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Retracted: Estimation of monthly mean solar radiation from air temperature in combination with other routinely observed meteorological data in Yangtze River Basin in China

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ABSTRACT: Solar radiation is the principal and fundamental energy for many physical, chemical and biological processes. However, it is measured at a limited number of meteorological stations in the world. Estimation of solar radiation from the measured meteorological variables offers an important alternative in the absence of measured solar radiation. In this paper, 12 developed models are studied comparatively, using long-term data from 14 sites in Yangtze River Basin in China, the performances are evaluated using the root mean square error (RMSE) and relative root mean square error (RRMSE). All the models fit the data adequately and can be used to estimate solar radiation. The newly developed model which used monthly mean daily maximum and minimum temperature, relative humidity, atmospheric pressure and the multiplication mean maximum temperature by minimum temperature gives the best performance, with the lowest RMSE (averaged 1.228 MJ m^{-2}) and RRMSE (averaged 11.37%). Therefore, its use is suggested to estimate solar radiation in Yangtze River Basin, and it is more applicable in an area with larger temperature range. Copyright © 2012 Royal Meteorological Society

KEY WORDS solar radiation; meteorological variables; model; Yangtze River Basin

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1. Introduction

Solar radiation at the Earth's surface is the principal and fundamental energy for many physical, chemical and biological processes, such as crop growth and plant photosynthesis, and it is also an essential and important variable to many simulation models studies, such as agriculture, environment, hydrology, meteorology and ecology. Hence, an accurate record of solar radiation is of vital importance. However, it is not widely available due to the cost and difficulty of maintenance and calibration of the measurement equipment (Hunt *et al.*, 1998), only a few meteorological stations measure solar radiation. For example, in the USA, less than 1% of meteorological stations are recording solar radiation (NCDC, 1995; Thorton and Running, 1999). In China, more than 2000 stations have records of meteorological data, only 122 stations are recording solar radiation. Therefore, developing methods to estimate solar radiation for a site where no solar radiation is readily available has been the focus of many studies.

Major methods including satellite-derived (Frulla *et al.*, 1988; Pinker *et al.*, 1995; Olseth and Skartveit, 2001; Şenkal, 2010), stochastic algorithm (Richardson, 1981; Hansen, 1999; Wilks and Wilby, 1999), empirical relationships (Ångström, 1924; Prescott, 1940; Hargreaves, 1981; Bristow and Campbell, 1984; Hargreaves *et al.*, 1985), interpolation (Hay and Suckling, 1979; Rivington *et al.*, 2006) and the learning machine method (Tymvios *et al.*, 2005; Cao *et al.*, 2006; Lam *et al.*, 2008; Jiang, 2009; Chen *et al.*, 2011) have been developed for the purpose. The common practice is to use the empirical relationship method to estimate solar radiation from the measured meteorological variables (Ångström, 1924; Prescott, 1940; Hargreaves, 1981; Bristow and Campbell, 1984; Hargreaves *et al.*, 1985), these data include sunshine duration, maximum and minimum air temperatures, relative humidity and precipitation. Although the sunshine-based method is generally more accurate (Podestá *et al.*, 2004; Trnka *et al.*, 2005), it is often limited since sunshine duration data are absent or incomplete or inaccessible to many researchers (Liu *et al.*, 2009). On the contrary, air temperatures are routinely measured at most meteorological stations. In this context, Hargreaves (1981) proposed an equation using the difference between maximum and minimum air temperatures. Others modified and tested this model in distinct places around the world (Hunt *et al.*, 1998; Annandale *et al.*, 2002; Chen *et al.*, 2004). However, the parameters and accuracy of these empirical formulae need to be calibrated and tested locally. To the authors' knowledge, no literature has studied on the solar radiation estimation in Yangtze River Basin up to now.

The Yangtze River Basin is characterized by abundant water resources, and thus plays a significant role in water supply for agriculture, because the economy of much of the Yangtze River Basin is focused largely on agricultural production. It is one of the major grain production areas of China and hence the eco-environmental models and crop growth simulation are widely studied. However, only a few meteorological stations provide solar radiation recorders. On the contrary, air temperature,

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relative humidity, atmospheric pressure and precipitation are routinely measured at most meteorological stations. Therefore, estimating solar radiation using these meteorological variables is of vital importance and significance. The main objectives of this study are (1) to estimate solar radiation using the common measured meteorological variables data, including maximum and minimum air temperatures, relative humidity, atmospheric pressure and precipitation and, (2), to propose the best model for the Yangtze River Basin.

2. Materials and method

2.1. Study area and sites

The current study focuses on the Yangtze River Basin (Figure 1). The Yangtze River is 6300 km long with a Basin area of 180×10^4 km^2 with decreasing altitude from west to east. A large part of the Yangtze River Basin is subject to a subtropical monsoon climate. A total of 14 stations with long-term available records of solar radiation are used in the present study. The mapping of stations roughly range from 26 to 34 °N, from 97 to 121 °E, and from 3 to 2394 m altitude. Table 1 shows the temporal period and the geographical information of the meteorological stations.

2.2. Data collection

The monthly mean daily solar radiation (MJ m^{-2}), air temperature (°C) including mean maximum temperature and minimum temperature, relative humidity (%), atmospheric pressure (kPa) and precipitation (mm) were used in this study. The data were obtained from the National Meteorological Information Center (NMIC), China Meteorological Administration (CMA). The period of records ranges from 6 to 30 years covering the period between 1961 and 2000. Quality control tests were conducted by the suppliers. A year with more than 5 days of missing or faulty data in the same month was discarded (e.g., 1992 for Nanchang and the year of 1984 for Wuhan). For each station, two data sets were created. About 70% of the total records were used to calibrate the parameters of the models in Table 2, and the remainder for evaluating the models.

