

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

Ji-Long Chen^{a,b} and Guo-Sheng Li^{a*}

^a *Research Center of Integrated Detection and Simulation of Regional Environment Change, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing, China*

^b *Research Center of Integrated Detection and Simulation of Regional Environment Change, Graduate University of Chinese Academy of Sciences, Beijing, China*

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

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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; Thornton 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 environmental models and crop growth simulation are widely studied. However, only a few meteorological stations provide solar radiation recorders. On the contrary, air temperature,

* Correspondence to: G.-S. Li, Research Center of Integrated Detection and Simulation of Regional Environment Change, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China. E-mail: ligscas@163.com

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 $180 \times 10^4 \text{ km}^2$ 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 ($^{\circ}\text{C}$) 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.

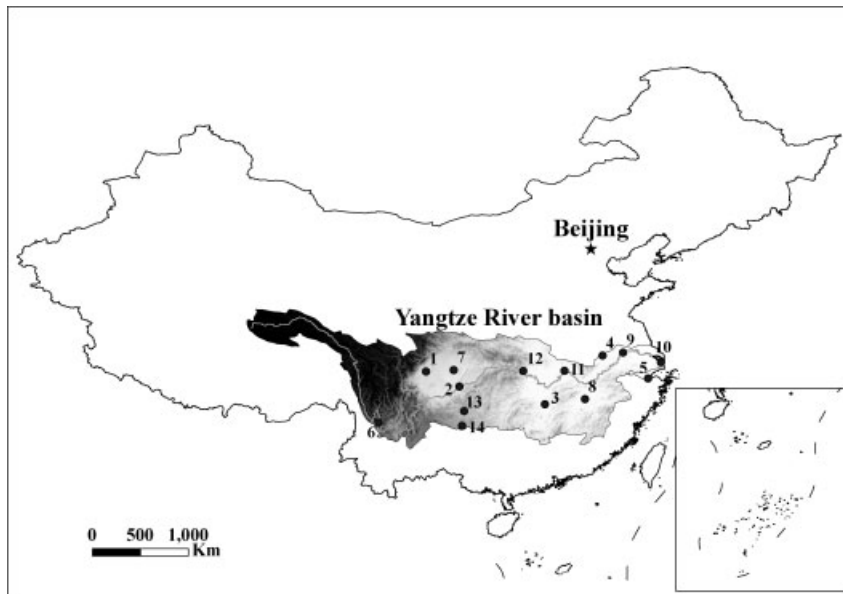


Figure 1. Location of the studied meteorological stations in Yangtze River Basin (stations are numbered in compliance with Table 1).

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

| Station ID | Station name | Latitude ($^{\circ}\text{N}$) | Longitude ($^{\circ}\text{E}$) | 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 | $Rs = Ra(a_1(T_{max} - T_{min})^{0.5} + a_2VP + b)$ | a_1, a_2, b |
| 5 | $Rs = Ra(a_1(T_{max} - T_{min})^{0.5} + a_3RH + b)$ | a_1, a_3, b |
| 6 | $Rs = Ra(a_1(T_{max} - T_{min})^{0.5} + a_4P + b)$ | a_1, a_4, b |
| 7 | $Rs = Ra(a_1(T_{max} - T_{min})^{0.5} + a_2VP + a_3RH + b)$ | a_1, a_2, a_3, b |
| 8 | $Rs = Ra(a_1(T_{max} - T_{min})^{0.5} + a_2VP + a_3RH + a_5VP \times RH + b)$ | a_1, a_2, a_3, a_5, b |
| 9 | $Rs = Ra(a_6T_{max} + a_7T_{min} + b)$ | a_6, a_7, b |
| 10 | $Rs = Ra(a_6T_{max} + a_7T_{min} + a_2VP + a_3RH + b)$ | a_2, a_3, a_6, a_7, b |
| 11 | $Rs = Ra(a_6T_{max} + a_7T_{min} + a_8T_{min} \times T_{max} + b)$ | a_6, a_7, a_8, b |
| 12 | $Rs = Ra(a_6T_{max} + a_7T_{min} + a_8T_{min} \times T_{max} + a_2VP + a_3RH + b)$ | $a_2, a_3, a_6, a_7, a_8, b$ |

^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).

