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Empirical models for estimating monthly global solar radiation: A most comprehensive review and comparative case study in China

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Abstract: Global solar radiation is a core component of scientific research and engineering application across a broad spectrum. However, its measurement is limited by a small number of observation stations due to the technical and financial restricts. Estimating solar radiation with the meteorological variables using empirical models is of benefit to obtain solar radiation data at global scale. Yet, there are various options of available empirical models to select the most suitable one. This study conducted a most comprehensive collection and review of empirical models employing the commonly measured meteorological variables and geographic factors. A total of 294 different types of empirical models were collected and classified into 37 groups according to input attributes. Such collection built an empirical model library providing an overall overview of the developed emperical models in literatures. Furthermore, the collected models were calibrated and evaluated at three meteorological stations in the Three Gorges Reservoir area in China. This study suggests that these model-comparing processes can assist the governments, scientists and engineers in tailoring the most fitted model for specific applications and in particular areas.

Keywords: Global solar radiation, empirical models, meteorological variables, comparisons, Three Gorges Reservoir

Nomenclature

φ	Latitude of the site (rad)
$K\varphi$	Altitude factor
λ	Longitude of the site (rad)
Z	Altitude of the site (m)
δ	Declination angle (rad)
n	The day of year
L	Mahmood-Hubbard transmissibility coefficient
Rs	Global solar radiation (MJ m^{-2})
Ra	Extraterrestrial solar radiation (MJ m^{-2})
S	Sunshine duration (h)
S_0	Potential sunshine duration (h)
Sn	Adjusted potential sunshine duration taking into account the natural horizon (h)
S_{04}	4^o corrected potential sunshine duration (h)
T	Average air temperature (℃)
Tmin	Minimum air temperature (℃)
Tmax	Maximum air temperature (℃)
∆T	Difference between maximum and minimum air temperatures (℃)
Rh	Relative humidity (%)
P	Precipitation (mm)
Pa	The transformed precipitation data
Ap	Atmospheric pressure (Kpa)
Aps	Standard sea level atmospheric pressure (KPa)
Vp	Vapor pressure (Kpa)
Es	Saturation vapor pressure (Kpa)
D	Vapor pressure deficit (Kpa)
Wv	wind velocity (m/s)
Wa	Atmospheric precipitable water vapor per unit volume of air (cm)
a, b_i, c_i, d_i, e_i, f_i and g_i	Empirical coefficients

1 Introduction

Global solar radiation is the principal and fundamental energy for many Earth’ surface and atmospheric processes such as plant photosynthesis and evapotranspiration [1-3]. It regulates the Earth’ temperature, while spatiotemporal variation of the radiation is the primary driver for global climate change [4]. Moreover, due to the global issues such as global warming [5] and environmental pollution [6] caused by the consumption of the fossil fuels [7-8], solar radiation has attracted increasing attentions as a clean, environmental-friendly, and inexhaustible energy [9-11], particularly in China. In the process of building agricultural [12], environmental [13], hydrological and ecological models [14], the global solar radiation is a critical variable. It is also crucial for designing solar furnaces [15], concentrating solar collectors [16] and sizing photovoltaic cells [17]. However, measurement of solar radiation is limited by a limited number of observation stations mainly due to the financial and technical limitations [18-20]. Lack of sufficient solar radiation data has been reported worldwide [21-23]. On the contrary, sunshine duration, air temperatures and other common meteorological variables are routinely measured at most stations [24-26]. Therefore, great efforts have been made to estimate global solar radiation from meteorological variables by means of empirical models [27-29].

Estimation of global solar radiation was initiated by Angstrom [30] and Prescott [31] who introduced the Angstrom-Prescott (A-P) model. This model was widely validated and evaluated at many locations around the world. Besharat et al [2] compared the accuracy of many A-P equations with different empirical coefficients in Iran. Giwa et al [8] validated the A-P model in Nigeria. Chukwujindu [10] evaluated the accuracy of A-P equations in Africa. Yao et al [32] evaluated the performance of A-P model in China. Several revised versions of the A-P model have been suggested by changing the structure of A-P model from linear to quadratic [33], cubic [34], exponential [35] or logarithmic [36]. The comparative studies indicated that some revised versions performed similarly to the A-P model [37]. Mohammadi et al [38] evaluated the accuracy of linear, quadratic, cubic and exponential models in Iran, and they found that these models had similar performances. Teke and Yildirim [39] estimated solar radiation using linear, quadratic and cubic models, and the evaluations showed that these models performed similarly in Eastern Mediterranean Region. Meher et al [40] compared the linear, quadratic, cubic, logarithmic and exponential models, and reported the insignificant difference among these models. Consequently, many modifications to the A-P model have been made by incorporating additional meteorological variables. Lee [41] and Saffaripour et al [42] incorporated air temperature and modified the A-P model. Bakirci Kadir [43] introduced relative humidity in an additive form and suggested a new form. Liu et al [44] revised the A-P using atmospheric pressure. Chen and Li [20] modified the A-P model using precipitation. Fan et al [45] introduced the combination of air temperature and precipitation to the A-P model. Okonkwo and Nwokoye [46] modified the A-P model using air temperature, relative humidity and precipitation.

