Estimation of solar radiation using two-step method 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. Estimation of solar radiation from other measured meteorological variables offers an important alternative in the absence of availability of measured solar radiation data. In this paper, we validate and assess four commonly used air temperature models to estimate solar radiation in Yangtze River basin. It is believed to be useful for the site where no measured solar radiation data is available, whereas the air temperatures are commonly measured.

Key words – Econ Solar radiation, Air temperature, A-P model, Two-step method, Determination equations.

1. Introduction

Solar radiation at the earth’s surface is the principal and fundamental energy source for many physical, chemical and biological processes, such as crop growth, plant photosynthesis, and it is also an essential and important variable to many simulation models studies, such as agriculture, environment, hydrology, meteorology, etc.
and ecology. Hence, accurate records of solar radiation are of vital importance. However, it is not widely available due to excessive cost and difficulties in maintenance and calibration of the measurement equipment (Hunt et al., 1998). This parameter is measured only at few meteorological stations. For example, in 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 98 stations are recording solar radiation (Chen et al., 2004). Therefore, developing method to estimate solar radiation for the site where no solar radiation is readily available has been the focus of many studies.

A number of methods, including satellite-derived (Frulla et al., 1988; Pinker et al., 1995; Olseth and Skartveit, 2001), stochastic algorithm (Richardson, 1981; Hansen, 1999; Wilks and Wilby, 1999) and empirical relationships (Ångström, 1924; Prescott, 1940; Hargreaves and Samani, 1982; Bristow and Campbell, 1984; Hargreaves et al., 1985), interpolation-based (Hay and Suckling, 1979; Rivington et al., 2006), learning machine method (Tynvios et al., 2005; Lam et al., 2008; Chen et al., 2011) have been developed for this purpose. Among them, the empirical relationship method is attractive for its simplicity, efficiency and much lower data requirement. Ångström (1924) first proposed a linear relationship between the ratio of average daily solar radiation to the corresponding value on a completely clear day and the ratio of average daily sunshine duration to the maximum possible sunshine duration. Prescott (1940) modified this method by replacing the clear sky radiation with the extraterrestrial radiation. Subsequently, the well-known sunshine-based Ångström-Prescott (A-P) model was developed. Despite its good performance, it is often limited by the lack of sufficient sunshine duration records. To obviate this difficulty, lots of air temperature-based models have been developed and widely used (Hargreaves and Samani, 1982; Bristow and Campbell, 1984; Hargreaves et al., 1985; Chen et al., 2004). These models allow widespread applications because air temperatures are routinely measured at most meteorological stations. However, a number of studies have shown that the sunshine-based A-P model significantly outperformed the temperature-based models (Iziomon and Mayer, 2002; Podestá et al., 2004; Trnka et al., 2005). Therefore, more accurate solar radiation estimation using air temperature is of vital importance and significance.

The much better performance of the sunshine-based A-P model over the temperature-based model seems to indicate that if the sunshine duration could be estimated from air temperature, then the estimated sunshine duration could be used as inputs for A-P model to estimate solar radiation, and the conversion in this way may be able to improve the estimation accuracy over the temperature-based models. We name this method as two-step estimation method (hereafter referred to two-step method), namely, estimate the sunshine duration using air temperature firstly, and then estimate solar radiation by A-P model using the estimated sunshine duration.

In the present work, four widely used air temperature-based models and a local regression model
are studied. The main objectives of this study are to (1) calibrate and validate the temperature-based models from data of 14 sites in Yangtze River basin in China; and (2) investigate and evaluate the two-step method.

2. Data and methodology

2.1. Sites and data set

The current study focuses on the Yangtze River basin (Fig. 1). The Yangtze River is 6300 km long with a basin area of $180 \times 10^4$ km$^2$ with decreasing altitude from west to east. The basin is characterized by abundant water resources, and thus plays significant role in water supply for agriculture industry, because economy of much of the Yangtze River basin is largely dependent on agricultural production. A large part of the Yangtze River basin is of subtropical monsoon climate type. Average annual precipitation in the basin varies from 270-500 mm in the west to 1600-1900 mm in the southeast (Zhang et al., 2008). Average annual sunshine hours ranges from 1000 h to 2500 h (Gong et al., 2006). 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° latitude North, from 97° to 121° longitude East, and from 3 to 3394 m altitude. Table 1 shows the temporal period of data calibration and validation and the geographical information of the meteorological stations.