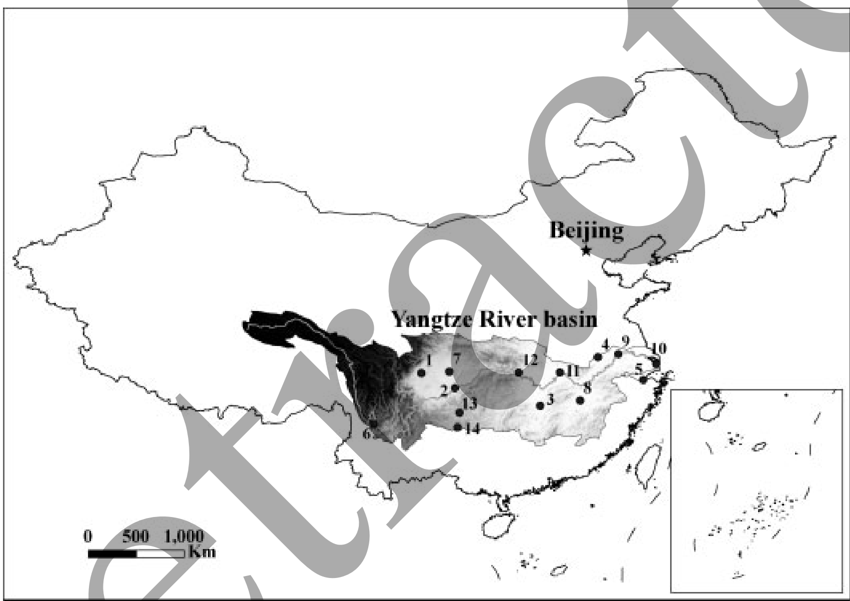

Figure 1. Location of the studied meteorological stations in Yangtze River Basin (stations are numbered in compliance with Table 1).

Table 1. Detailed information of the studied 14 stations in Yangtze River Basin.

Station ID	Station name	Latitude (°N)	Longitude (°E)	Altitude (m)	Calibration period	Validation period
1	Chengdu	30.67	104.02	506	1973–1992	1993–2000
2	Chongqing	29.58	106.47	259	1973–1992	1993–2000
3	Changsha	28.22	112.92	68	1987–1996	1997–2000
4	Hefei	31.87	117.23	28	1978–1992	1993–2000
5	Hangzhou	30.23	120.17	42	1973–1992	1993–2000
6	Lijiang	26.83	100.47	2394	1977–1992	1993–2000
7	Nanchong	30.78	106.10	309	1974–1985	1986–1990
8	Nanchang	28.60	115.92	47	1973–1991	1993–2000
9	Nanjing	32.00	118.80	9	1973–1992	1993–2000
10	Shanghai	31.17	121.43	3	1961–1983	1983–1990
11	Wuhan	30.62	114.13	23	1973–1983, 1985–1992	1993–2000
12	Yichang	30.70	111.30	133	1973–1992	1993–2000
13	Zunyi	27.7	106.88	844	1973–1984	1985–1990
14	Guiyang	26.58	106.72	1074	1973–1992	1993–2000

Table 2. General formulae of monthly mean daily solar radiation estimation using the routinely measured meteorological variables.

Model no.	Equation[a]	Parameter
1[b]	$Rs = Ra(a_1(T_{\max} - T_{\min})^{0.5} + b)$	a_1, b
2[c]	$Rs = Ra(a_1 \ln(T_{\max} - T_{\min}) + b)$	a_1, b
3	$Rs = Ra(a_1(T_{\max} - T_{\min}) + b)$	a_1, b
4	$Rs = Ra(a_1(T_{\max} - T_{\min})^{0.5} + a_2 VP + b)$	a_1, a_2, b
5	$Rs = Ra(a_1(T_{\max} - T_{\min})^{0.5} + a_3 RH + b)$	a_1, a_3, b
6	$Rs = Ra(a_1(T_{\max} - T_{\min})^{0.5} + a_4 P + b)$	a_1, a_4, b
7	$Rs = Ra(a_1(T_{\max} - T_{\min})^{0.5} + a_2 VP + a_3 RH + b)$	a_1, a_2, a_3, b
8	$Rs = Ra(a_1(T_{\max} - T_{\min})^{0.5} + a_2 VP + a_3 RH + a_5 VP \times RH + b)$	a_1, a_2, a_3, a_5, b
9	$Rs = Ra(a_6 T_{\max} + a_7 T_{\min} + b)$	a_6, a_7, b
10	$Rs = Ra(a_6 T_{\max} + a_7 T_{\min} + a_2 VP + a_3 RH + b)$	a_2, a_3, a_6, a_7, b
11	$Rs = Ra(a_6 T_{\max} + a_7 T_{\min} + a_8 T_{\min} \times T_{\max} + b)$	a_6, a_7, a_8, b
12	$Rs = Ra(a_6 T_{\max} + a_7 T_{\min} + a_8 T_{\min} \times T_{\max} + a_2 VP + a_3 RH + b)$	$a_2, a_3, a_6, a_7, a_8, b$

[a] $T_{\max}$, $T_{\min}$, *VP, RH, P* are monthly mean daily maximum temperature, minimum temperature, atmospheric pressure, relative humidity, and precipitation, respectively.
[b] Hargreaves *et al*. (1985). [c] Chen *et al*. (2004).

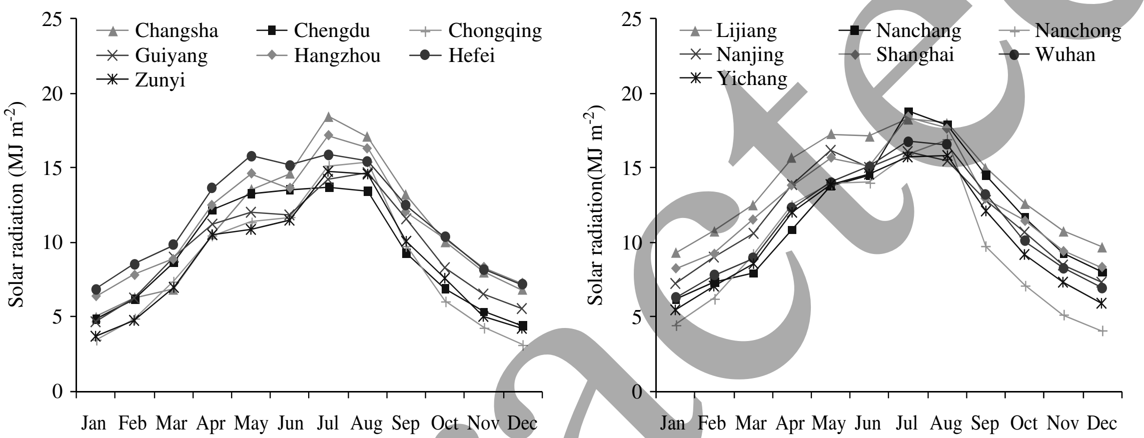

Figure 2. Distribution of the monthly mean daily solar radiation of the studied sites in Yangtze River Basin.