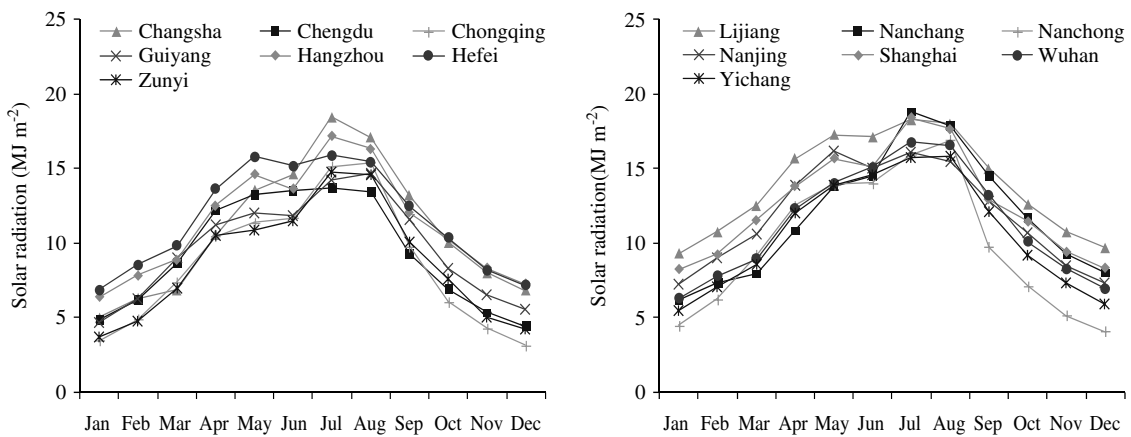


Figure 2. Distribution of the monthly mean daily solar radiation of the studied sites in Yangtze River Basin.

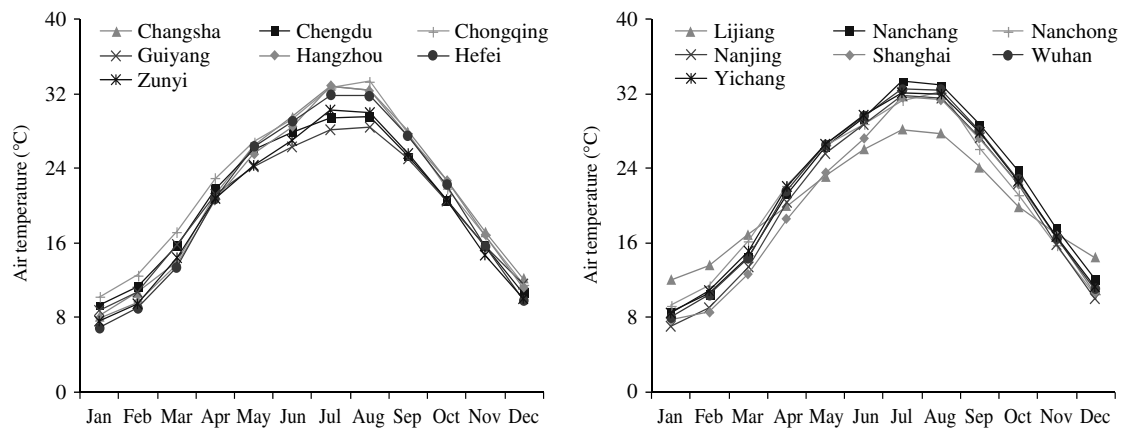


Figure 3. Distribution of the monthly mean daily maximum air temperature of the studied sites in Yangtze River Basin.