The monthly mean daily solar radiation (MJ m$^{-2}$ d$^{-1}$), sunshine duration (h), air temperature (°C), including mean maximum temperature and minimum temperature are 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 of data. A year with more than 5 days of missing or faulty data in the same month was discarded (e.g., the year of 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 for calibrating the parameters, and the remaining records were used for evaluating the model (Table 1).

2.2. Temperature-based solar radiation estimation models

2.2.1. H-S model

Hargreaves and Samani (1982) suggested a solar radiation estimation model that is a function of extraterrestrial radiation, maximum and minimum temperatures as follow:

$$\frac{R_s}{R_a} = a(T_{\text{max}} - T_{\text{min}})^{0.5}$$

(1)
TABLE 2

The empirical parameters of the temperature-based models *

| Station   | H-S model \(a\) | \(R^2\) | H-S model \(b\) | \(R^2\) | Chen model \(a\) | \(b\) | \(R^2\) | Local Rs model \(a\) | \(b\) | \(R^2\) |
|-----------|----------------|--------|----------------|--------|----------------|-------|--------|----------------------|-------|--------|
| Chengdu   | 0.112          | 0.500  | 0.196          | -0.227 | 0.614         | 0.261 | -0.213 | 0.617               | 0.036 | 0.036 |
| Chongqing | 0.105          | 0.577  | 0.225          | -0.305 | 0.813         | 0.267 | -0.225 | 0.787               | 0.046 | 0.037 |
| Changsha  | 0.126          | 0.365  | 0.298          | -0.466 | 0.550         | 0.392 | -0.437 | 0.559               | 0.055 | 0.068 |
| Hefei     | 0.129          | 0.463  | 0.247          | -0.337 | 0.600         | 0.353 | -0.369 | 0.605               | 0.043 | 0.019 |
| Hangzhou  | 0.129          | 0.370  | 0.249          | -0.330 | 0.483         | 0.332 | -0.314 | 0.482               | 0.046 | 0.005 |
| Lijiang   | 0.165          | 0.612  | 0.329          | -0.559 | 0.817         | 0.547 | -0.773 | 0.816               | 0.049 | 0.012 |
| Nanchang  | 0.124          | 0.608  | 0.233          | -0.279 | 0.783         | 0.283 | -0.209 | 0.769               | 0.047 | 0.006 |
| Nanjing   | 0.106          | 0.423  | 0.253          | -0.405 | 0.643         | 0.336 | -0.386 | 0.640               | 0.047 | 0.065 |
| Shanghai  | 0.132          | 0.390  | 0.169          | -0.107 | 0.403         | 0.236 | -0.121 | 0.404               | 0.027 | 0.152 |
| Wuhan     | 0.153          | 0.360  | 0.229          | -0.210 | 0.405         | 0.312 | -0.209 | 0.407               | 0.042 | 0.104 |
| Yichang   | 0.120          | 0.383  | 0.243          | -0.344 | 0.515         | 0.328 | -0.337 | 0.511               | 0.044 | 0.011 |
| Zunyi     | 0.101          | 0.549  | 0.233          | -0.360 | 0.814         | 0.292 | -0.304 | 0.786               | 0.045 | 0.065 |
| Guiyang   | 0.106          | 0.423  | 0.253          | -0.405 | 0.643         | 0.336 | -0.386 | 0.640               | 0.047 | 0.065 |

* The metric \(R^2\), varying from 0 to 1, is adopted to measure the degree of success of a fit in explaining data variation, with 0 denoting that model does not explain any variation and 1 denoting that it perfectly explains the observed variation.

- \(^a\) Hargreaves and Samani (1982)
- \(^b\) Hargreaves et al. (1985)
- \(^c\) Chen et al. (2004)
- \(^d\) See Eqn. (7)

where \(R_s\) is monthly mean daily actual global radiation (MJ m\(^{-2}\) d\(^{-1}\)), \(T_{\text{max}}\) and \(T_{\text{min}}\) are maximum and minimum temperature, respectively, \(Ra\) is monthly mean daily extraterrestrial solar radiation (MJ m\(^{-2}\) d\(^{-1}\)), which is a function of latitude and day of the year. The detailed procedure for calculation of extraterrestrial radiation can be found in Allen et al. (1998), where ‘\(a\)’ is empirical parameter, which was recommended to be 0.16 for interior regions and 0.19 for coastal regions. In the present work, parameter listed in Table 2 is locally calibrated for each station using the training data set.