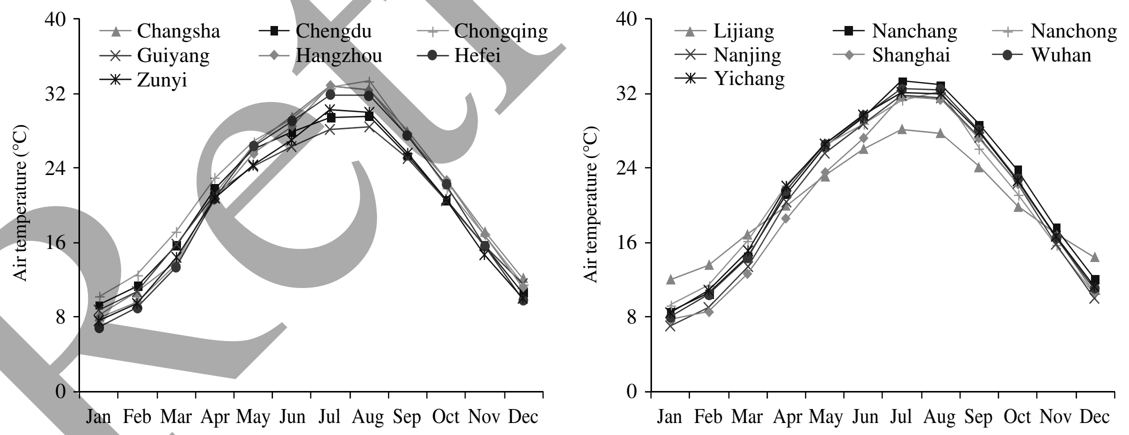

Figure 3. Distribution of the monthly mean daily maximum air temperature of the studied sites in Yangtze River Basin.

2.3. Data description

Figures 2–4 show the distributions of the monthly mean daily solar radiation, maximum and minimum temperature of the studied sites in Yangtze River Basin, respectively. In general, the solar radiation of each site shows a similar change trend with the maximum in summer (June, July and August, averaged 16.26 MJ m^{-2} in July) and minimum in winter (December, January and February, averaged 6.28 MJ m^{-2} in January). The mean maximum and minimum temperatures have a similar tendency with July or August as the warmest month and January as the coldest month. Figures 5–7 show the distributions of monthly mean daily atmospheric pressure, relative humidity, and precipitation, respectively. The atmospheric pressure of each site shows the very similar change trend, with the maximum in December (averaged 99.58 kPa) and minimum in July (averaged 97.51 kPa). The rain mainly occurrs in summer which could account for 36–63% (averaged 45%) of the annual

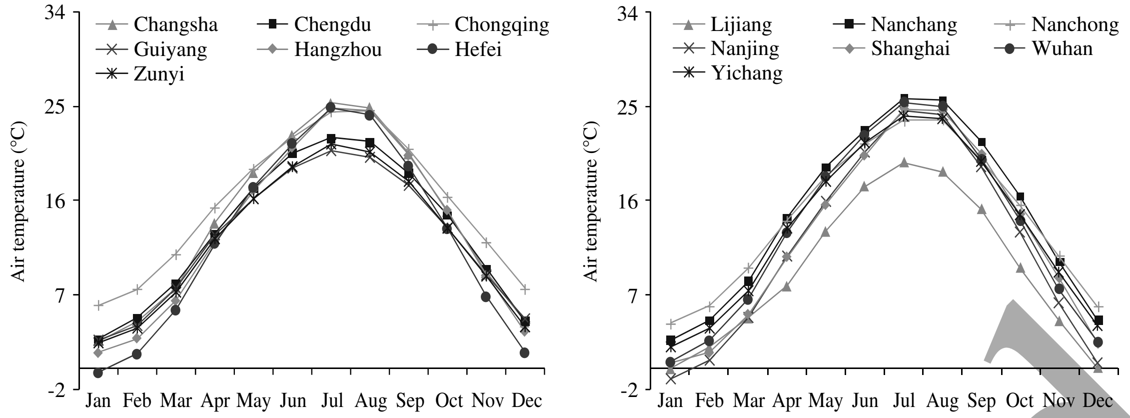

Figure 4. Distribution of the monthly mean daily minimum air temperature of the studied sites in Yangtze River Basin.

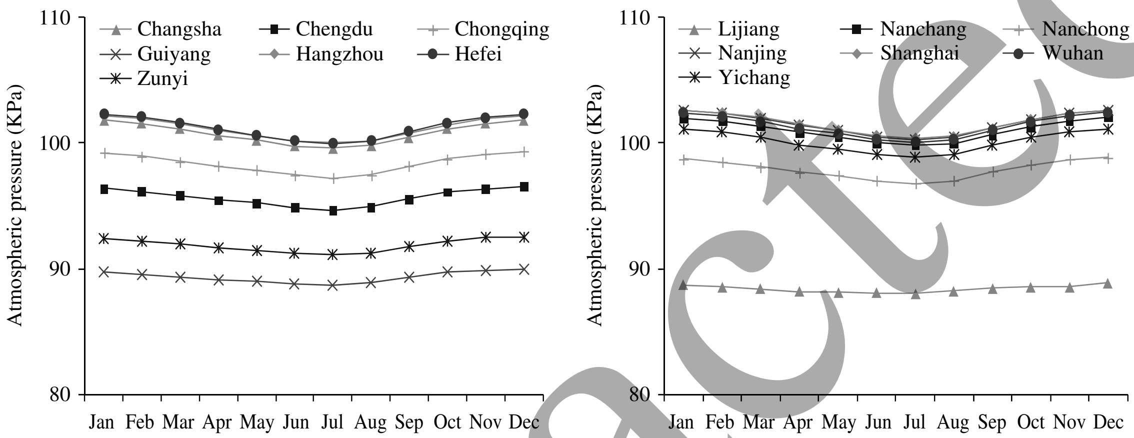

Figure 5. Distribution of the monthly mean daily atmospheric pressure of the studied sites in Yangtze River Basin.

