is more consistent with the measured values than models in the literature of each group, and model 5 is the most accurate. So, they are more suitable for calculating diffuse and direct solar radiation under complicated weather conditions in Shanghai.

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