2.2.2. H-Sm model

Hargreaves et al. (1985) further modified the H-S model by adding an empirical correction parameter and obtained the following equation:

\[
\frac{R_s}{Ra} = a(T_{\text{max}} - T_{\text{min}})^{0.5} + b
\]  

(2)

where, \(a\) and \(b\) are empirical parameters as listed in Table 2.

2.2.3. B-C model

Bristow and Campbell (1984) studied the relationship between solar radiation and maximum, minimum temperature and developed the equation given below:

\[
R_s = aRa[1 - \exp(-b(\Delta T_i)^c)]
\]  

(3)

\(a\), \(b\) and \(c\) are parameters, values widely used for these coefficients are 0.7 for \(a\), 2.4 for \(c\) and the value of \(b\) can be calculated from the equation:

\[
b = 0.036 \exp(-0.154\overline{\Delta T})
\]  

(4)

where, \(\overline{\Delta T}\) is the monthly average of the \(\Delta T_i\) daily values, \(\Delta T_i\) is the air temperature difference calculated by subtracting the average \(T_{\text{min}}\) of the current and the next day from the \(T_{\text{max}}\) of the current day:

\[
\Delta T_i = T_{\text{max},i} - \frac{T_{\text{min},i} + T_{\text{min},i+1}}{2}
\]  

(5)
| Station   | A-P model |   | local S model |   |
|-----------|-----------|---|---------------|---|
|           | a         | b | R²            | a | b | c | R² |
| Chengdu   | 0.550     | 0.164 | 0.747 | 0.052 | -0.047 | -0.193 | 0.715 |
| Chongqing | 0.585     | 0.118 | 0.867 | 0.060 | -0.055 | -0.218 | 0.828 |
| Changsha  | 0.621     | 0.125 | 0.867 | 0.074 | -0.066 | -0.314 | 0.767 |
| Hefei     | 0.590     | 0.103 | 0.773 | 0.067 | -0.064 | -0.130 | 0.678 |
| Hangzhou  | 0.586     | 0.127 | 0.786 | 0.074 | -0.072 | -0.187 | 0.607 |
| Lijiang   | 0.576     | 0.225 | 0.873 | 0.065 | -0.074 | -0.116 | 0.903 |
| Nanchong  | 0.583     | 0.155 | 0.872 | 0.065 | -0.060 | -0.234 | 0.856 |
| Nanchang  | 0.579     | 0.120 | 0.915 | 0.096 | -0.089 | -0.345 | 0.757 |
| Nanjing   | 0.536     | 0.147 | 0.785 | 0.055 | -0.051 | -0.104 | 0.595 |
| Shanghai  | 0.565     | 0.158 | 0.867 | 0.076 | -0.070 | -0.192 | 0.505 |
| Wuhan     | 0.564     | 0.110 | 0.771 | 0.069 | -0.060 | -0.243 | 0.709 |
| Yichang   | 0.594     | 0.120 | 0.810 | 0.065 | -0.060 | -0.208 | 0.712 |
| Zunyi     | 0.580     | 0.131 | 0.895 | 0.058 | -0.053 | -0.263 | 0.817 |
| Guiyang   | 0.582     | 0.133 | 0.870 | 0.057 | -0.049 | -0.267 | 0.747 |

* The metric R², varying from 0 to 1, is adopted to measure the degree of success of a fit in explaining data variation, with 0 denoting that model does not explain any variation and 1 denoting that it perfectly explains the observed variation.

Ångström (1924); Prescott (1940); See Eqn.(9)

where, \( T_{max,i} \), \( T_{min,i} \), \( T_{min,i+1} \) are \( T_{max} \), \( T_{min} \) in \( i \)th day, \( T_{min} \) in \((i + 1)\)th day, respectively.

### 2.2.4. Chen model

Chen et al. (2004) presented a new model as follow:

\[
\frac{R_s}{R_a} = a \ln (T_{max} - T_{min}) + b \tag{6}
\]

where, \( a \) and \( b \) are empirical parameters listed in Table 2.