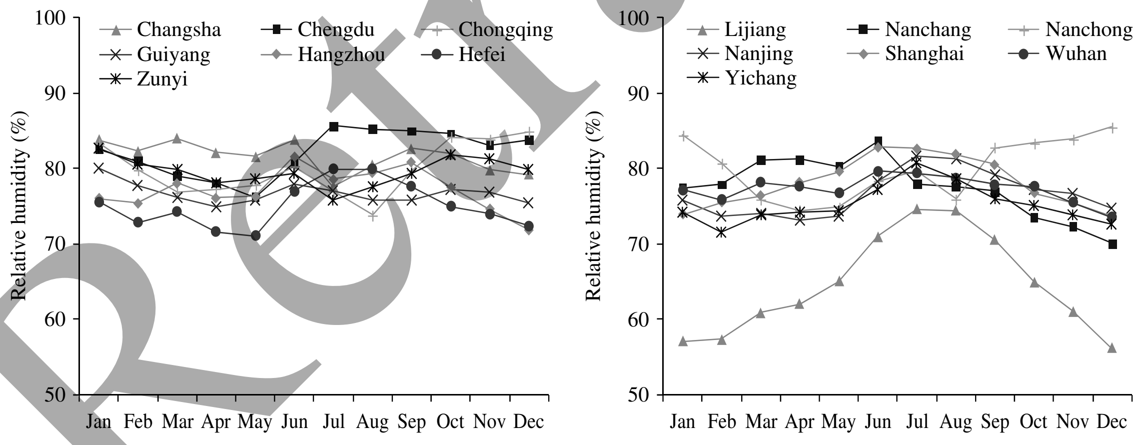

Figure 6. Distribution of the monthly mean daily relative humidity of the studied sites in Yangtze River Basin.

precipitation. The relative humidity ranged between 56 and 86% (averaged 78%). It is obvious that the solar radiation and the routinely measured meteorological variables show a monthly behaviour.

2.4. Method

A total of 12 models using routinely measured meteorological variables were developed and compared in this study (Table 2). Models 1–3 used the difference between mean maximum and minimum temperatures, among them, model 1 was developed by Hargreaves *et al*. (1985), and model 2 by Chen *et al*. (2004); models 4–8 are modifications to model 1 by introducing other routinely measured meteorological variables; model 9 which used mean maximum and minimum temperatures differs from models 1–3 which used the difference between mean maximum and minimum temperatures; models 10–12 are modifications to model 9. A common feature of these models is that they account for latitude, solar declination, elevation, day length and atmospheric transmissivity by including the extraterrestrial

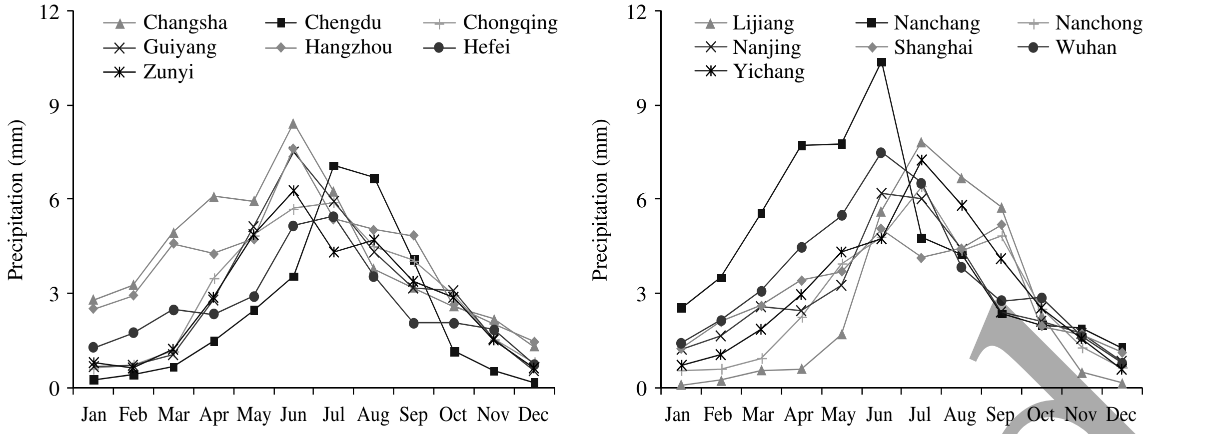

Figure 7. Distribution of the monthly mean daily precipitation of the studied sites in Yangtze River Basin.

radiation (Ra) term in the model, calculated using the equations detailed by Allen *et al*. (1998):

$$Ra = 37.6d(\omega \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega) \quad (1)$$

$$d = 1 + 0.033\cos\left(\frac{2\pi}{365}n\right) \quad (2)$$

$$\delta = 0.4093\sin\left(\frac{2\pi}{365}n - 1.39\right) \quad (3)$$

$$\omega = \arccos(-\tan\varphi \tan\delta) \quad (4)$$

where d is the relative distance between the Sun and the Earth, ω is sunset hour angle (rad), φ is latitude (rad), δ is solar declination angle (rad), n is the number of the day of the year starting from the first of January.

2.5. Performance criteria

To assess the performance of models, root mean square error (RMSE), relative root mean square error (RRMSE) (%) and co-efficient of determination (R^2) were determined. R^2 is commonly calculated based on the calibration dataset and RMSE, and RRMSE based on the validation dataset. The metric R^2 varying from 0 to 1 was adopted to measure the fit of the model on calibration data, the higher the value, the better the fit. The RMSE provides information on the short term performance of the correlations by allowing a term by term comparison of the actual deviation between the estimated and measured values. The smaller the value, the better is the model's performance. RRMSE is a dimensionless index allowing comparisons among a range of different model responses regardless of units. The values of RRMSE range from 0 to infinity. The smaller RRMSE, the better is the model's performance. RMSE and RRMSE are calculated by the following equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad (5)$$

$$RRMSE = \frac{100}{\overline{y}}\sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad (6)$$

where n, y, $\hat{y}$ and $\overline{y}$ represent the number of testing data, the observed value, the estimated value and the average value of the observation, respectively.