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 occurs in summer which could account for 36–63% (averaged 45%) of the annual

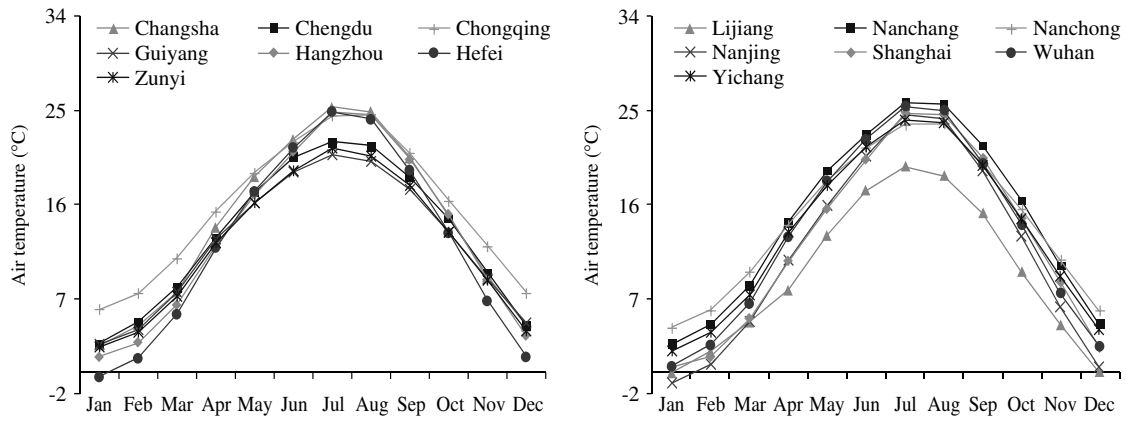


Figure 4. Distribution of the monthly mean daily minimum air temperature of the studied sites in Yangtze River Basin.

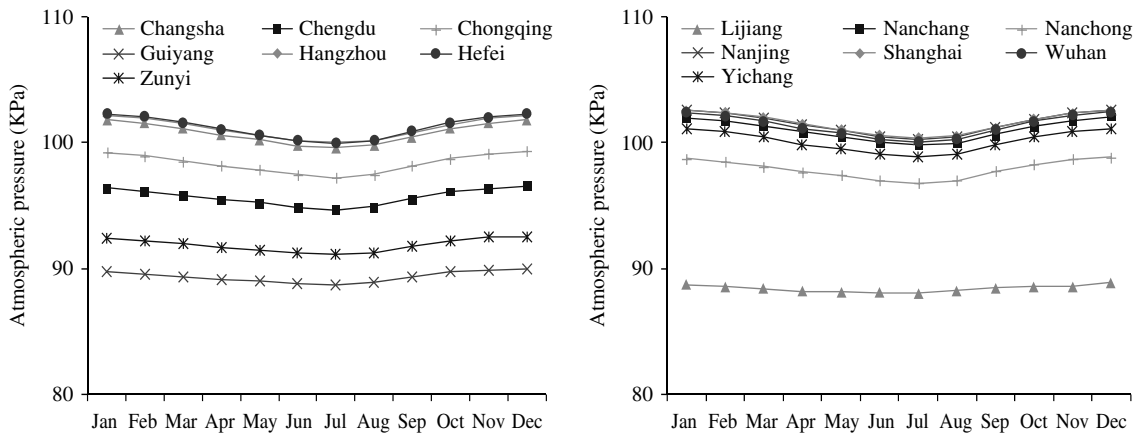


Figure 5. Distribution of the monthly mean daily atmospheric pressure of the studied sites in Yangtze River Basin.

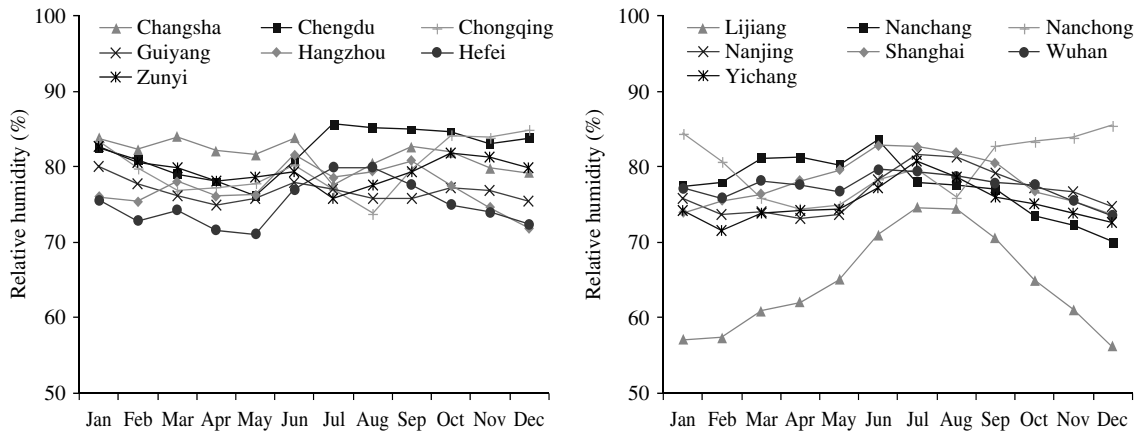


Figure 6. Distribution of the monthly mean daily relative humidity of the studied sites in Yangtze River Basin.