### 2.2.5. Local model

In addition to these well-known models, we propose the following equation based on the investigation of relationship between \( R_s/R_a \) and maximum, minimum temperature (hereafter referred to local \( R_s \) model).

\[
\frac{R_s}{R_a} = a(T_{max} - T_{min}) + b \tag{7}
\]

where, \( a \) and \( b \) are empirical parameters as listed in Table 2.

### 2.3. Sunshine-based A-P model

A-P model was proposed by Ångström (1924) and further modified by Prescott (1940). The original form of this model is:

\[
\frac{R_s}{R_a} = a \frac{S}{S_0} + b \tag{8}
\]

where, \( a \) and \( b \) are empirical parameters which are calibrated from regression analysis between \( S/S_0 \) and \( R_s/R_a \). \( S \) is monthly mean daily actual duration of sunshine hours (h), \( S_0 \) is monthly mean daily maximum possible sunshine duration (h) which is calculated using the equations detailed by Allen et al. (1998).

### 2.4. Sunshine duration estimation model

In this paper, we propose a formula to estimate monthly mean daily sunshine duration using maximum and minimum temperature in Yangtze River basin (hereafter referred to local \( S \) model).

\[
\frac{S}{S_0} = a T_{max} + b T_{min} + c \tag{9}
\]
where, a, b and c are empirical parameters listed in Table 3 which are locally determined using the calibration data set.

2.5. Performance criteria

To assess the performance of models, root mean square error (RMSE), relative root mean square error (RRMSE) (%), mean absolute bias error (MABE), mean absolute percentage error (MAPE) (%) and coefficient of determination ($R^2$) are determined. The metric $R^2$ is adopted to measure the fit of the model on calibration data, and the correlation between the estimated and observed values. The former four indicators are calculated by the following equations:

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

TABLE 4
Root mean square error (RMSE in MJ m⁻³), relative root mean square error (RRMSE), Mean absolute bias error (MABE in MJ m⁻³) and mean absolute percentage error (MAPE) of the temperature-based models and the two-step method

| Station     | Chen model¹ | Local Rs model² | Two-step method |
|-------------|-------------|-----------------|-----------------|
|             | RMSE       | RRMSE          | MABE            | MAPE          |
|             |             |                 |                 |               |
| Chengdu     | 1.404       | 16.30%          | 1.130           | 15.84%        |
|             | 1.336       | 15.51%          | 1.138           | 16.06%        |
|             | 1.320       | 15.33%          | 1.128           | 15.57%        |
| Chongqing   | 1.183       | 15.66%          | 0.894           | 0.0943        |
|             | 1.157       | 13.29%          | 0.839           | 9.11%         |
|             | 1.101       | 12.64%          | 0.759           | 8.33%         |
| Changsha    | 2.252       | 21.03%          | 1.767           | 17.59%        |
|             | 2.266       | 21.16%          | 1.704           | 15.40%        |
|             | 2.106       | 15.14%          | 1.320           | 10.20%        |
| Hefei       | 2.195       | 18.01%          | 1.513           | 11.36%        |
|             | 2.206       | 18.10%          | 1.524           | 11.24%        |
|             | 1.846       | 15.14%          | 1.320           | 10.20%        |
| Hangzhou    | 2.040       | 17.47%          | 1.469           | 12.29%        |
|             | 2.050       | 17.55%          | 1.511           | 12.60%        |
|             | 1.934       | 16.56%          | 1.423           | 11.98%        |
| Lijiang     | 1.583       | 10.01%          | 1.265           | 8.15%         |
|             | 1.564       | 9.30%           | 1.250           | 7.40%         |
|             | 1.413       | 8.40%           | 1.103           | 6.55%         |
| Nanchong    | 1.575       | 17.00%          | 1.239           | 16.12%        |
|             | 1.613       | 17.41%          | 1.209           | 15.27%        |
|             | 1.560       | 16.84%          | 1.177           | 14.41%        |
| Nanchang    | 2.294       | 22.66%          | 1.736           | 16.07%        |
|             | 2.336       | 23.08%          | 1.734           | 15.55%        |
|             | 1.574       | 13.25%          | 1.260           | 11.17%        |
| Nanjing     | 1.629       | 13.67%          | 1.229           | 10.27%        |
|             | 1.629       | 13.67%          | 1.224           | 10.29%        |
|             | 1.358       | 11.39%          | 1.075           | 9.03%         |
| Shanghai    | 2.052       | 17.13%          | 1.615           | 13.82%        |
|             | 2.043       | 17.05%          | 1.612           | 13.82%        |
|             | 1.949       | 16.27%          | 1.462           | 12.63%        |
| Wuhan       | 2.495       | 21.88%          | 1.838           | 15.10%        |
|             | 2.459       | 21.56%          | 1.809           | 14.85%        |
|             | 1.678       | 14.71%          | 1.345           | 12.87%        |
| Yichang     | 1.957       | 18.20%          | 1.431           | 21.61%        |
|             | 1.972       | 18.33%          | 1.459           | 21.59%        |
|             | 1.697       | 15.78%          | 1.220           | 19.42%        |
| Zunyi       | 1.239       | 19.79%          | 0.732           | 10.24%        |
|             | 1.167       | 18.64%          | 0.711           | 8.64%         |
|             | 1.119       | 13.40%          | 0.673           | 9.26%         |
| Guiyang     | 2.294       | 22.66%          | 1.736           | 16.07%        |
|             | 2.336       | 23.08%          | 1.734           | 15.55%        |
|             | 1.702       | 16.82%          | 1.298           | 12.56%        |