3. Result

3.1. Performances of models

Regression parameters and performance indicators of the models are presented in Tables 3 and 4, respectively. Overall, all the models give good estimation performances with RMSE < 2.5 MJ m^{-2} (averaged 1.582 MJ m^{-2}) and RRMSE < 25% (averaged 14.59%). Among these models, model 12 which used monthly mean daily maximum and minimum temperature, relative humidity, atmospheric pressure and the multiplication mean maximum temperature by minimum temperature, gives the best performance, with the lowest RMSE (averaged 1.228 MJ m^{-2}) and RRMSE (averaged 11.37%).

Models 1–3 using the difference between mean maximum and minimum temperature have the similar equation expressions: they differ in the form of the term $T_{\max}-T_{\min}$. The square root of $T_{\max}-T_{\min}$, logarithm of $T_{\max}-T_{\min}$, and $T_{\max}-T_{\min}$ are used in models 1, 2 and 3, respectively. Model 1 was developed by Hargreaves *et al*. (1985) to solve the problem of availability of sunshine data: it is widely used since the air temperature is commonly observed and easily available. Chen *et al*. (2004) proposed an equation (model 2) using the logarithm of $T_{\max}-T_{\min}$ and found it performed better than Hargreaves' model (model 1). However, in the present work, the three models have similar R^2 (averaged 0.599, 0.597, and 0.595, respectively), RMSE (averaged 1.856, 1.861, and 1.853 MJ m^{-2}, respectively) and RRMSE (averaged 17.05, 17.20, and 17.01%, respectively), indicating that they give similar estimation accuracy. Furthermore, this suggests that that the variations of term $T_{\max}-T_{\min}$ are generally not very effective and give no significant improvement.

Models 4–8 are modifications to model 1 by introducing other routinely measured meteorological variables. Among the models modified by adding the atmospheric pressure, relative humidity, and precipitation only (models 4, 5 and 6, respectively), model 4 is superior to models 5 and 6, it shows a 0.30–22.49% (averaged 7.53%) lower RMSE than model 1, indicating that inclusion of atmospheric pressure can effectively improve the estimation accuracy. However, it is not very effective to introduce precipitation only, as can been seen in Table 4, where model 6 shows similar RMSE (averaged 1.843 MJ m^{-2})

and RRMSE (averaged 16.89%) with those of model 1 (averaged RMSE of 1.856 MJ m^{-2}, and RRMSE of 17.05%). Model 7, modified by introducing the mean atmospheric pressure and relative humidity, and model 8, modified by introducing the atmospheric mean pressure, relative humidity and the multiplication atmospheric pressure by relative humidity, are superior to models 4–6, they significantly improve the estimation accuracy and show a 1.41–32.02% (averaged 13.53%), and 1.56–31.07% (averaged 14.04%) lower RMSE than model 1, respectively. However, model 8 gives similar values of RMSE (averaged 1.576 MJ m^{-2}) and RRMSE (averaged 14.47%) with those of model 7 (averaged RMSE of 1.590 MJ m^{-2}, and RRMSE of 14.62%), indicating that the multiplication mean atmospheric pressure by relative humidity is not effective and give no significant improvement.

Model 9, which used mean maximum and minimum temperature, differs from models 1–3 which used the difference between mean maximum and minimum temperature. It gives better performance than models 1–3. In terms of RMSE, the accuracy could be on average 15.06, 15.75, and 15.23%

Table 3. The empirical parameters of the studied models.

Station	Model 1			Model 2			Model 3			Model 4			
	a_1	b	R^2	a_1	b	R^2	a_1	b	R^2	a_1	a_2	b	R^2
Chengdu	0.196	−0.227	0.614	0.036	0.036	0.605	0.261	−0.213	0.617	0.156	−0.037	3.373	0.725
Chongqing	0.225	−0.305	0.813	0.046	−0.037	0.829	0.267	−0.225	0.787	0.197	−0.017	1.483	0.819
Changsha	0.298	−0.466	0.550	0.055	−0.068	0.534	0.392	−0.437	0.559	0.262	−0.051	4.814	0.712
Hefei	0.247	−0.337	0.600	0.043	0.019	0.591	0.353	−0.369	0.605	0.251	−0.015	1.205	0.628
Hangzhou	0.249	−0.330	0.483	0.046	0.005	0.480	0.332	−0.314	0.482	0.240	−0.013	1.008	0.497
Lijiang	0.329	−0.559	0.817	0.049	−0.012	0.813	0.547	−0.773	0.816	0.325	0.027	−2.598	0.819
Nanchong	0.248	−0.312	0.768	0.050	−0.010	0.781	0.300	−0.238	0.747	0.196	−0.028	2.519	0.828
Nanchang	0.331	−0.507	0.622	0.064	−0.082	0.618	0.419	−0.443	0.619	0.312	−0.027	2.320	0.666
Nanjing	0.160	−0.086	0.403	0.027	0.152	0.399	0.236	−0.121	0.404	0.174	−0.019	1.795	0.454
Shanghai	0.229	−0.210	0.405	0.042	0.104	0.401	0.312	−0.209	0.407	0.251	−0.024	2.174	0.462
Wuhan	0.209	−0.238	0.340	0.035	0.070	0.328	0.306	−0.279	0.349	0.244	−0.049	4.620	0.544
Yichang	0.243	−0.344	0.515	0.044	−0.011	0.511	0.328	−0.337	0.511	0.222	−0.016	1.315	0.536
Zunyi	0.233	−0.360	0.814	0.045	−0.065	0.831	0.292	−0.304	0.786	0.215	−0.020	1.492	0.822
Guiyang	0.253	−0.405	0.643	0.047	−0.065	0.640	0.336	−0.386	0.640	0.233	−0.030	2.308	0.669