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

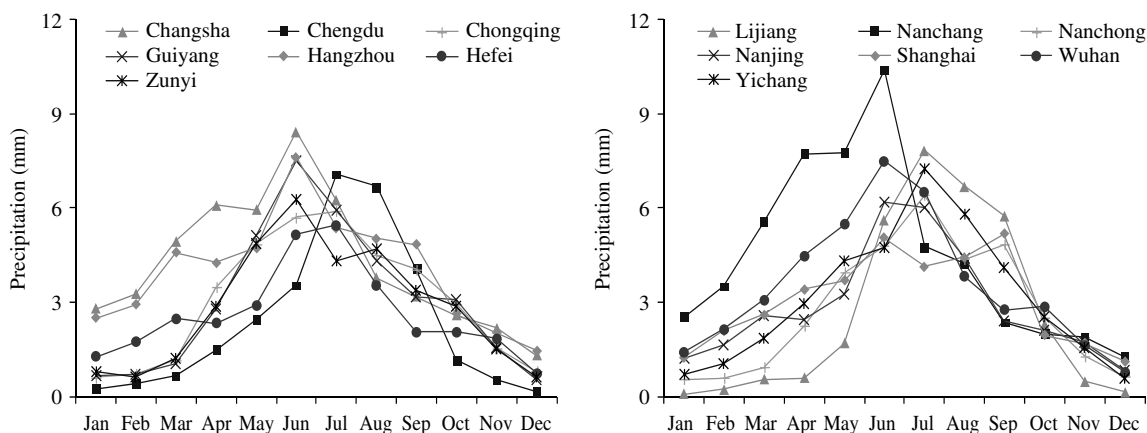


Figure 7. Distribution of the monthly mean daily precipitation of the studied sites in Yangtze River Basin.

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

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

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

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

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

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:

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

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

where n , y , \hat{y} and \bar{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 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 be 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 | | | |
|-----------|-----------------------|----------|-----------------------|-----------------------|----------|-----------------------|-----------------------|----------|-----------------------|-----------------------|-----------------------|----------|-----------------------|
| | <i>a</i> ₁ | <i>b</i> | <i>R</i> ² | <i>a</i> ₁ | <i>b</i> | <i>R</i> ² | <i>a</i> ₁ | <i>b</i> | <i>R</i> ² | <i>a</i> ₁ | <i>a</i> ₂ | <i>b</i> | <i>R</i> 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 | | | | |
|-----------|-----------------------|-----------------------|----------|-----------------------|-----------------------|-----------------------|----------|-----------------------|-----------------------|-----------------------|-----------------------|----------|-----------------------|
| | <i>a</i> ₁ | <i>a</i> ₃ | <i>b</i> | <i>R</i> ² | <i>a</i> ₁ | <i>a</i> ₄ | <i>b</i> | <i>R</i> ² | <i>a</i> ₁ | <i>a</i> ₂ | <i>a</i> ₃ | <i>b</i> | <i>R</i> 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 | | | | |
|-----------|-----------------------|-----------------------|-----------------------|-----------------------|----------|-----------------------|-----------------------|-----------------------|----------|-----------------------|-----------------------|-----------------------|-----------------------|----------|-----------------------|
| | <i>a</i> ₁ | <i>a</i> ₂ | <i>a</i> ₃ | <i>a</i> ₅ | <i>b</i> | <i>R</i> ² | <i>a</i> ₆ | <i>a</i> ₇ | <i>b</i> | <i>R</i> ² | <i>a</i> ₆ | <i>a</i> ₇ | <i>a</i> ₈ | <i>b</i> | <i>R</i> 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 be 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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