¹Hargreaves and Samani (1982); ²Hargreaves et al. (1985); ³Bristow and Campbell (1984); ⁴Chen et al. (2004); ⁵See Eqn. (7)
### TABLE 5
The relative improvement of Root mean square error (RIrmse) and mean absolute bias error (RImabe) of the two-step method over the temperature-based models

| Station  | H-S model | H-Sm model | B-C model | Chen model | Local Rs model |
|----------|------------|------------|-----------|------------|---------------|
|          | RIrmse     | RImabe     | RIrmse    | RImabe     | RIrmse        |
| Chengdu  | 11.30%     | 12.83%     | 3.10%     | 0.27%      | 2.96%         |
| Chongqing| 43.94%     | 46.73%     | 11.11%    | 16.21%     | 26.84%        |
| Changsha | 36.06%     | 36.05%     | 24.54%    | 23.10%     | 27.66%        |
| Hefei    | 19.11%     | 14.16%     | 16.17%    | 13.00%     | 13.94%        |
| Hangzhou | 15.23%     | 12.95%     | 5.21%     | 4.28%      | 7.76%         |
| Lijiang  | 36.12%     | 41.58%     | 12.36%    | 15.51%     | 21.83%        |
| Nanchong | 4.08%      | 14.71%     | 1.58%     | 3.56%      | 1.68%         |
| Nanchang | 34.62%     | 33.09%     | 31.99%    | 27.33%     | 32.18%        |
| Nanjing  | 14.68%     | 11.09%     | 16.64%    | 12.26%     | 16.19%        |
| Shanghai | 6.27%      | 10.69%     | 4.78%     | 9.29%      | 5.32%         |
| Wuhan    | 26.32%     | 23.10%     | 32.30%    | 26.28%     | 31.34%        |
| Yichang  | 19.85%     | 16.12%     | 13.52%    | 15.64%     | 14.94%        |
| Zunyi    | 34.40%     | 16.85%     | 4.91%     | 21.00%     | 17.07%        |
| Guiyang | 29.29%     | 31.07%     | 26.44%    | 25.15%     | 26.64%        |

*Hargreaves and Samani (1982); aHargreaves et al. (1985); c Bristow and Campbell (1984); d Chen et al. (2004); e See Eqn. (7)*

\[
\text{RRMSE} = 100 \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2} 
\]

\[
\text{MABE} = \frac{1}{n} \sum_{i=1}^{n} |y_i - \hat{y}_i| 
\]

\[
\text{MAPE} = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{y_i - \hat{y}_i}{y_i} \right| 
\]

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. Lower values of RMSE, RRMSE, MABE, and MAPE indicate a better estimation accuracy of the model.