Station	Model 5				Model 6				Model 7				
	a_1	a_3	b	R^2	a_1	a_4	b	R^2	a_1	a_2	a_3	b	R^2
Chengdu	0.213	0.183	−0.422	0.621	0.182	6.557E-03	−0.204	0.702	0.152	−0.037	−0.043	3.486	0.725
Chongqing	0.194	−0.293	0.005	0.821	0.229	−1.272E-03	−0.312	0.813	0.146	−0.024	−0.378	2.562	0.832
Changsha	0.221	−0.542	0.180	0.578	0.304	2.105E-03	−0.491	0.553	0.140	−0.058	−0.832	6.474	0.776
Hefei	0.237	−0.055	−0.266	0.601	0.255	1.651E-03	−0.364	0.602	0.212	−0.019	−0.212	1.870	0.638
Hangzhou	0.218	−0.207	−0.084	0.495	0.237	−3.338E-03	−0.283	0.493	0.105	−0.043	−0.749	5.040	0.576
Lijiang	0.300	−0.075	−0.415	0.819	0.270	−7.381E-03	−0.340	0.827	0.244	0.075	−0.192	−5.862	0.828
Nanchong	0.240	0.005	−0.301	0.802	0.231	3.413E-03	−0.284	0.811	0.169	−0.031	−0.152	3.051	0.831
Nanchang	0.291	−0.225	−0.226	0.634	0.314	−3.116E-03	−0.448	0.633	0.133	−0.062	−0.856	6.947	0.767
Nanjing	0.156	−0.036	−0.044	0.403	0.159	−2.060E-04	−0.082	0.403	0.149	−0.022	−0.203	2.316	0.463
Shanghai	0.207	−0.155	−0.028	0.411	0.210	−3.856E-03	−0.144	0.415	0.151	−0.054	−0.884	6.138	0.565
Wuhan	0.197	−0.082	−0.138	0.341	0.211	2.638E-04	−0.244	0.340	0.189	−0.052	−0.377	5.425	0.565
Yichang	0.260	0.141	−0.495	0.522	0.243	2.642E-03	−0.352	0.523	0.210	−0.019	−0.071	1.748	0.536
Zunyi	0.215	−0.286	−0.082	0.823	0.228	2.123E-03	−0.352	0.817	0.191	−0.023	−0.329	2.099	0.833
Guiyang	0.203	−0.404	0.041	0.666	0.251	3.259E-03	−0.406	0.657	0.151	−0.043	−0.593	4.147	0.714

Station	Model 8						Model 9				Model 11				
	a_1	a_2	a_3	a_5	b	R^2	a_6	a_7	b	R^2	a_6	a_7	a_8	b	R^2
Chengdu	0.149	0.120	17.902	−0.188	−11.516	0.729	0.032	−0.028	0.019	0.757	0.030	−0.032	1.770E-04	0.051	0.768
Chongqing	0.167	−0.446	−52.417	0.531	43.807	0.862	0.039	−0.036	−0.032	0.844	0.032	−0.042	3.511E-04	0.070	0.871
Changsha	0.157	−0.164	−14.262	0.134	17.117	0.778	0.044	−0.038	−0.075	0.773	0.044	−0.057	5.371E-04	−0.003	0.843
Hefei	0.217	0.109	16.687	−0.167	−11.128	0.648	0.043	−0.041	−0.007	0.633	0.045	−0.058	4.519E-04	0.001	0.738
Hangzhou	0.102	−0.109	−9.231	0.083	11.739	0.577	0.043	−0.041	−0.002	0.525	0.042	−0.053	3.789E-04	0.041	0.588
Lijiang	0.246	0.060	−1.817	0.021	−4.722	0.828	0.034	−0.042	0.216	0.854	0.031	−0.051	4.722E-04	0.267	0.858
Nanchong	0.174	−0.270	−29.490	0.300	26.382	0.845	0.041	−0.038	−0.002	0.816	0.036	−0.043	3.017E-04	0.075	0.838
Nanchang	0.137	−0.145	−11.847	0.109	15.368	0.769	0.056	−0.052	−0.085	0.714	0.052	−0.062	3.763E-04	−0.010	0.759
Nanjing	0.152	0.081	13.282	−0.133	−8.186	0.469	0.030	−0.028	0.098	0.478	0.032	−0.041	3.702E-04	0.093	0.569
Shanghai	0.160	0.152	25.107	−0.255	−14.851	0.577	0.048	−0.045	0.019	0.506	0.049	−0.065	6.022E-04	0.058	0.706
Wuhan	0.185	−0.244	−25.282	0.245	24.936	0.574	0.041	−0.036	−0.044	0.586	0.041	−0.053	5.308E-04	−0.005	0.692
Yichang	0.213	0.066	11.086	−0.111	−6.795	0.540	0.038	−0.035	0.001	0.571	0.037	−0.045	3.097E-04	0.044	0.605
Zunyi	0.196	−0.402	−44.403	0.480	36.883	0.845	0.037	−0.034	−0.049	0.872	0.035	−0.038	2.113E-04	−0.015	0.882
Guiyang	0.151	−0.074	−4.248	0.041	6.925	0.714	0.040	−0.036	−0.065	0.748	0.039	−0.046	3.413E-04	−0.025	0.773

Table 3. (*Continued*).

Station	Model 10						Model 12						
	a_2	a_3	a_6	a_7	b	R^2	a_2	a_3	a_6	a_7	a_8	b	R^2
Chengdu	0.003	−0.138	0.030	−0.025	−0.131	0.761	0.026	−0.287	0.026	−0.030	3.281E-04	−2.209	0.786
Chongqing	0.020	−0.472	0.027	−0.021	−1.617	0.863	0.034	−0.314	0.027	−0.033	3.535E-04	−3.062	0.887
Changsha	0.063	−0.876	0.016	−0.002	−5.624	0.861	0.082	−0.474	0.026	−0.027	4.590E-04	−7.841	0.897
Hefei	0.030	−0.345	0.031	−0.026	−2.745	0.661	0.051	−0.247	0.037	−0.045	4.776E-04	−4.938	0.770
Hangzhou	0.044	−0.905	0.013	−0.003	−3.578	0.674	0.062	−0.678	0.020	−0.020	3.119E-04	−5.694	0.708
Lijiang	0.003	−0.028	0.033	−0.040	0.001	0.854	0.054	−0.109	0.025	−0.049	7.190E-04	−3.698	0.861
Nanchong	−0.002	−0.128	0.036	−0.033	0.376	0.849	0.013	−0.161	0.031	−0.037	2.834E-04	−1.048	0.869
Nanchang	0.035	−0.682	0.025	−0.015	−2.992	0.816	0.080	−0.432	0.029	−0.030	4.069E-04	−7.731	0.856
Nanjing	0.038	−0.390	0.023	−0.017	−3.410	0.520	0.053	−0.331	0.026	−0.031	3.963E-04	−4.999	0.620
Shanghai	0.015	−0.925	0.030	−0.023	−0.715	0.639	0.053	−0.418	0.041	−0.051	5.809E-04	−5.028	0.785
Wuhan	0.029	−0.425	0.029	−0.021	−2.616	0.616	0.058	−0.013	0.039	−0.048	5.844E-04	−5.912	0.717
Yichang	0.048	−0.148	0.034	−0.025	−4.783	0.609	0.083	0.005	0.037	−0.043	4.834E-04	−8.402	0.678
Zunyi	0.041	−0.396	0.032	−0.026	−3.512	0.900	0.058	−0.282	0.032	−0.033	2.932E-04	−5.176	0.916
Guiyang	0.022	−0.471	0.030	−0.024	−1.653	0.793	0.057	−0.322	0.033	−0.041	4.988E-04	−4.816	0.834

Table 4. Root mean square error (RMSE in MJ m^{-2}) and Relative root mean square error (RRMSE) of the studied models.

Station	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	RMSE	RRMSE (%)	RMSE	RRMSE (%)	RMSE	RRMSE (%)	RMSE	RRMSE (%)	RMSE	RRMSE (%)	RMSE	RRMSE (%)
Chengdu	1.322	15.36	1.321	15.34	1.336	15.51	1.266	14.70	1.267	14.71	1.250	14.51
Chongqing	1.238	14.22	1.363	15.66	1.257	13.29	1.197	13.75	1.224	14.06	1.260	14.47
Changsha	2.250	21.01	2.252	21.03	2.266	21.16	1.868	17.44	2.178	20.33	2.261	21.11
Hefei	2.202	18.07	2.195	18.01	2.206	18.10	1.941	15.92	2.186	17.93	2.208	18.12
Hangzhou	2.041	17.47	2.040	17.47	2.050	17.55	1.982	16.97	2.007	17.18	2.052	17.57
Lijiang	1.612	9.59	1.683	10.01	1.564	9.30	1.607	9.56	1.591	9.46	1.624	9.66
Nanchong	1.698	18.33	1.681	18.14	1.730	18.68	1.611	17.39	1.575	17.00	1.606	17.33
Nanchang	2.017	16.98	1.997	16.81	2.048	17.25	1.794	15.10	2.006	16.89	2.027	17.07
Nanjing	1.629	13.67	1.629	13.67	1.629	13.67	1.474	12.36	1.624	13.62	1.628	13.66
Shanghai	2.047	17.08	2.052	17.13	2.043	17.05	2.026	16.91	2.041	17.03	2.018	16.84
Wuhan	2.479	21.73	2.495	21.88	2.459	21.56	1.921	16.84	2.411	21.14	2.478	21.72
Yichang	1.962	18.24	1.957	18.20	1.972	18.33	1.815	16.88	1.901	17.67	1.872	17.40
Zunyi	1.176	14.09	1.239	14.85	1.142	13.68	1.166	13.78	1.193	14.09	1.190	14.06
Guiyang	2.314	22.86	2.294	22.66	2.336	23.08	2.126	21.00	2.255	22.27	2.151	21.25

Station	Model 7		Model 8		Model 9		Model 10		Model 11		Model 12	
	RMSE	RRMSE (%)	RMSE	RRMSE (%)	RMSE	RRMSE (%)	RMSE	RRMSE (%)	RMSE	RRMSE (%)	RMSE	RRMSE (%)
Chengdu	1.213	14.08	1.211	14.07	1.404	16.30	1.349	15.66	1.402	16.27	1.332	15.47
Chongqing	1.124	12.91	1.004	11.53	1.041	11.95	0.942	10.82	0.788	9.05	0.710	8.15
Changsha	1.680	15.68	1.646	15.37	1.664	15.54	1.321	12.34	1.164	10.87	0.955	8.92
Hefei	1.830	15.02	1.847	15.16	1.871	15.35	1.664	13.65	1.594	13.08	1.452	11.92
Hangzhou	1.783	15.26	1.777	15.21	1.883	16.12	1.466	12.55	1.621	13.88	1.316	11.26
Lijiang	1.555	9.25	1.559	9.27	1.407	8.37	1.402	8.34	1.407	8.37	1.392	8.28
Nanchong	1.515	16.35	1.475	15.92	1.614	17.42	1.401	15.12	1.495	16.13	1.197	12.92
Nanchang	1.499	12.62	1.499	12.62	1.565	13.17	1.105	9.30	1.357	11.43	0.780	6.57
Nanjing	1.445	12.12	1.435	12.04	1.376	11.54	1.241	10.42	1.090	9.14	0.911	7.65
Shanghai	1.946	16.24	1.957	16.33	2.001	16.02	2.001	16.70	1.649	13.76	1.594	13.31
Wuhan	1.685	14.77	1.709	14.98	1.693	14.84	1.469	12.88	1.498	13.13	1.377	12.07
Yichang	1.813	16.86	1.783	16.57	1.688	15.69	1.651	15.35	1.515	14.09	1.399	13.00
Zunyi	1.160	13.70	1.158	13.68	1.167	13.98	1.136	13.42	1.127	13.50	1.110	13.11
Guiyang	2.006	19.81	2.010	19.86	1.781	17.59	1.736	17.15	1.674	16.53	1.672	16.52

higher than models 1–3, respectively, and at some sites (e.g., Changsha, Nanchang, Guiyang and Wuhan), the accuracy could be 22–31% higher. Model 10, which is a modification to model 9 as model 7 is to model 1, shows an average 10.03% lower RMSE than model 9. Model 11, a modification to model 9 by introducing the multiplication of mean maximum temperature by minimum temperature, performs better and has an average 12.39% lower RMSE than model 9, and at some sites (e.g., Nanjing, Nanchang and Chongqing), the accuracy could be 20–30% higher, indicating that inclusion

Table 5. Correlation co-efficients between root mean square error (RMSE), relative root mean square error (RRMSE) and latitude, longitude, altitude, mean daily maximum temperature (T_{max}), mean daily minimum temperature (T_{min}), the difference between T_{max} and T_{min} ($T_{max}-T_{min}$), atmospheric pressure (VP), relative humidity (RH), and precipitation (P).