The relative improvement of RMSE (RIrmse) and MABE (RImabe) were used to measure the improvement of the evaluated model accuracy over the reference model accuracy:

\[
\text{RIrmse} = \frac{\text{RMSE}_r - \text{RMSE}_e}{\text{RMSE}_r} 
\]

\[
\text{RImabe} = \frac{\text{MABE}_r - \text{MABE}_e}{\text{MABE}_r} 
\]

where, RMSEr and MABEr are the root mean square error and mean absolute bias error for the reference model, respectively. RMSEE and MABEE are the root mean square error and mean absolute bias error for the evaluated model, respectively. Higher values of RIrmse and RImabe indicate a better improvement over the reference model.

### 3. Results and discussion

#### 3.1. Performances of the temperature-based models

The performances of the five temperature-based models are presented in Table 4. Overall, all the temperature-based models give good performances with the RRMSE < 25% (averaged 18.28%) and MAPE < 23% (average 14.94%). The H-Sm, Chen and local Rs models give quite similar values of RMSE (averaged 1.872, 1.871, 1.867 MJ m\(^{-2}\), respectively), RRMSE (averaged 17.72%, 17.96%, 17.69%, respectively), MABE (averaged 1.409, 1.399, 1.386 MJ m\(^{-2}\), respectively), and MAPE (averaged 13.79%, 13.80%, 13.40%, respectively). These three models have similar equation expressions, they
differ in the form of the term $T_{\text{max}}-T_{\text{min}}$, namely, the square root of $T_{\text{max}}-T_{\text{min}}$, logarithm of $T_{\text{max}}-T_{\text{min}}$, and $T_{\text{max}}-T_{\text{min}}$ for the H-Sm, Chen model, and local $R_s$ model, respectively. However, they give nearly identical performances according to the indicators of RMSE, RRMSE, MABE and MAPE, indicating that the variations of term $T_{\text{max}}-T_{\text{min}}$ are generally not very effective and gave no significant improvement. Evidently, the modified H-S model (H-Sm model) by adding a empirical parameter outperforms the original H-S model, in terms of RMSE, the accuracy could be on average 11.41% higher, and at some sites (Chongqing, Lijiang and Zunyi), the accuracy could be 27-36% higher.

3.2. Performance of the two-step method

Despite the simplicity and significant performance of A-P model, it is often limited by the lack of available sunshine duration records. Therefore, in the present work, an attempt has been made to estimate sunshine duration by local $S$ model [Eqn. (9)] using air temperature. Consequently, the estimated sunshine duration is used as input for A-P model to estimate solar radiation, and the performance is presented in Table 4. We have named this method as two-step method. Such a method has not been studied before, which may be contributed to the lack of study on the relationship between the air temperature and sunshine duration. Another reason may be that there are two estimation processes which may largely decrease the performance accuracy. However, in the present work, the two-step method gives good performance with the RMSE $< 2$ MJ m$^{-2}$ (averaged 1.568 MJ m$^{-2}$), RRMSE $< 20\%$ (averaged 14.46%), MABE $< 1.5$ MJ m$^{-2}$ (averaged 1.184 MJ m$^{-2}$), and MAPE $< 20\%$ (averaged 11.96%) as shown in Table 4. Therefore, it could be used to estimate solar radiation in Yangtze River basin.

3.3. Comparison of the two-step method between temperature-based models

Performance comparisons of the two-step method and temperature-based models given in Table 4 shows that the two-step method gives the lowest RMSE of 1.525 ± 0.424 MJ m$^{-2}$ (averaged 1.568 MJ m$^{-2}$), RRMSE of 12.62% ± 4.22% (averaged 14.46%), MABE of 1.068 ± 0.395 MJ m$^{-2}$ (averaged 1.184 MJ m$^{-2}$), and MAPE of 12.98% ± 6.43% (averaged 11.96%) within the same station. The results of studies on relative improvement of the two-step method over the temperature-based models are presented in Table 5. Evidently, the two-step method significantly outperforms the temperature-based models, with the averaged RLRmse of 23.66%, 17.60%, 14.64%, and 14.06%, Rlmabe of 22.93%, 15.21%, 19.98%, 14.13%, and 13.36% over H-S, H-Sm, B-C, Chen and Local $R_s$ model, respectively. These results further confirm that the two-step method can significantly improve the estimation accuracy over the temperature-based models which directly estimate solar radiation using air temperature only.

3.4. Determination of model parameters

The two-step method has substantial potential for application in solar radiation estimation due to the greater availability of air temperature data and the significant performance, but it requires the long-term observations of solar radiation and sunshine duration to calibrate the parameters, including the parameters of the A-P model and local $S$ model. Generally, the parameters of two-step method (a, b of A-P model and a, b, c of local $S$ model in Table 3) vary from station to station as shown in Table 3, namely, they are site dependent. And it is therefore open to question how transferable these calibration values are to other locations without measured solar radiation and sunshine duration data for calibration. No literature has reported the use of uniform set of determination equations of the parameters in a large area. Therefore, in the present work, based on the investigation of the relation between the parameters and geographical information (longitude, latitude and altitude in Table 1), mean daily extraterrestrial radiation and solar radiation, we propose the determination equations of parameters of the two-step method in Yangtze River basin as follows:

For the parameters of A-P model, the determination equations are:

\[
a = -0.3494 \sin(\phi) - 1.1321 \sin(\lambda) - 0.1311 \frac{\sin(\phi)}{\cos(\lambda)} + 3.306 \times 10^{-6} \beta + 1.1636
\]  
\[
b = -0.5082 \sin(\phi) + 0.1458 \sin(\lambda) - 0.0106 \frac{\sin(\phi)}{\cos(\lambda)} - 1.6108 \times 10^{-5} \beta + 0.7168
\]

For the parameters of local $S$ model, the determination equations are:

\[
a = -0.0279 \phi + 5.8570 \times 10^{-4} \lambda - 0.0771 Ra + 0.5057 S_0 - 3.3985 \times 10^{-5} \beta - 2.7931
\]  
\[
b = 0.0323 \phi - 6.3304 \times 10^{-4} \lambda + 0.0956 Ra - 0.6195 S_0 + 3.2338 \times 10^{-5} \beta + 3.4581
\]  
\[
c = 0.0767 \phi + 4.0649 \times 10^{-3} \lambda - 0.0916 Ra - 0.7524 S_0 + 1.7810 \times 10^{-4} \beta + 3.1221
\]
where, $\varphi$, $\lambda$, $\beta$, $R_a$ and $S_o$ are the latitude (rad), longitude (rad), altitude (m), mean daily extra-terrestrial solar radiation and maximum possible sunshine duration (h), respectively.

The determined parameters by the corresponding equation are presented in Table 6. It is found that, in general, the parameters determined by these equations are relatively close to the corresponding values (Table 3) calibrated from the data set, indicating that these determination equations give good performances, with the RMSE of 0.015, 0.010, 0.006, 0.006, and 0.022, RRMSE of 2.59%, 8.33%, 2.64%, and 9.98% for parameter a, b, c of local S model, respectively. Therefore, they could be used to determine the parameters of the two-step method.

### TABLE 6

Empirical parameters of the two-step method determined by the corresponding determination equation

| Station   | A-P model $^a$ | Local S model $^b$ | RMSE   | RRMSE   | MABE    | MAPE   |
|-----------|----------------|-------------------|--------|---------|---------|--------|
| Chengdu   | 0.569          | 0.055             | -0.051 | -2.07%  |         |        |
| Chongqing | 0.583          | 0.064             | -0.058 | -2.61%  |         |        |
| Changsha  | 0.597          | 0.084             | -0.076 | -3.39%  |         |        |
| Hefei     | 0.565          | 0.066             | -0.062 | -1.44%  |         |        |
| Hangzhou  | 0.576          | 0.076             | -0.071 | -2.11%  |         |        |
| Lijiang   | 0.566          | 0.065             | -0.074 | -1.17%  |         |        |
| Nanchong  | 0.572          | 0.056             | -0.052 | -1.94%  |         |        |
| Nanchang  | 0.592          | 0.083             | -0.076 | -3.10%  |         |        |
| Nanjing   | 0.563          | 0.061             | -0.056 | -1.11%  |         |        |
| Shanghai  | 0.568          | 0.073             | -0.068 | -1.66%  |         |        |
| Wuhan     | 0.577          | 0.071             | -0.065 | -2.19%  |         |        |
| Yichang   | 0.576          | 0.065             | -0.060 | -2.07%  |         |        |
| Zunyi     | 0.590          | 0.057             | -0.051 | -2.52%  |         |        |
| Guiyang   | 0.595          | 0.058             | -0.051 | -2.71%  |         |        |
| RMSE      | 0.015          | 0.006             | 0.006  | 0.022   |         |        |
| RRMSE     | 2.59%          | 7.06%             | 8.33%  | 2.64%   | 9.98%   |        |