Indicator	Latitude	Longitude	Altitude	T_{max}	T_{min}	$T_{max}-T_{min}$	VP	RH	P
RMSE	0.008	−0.001	0.264	−0.447	−0.355	0.309	−0.262	−0.305	−0.355
RRMSE	0.028	−0.194	0.044	−0.350	0.008	−0.529*	−0.069	0.270	−0.359

* Significant at 0.05 significance level.

of the multiplication mean maximum temperature by minimum temperature can significantly improve the estimation accuracy.

Model 12 which gives the best performance (averaged RMSE of 1.228 MJ m^{-2}, RRMSE of 11.37%) significantly outperforms models 10 and 11. It shows a 1–29% (averaged 13.98%, and 1–42% (averaged 11.51%) lower RMSE than them, respectively. This further confirms that the inclusion of atmospheric pressure and relative humidity, and the multiplication mean maximum temperature by minimum temperature can significantly improve the estimation accuracy. Model 12 gives the best performance and is therefore suggested to estimate solar radiation in Yangtze River Basin. The following analysis will be limited to results of model 12.

3.2. Analyses of influencing factors of model accuracy

The model accuracy varies from station to station as shown in Table 4. The correlation analysis between RMSE, RRMSE and other factors including longitude, latitude, altitude, mean maximum temperature and minimum temperature, the difference between mean maximum and minimum temperature, atmospheric pressure, relative humidity, and precipitation are investigated, and the summary is presented in Table 5. RMSE and RRMSE show very weak correlations with longitude, latitude, altitude, mean maximum temperature, mean minimum temperature, atmospheric pressure, relative humidity and precipitation. RRMSE correlates significantly with the difference between mean maximum and minimum temperature ($r = -0.529$, $p < 0.05$), generally indicating that the model is more applicable in areas with larger temperature range. Although air temperature changes are not due only to solar radiation, solar radiation loading is the predominant mechanism forcing diurnal air temperature range, as can been seen from Table 3. Air temperature range could account for 35–82% (averaged 60%) of the solar radiation variation in the study area. RMSE is an absolute measure of fit and site-specific, For example, model 11 gives higher RMSE in Shanghai (1.649 MJ m^{-2}) than that in Nanchong (1.495 MJ m^{-2}), but model 11 actually performs slightly better in Nanchong than in Shanghai because the solar radiation in Shanghai (averaged 12.655 MJ m^{-2}) is much higher than that in Nanchong (averaged 9.944 MJ m^{-2}). So it is suggested to use the RRMSE to measure the model performance when make comparisons among different sites.

3.3. Correlations of model parameter with common factors

The parameters generally vary from station to station: they are site dependent. Therefore, it is worthwhile investigating the relation between the parameters and factors mentioned above, and the result is presented in Table 6. All the parameters of model 12 show very weak correlation with latitude, longitude, altitude and mean maximum temperature. Parameter a_2 is significantly correlated with precipitation ($r = 0.678$, $p < 0.01$): a_8 is significantly correlated with mean minimum temperature ($r = -0.645$, $p < 0.05$), relative humidity ($r = -0.718$, $p < 0.01$), and the difference between mean maximum and minimum temperature ($r = 0.732$, $p < 0.01$); parameter b correlates significantly with precipitation ($r = -0.698$, $p < 0.01$); None of the above factors correlates significantly with parameters a_3, a_6, and a_8. The significant correlations are important in increasing the availability of the model parameters.

4. Conclusion

Estimation of solar radiation from the measured meteorological variables offers an important alternative in the absence of measured solar radiation. Monthly mean daily solar radiation and routinely observed meteorological data, including maximum and minimum temperature, relative humidity, atmospheric pressure and precipitation at 14 sites in the Yangtze River Basin in China, were gathered and analysed: 12 developed models are comparatively studied and evaluated using the root mean square error (RMSE) and relative root mean square error (RRMSE). All the models fit the data adequately and can be used to estimate solar radiation. The newly developed

Table 6. Correlation co-efficients between parameters of model 12 and latitude, longitude, altitude, mean daily maximum temperature (T_{max}), mean daily minimum temperature (T_{min}), the difference between T_{max} and T_{min} ($T_{max}-T_{min}$), atmospheric pressure (VP), relative humidity (RH), and precipitation (P).

Parameter	Latitude	Longitude	Altitude	T_{max}	T_{min}	$T_{max}-T_{min}$	VP	RH	P
a_2	−0.275	0.400	−0.125	0.093	−0.075	0.173	0.141	−0.177	0.678**
a_3	0.069	−0.468	0.286	−0.016	−0.228	0.329	−0.284	−0.346	−0.493
a_6	0.286	0.242	−0.258	−0.058	0.047	−0.108	0.256	0.052	−0.199
a_7	−0.019	0.113	−0.322	0.350	0.461	−0.457	0.311	0.522	0.431
a_8	−0.220	−0.012	0.436	−0.349	−0.645*	0.732**	−0.409	−0.718**	−0.038
B	0.112	−0.501	0.316	−0.219	−0.073	−0.034	−0.330	0.033	−0.698**

* Significant at 0.05 significance level. ** Significant at 0.01 significance level.

model which used monthly mean maximum and minimum temperature, relative humidity, atmospheric pressure and the multiplication mean maximum temperature by minimum temperature gives the best performance, and it is more applicable in areas with larger temperature range.

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