$^a$ Ångström (1924); Prescott (1940); $^b$ See Eqn. (9); $^c$ See Eqn. (16); $^d$ See Eqn. (17); $^e$ See Eqn. (18); $^f$ See Eqn. (19); $^g$ See Eqn. (20)

### TABLE 7

Root mean square error (RMSE in MJ m$^{-2}$), Relative root mean square error (RRMSE), Mean absolute bias error (MABE in MJ m$^{-2}$) and mean absolute percentage error (MAPE) of the two-step method with the parameters determined by the corresponding determination equation

| Station   | RMSE  | RRMSE | MABE  | MAPE  |
|-----------|-------|-------|-------|-------|
| Chengdu   | 1.593 | 18.50%| 1.371 | 18.70%|
| Chongqing | 1.261 | 14.48%| 0.981 | 11.67%|
| Changsha  | 1.723 | 16.09%| 1.357 | 13.81%|
| Hefei     | 1.597 | 13.10%| 1.131 | 9.08% |
| Hangzhou  | 2.282 | 19.54%| 1.741 | 15.79%|
| Lijiang   | 1.431 | 8.51% | 1.124 | 6.66% |
| Nanchang  | 1.034 | 11.16%| 0.722 | 8.39% |
| Nanjing   | 1.770 | 14.90%| 1.424 | 12.54%|
| Shanghai  | 1.417 | 11.89%| 1.106 | 9.35% |
| Wuhan     | 1.858 | 16.29%| 1.436 | 12.88%|
| Yichang   | 1.665 | 15.48%| 1.207 | 19.22%|
| Zunyi     | 1.430 | 17.14%| 1.119 | 14.22%|
| Guiyang   | 1.921 | 18.97%| 1.481 | 13.98%|

consequently used to estimate $S/S_o$, which is later used as input to estimate solar radiation by A-P model using the parameter a determined by Eqn. (16) and b by Eqn. (17), and the performances are presented in Table 7 and Fig. 2. Good performance of the two-step method is found, with the RMSE < 2.5 MJ m$^{-2}$ (averaged 1.623 MJ m$^{-2}$), RRMSE < 20% (averaged 15.04%), MABE < 1.8 MJ m$^{-2}$ (averaged 1.253 MJ m$^{-2}$), MAPE < 20% (averaged 12.67%) and $R^2 > 0.8$(averaged 0.881). And there is a substantially good agreement between the estimated and observed values as shown in Fig. 2, where the points tend to line up around the 1:1 line, further indicating that the estimated solar radiation are close to the observed. Therefore, the two-step method with the parameters determined by equations could be used to estimate solar radiation in Yangtze River basin.

### 4. Conclusion

Solar radiation is an essential and important variable for use in many simulation models. Estimation of solar radiation from other commonly measured meteorological variables is generally done when direct measurement are not readily available. In this work, we present the two-step method to estimate solar radiation from the commonly measured air temperature, namely, estimate sunshine
Fig. 2. Scatter plots of the observed vs estimated solar radiation at 14 stations in Yangtze River basin.
duration by local $S$ model [Eqn. (9)] using air temperature firstly, consequently, the estimated sunshine duration is used as inputs for A-P model to estimate solar radiation. The model performance indicators of RMSE, RRMSE, MABE, and MAPE illustrate that the two-step method gives good results. Further comparisons show that the two-step method significantly outperforms the temperature-based models. Therefore, it could be used to estimate solar radiation in Yangtze River basin, and it can significantly improve the estimation accuracy over the temperature-based models which directly estimate solar radiation using air temperature only.

We believe that the proposed two-step method has substantial potential for direct application in solar radiation estimation due to the greater availability of air temperature data and it significant improved performance over the temperature-based models. Therefore, the determination equations of parameters of the two-step method are proposed for Yangtze River basin. They give good performances in terms of RMSE and RRMSE. Consequently, the two-step method using the estimated parameters is further evaluated, and it is found that the estimated values agree well with the measured solar radiation. Therefore, the two-step method with the parameters determined by the equations as proposed in the paper could be used in Yangtze River basin, and it is believed to be particularly useful for the sites where no solar radiation and sunshine duration data is available, whereas the air temperatures are commonly measured.

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