Sunshine duration models are often limited due to the unavailability of sunshine duration data [47-48]. To solve this problem, Hargreaves and Samani [49] proposed a simple model (H-S model) using air temperature range (difference between minimum and maximum air temperatures). This model was widely modified by others [50]. Chen and Li [20] and Hassan et al [51] introduced the effect of precipitation to modify the H-S model. Li et al [52] and Korachagaon and Bapat [53] revised the H-S model using relative humidity. Chen et al [54] modified the H-S model using atmospheric pressure, relative humidity and precipitation. Bristow and Campbell [55] developed a model (B-C model) as exponential function of temperature range. Many modifications to the B-C model have subsequently been made, and most modifications are centered on the adjustment of the coefficients. However, comparative studies suggested that such modifications yielded little improvement [56]. Although the H-S and B-C models are empirically derived, they were based on the theoretical assumption that temperature range is mainly derived by the radiation [57]. Many validations showed that the performances of H-S and B-C models and their modifications varied greatly from regions to regions, and the accuracies were affected by the geographic location and local climates [56].

In addition to the two categories of the models reviewed above, some scholars have explored the estimation of solar radiation using relative humidity, precipitation and atmospheric pressure which are also easily and widely available. Kolebaje et al [58] presented a power model using relative humidity for West Africa. Adaramola [59] developed a linear model using precipitation. Kamal [60] obtained a linear model using atmospheric pressure. Akpabio et al [61] proposed a multivariate linear model using relative humidity and precipitation in Nigeria.

Huge efforts have been made to estimate solar radiation with empirical model. However, it is still a challenging task to develop better accuracy models due to the complex process of radiation [62]. Because long-term meteorological data are easily available, it is preferred to select a suitable model for particular regions instead of developing new models. However, the number of the empirical models is so large that it is difficult to choose the most appropriate one [5]. Thus, several studies have reviewed the empirical models from literatures. Yildirim et al [1] investigated the efficiency of 10 different models for estimating solar radiation in Turkey. Besharat et al [2] comprehensively reviewed 78 empirical models for the selection of most accurate one for Iran. Despotovic et al [5] evaluated 101 sunshine duration models using long term meteorological data throughout the world. Bayrakci et al [9] compared 105 empirical models from literatures and 7 new models and proposed the most appropriate one for Turkey. Chukwujindu [10] reviewed 65 empirical models which were classified into six categories according to the input meteorological variables. Yildirim et al [13] presented a quantitative collection of empirical models based on different meteorological variables and suggested the most accurate model in Turkey. Mohamed et al [21] evaluated 11 different empirical models and introduced the best one for Africa. Zhang et al [22] conducted a critical literature review and compared the models for estimation of solar radiation at different scales. Yao et al [32] evaluated the accuracy of 118 equations at Shanghai in China. Bakirci [63] reviewed 60 different solar radiation models in the literature. Evrendilek and Ertekin [64] compared 78 different empirical models and selected the most robust one for Turkey. Later, Sonmete et al [65] examined 147 solar radiation models and proposed the best one for Turkey.

In these reviews, many equations have the same formulas just with different coefficients. Besharat et al [2] reviewed 64 equations using sunshine duration. These equations were classified into 35 models. Chukwujindu [10] collected 732 equations which can be classified into 65 models. The 105 sunshine duration models reviewed by Bayrakci et al [9] can be classified into 12 models according to the mathematical expression. Similarly, the 101 models reviewed by Despotovic et al [5] can be classified into 20 models. The 118 equations compared by Yao et al [32] can be classified into 14 models. However, after a most comprehensive investigation of a large number of literatures, we collected 294 different empirical models which can be classified into 37 groups according to the input variables. This indicates that those reviews only presented a small portion of the empirical models and further suggests a more comprehensive study.

Therefore, the main objective of this study is to conduct a most comprehensive collection and review of the empirical models based on the commonly measured meteorological variables including sunshine duration, average temperature, minimum temperature, maximum temperature, relative humidity, precipitation, atmospheric pressure, vapor pressure, and wind velocity. In addition, geographic factors including the latitude, longitude, and altitude of the site, solar declination angle, and the day of the year are easily available. Thus, models employing these geographic factors are also presented in this study. Such comprehensive review would build a model library providing an overview of the developed empirical models in literatures. Furthermore, in order to compare the performances of the collected models, these models are validated and evaluated at three meteorological stations in Three Gorges Reservoir Area (TGRA), China. This would be helpful for researchers and engineers to tailor the most fitted model for applications in agriculture, climate, ecology and energy studies.

2 Materials and method

2.1 Case study area

TGRA (Fig.1) is located at the upstream of the Yangtze River in China, to the east of Sichuan Basin, to the north of Daba Mountain, and bordering the western Middle-Lower Yangtze river plain. It stretches along the Yangtze River from Jiangjin county in Chongqing municipality to Yichang city in Hubei province, with the area of 5.8×10^4 km^2 [66]. The geography is complex and the elevation generally decreases from northeast to southwest [67]. The region is dominated by mountainous and hilly areas [68]. TGRA is located in the transfer zone between the northern temperate zone and the subtropical zone. The climate of TGRA is subtropical monsoon climate which is characterized by four distinct seasons with a hot, humid summer, and mild to cool winter [24]. Annual mean temperature is between 16.5℃and 19℃, and annual precipitation is about 1100mm 69 [66].

2.2 Sites and data collection

Three stations with available records of global solar radiation and meteorological variables were used in this work (Fig.1). The observed meteorological variables include sunshine duration, maximum temperature, minimum temperature, average temperature, relative humidity, precipitation, atmospheric pressure, vapor pressure, and wind velocity. Chongqing station (29^o 35′N and 106^o 28′ E) lies at 259.1m above sea level located in the upper section of TGRA. Yichang station (30^o 42′N and 111^o 18′ E) is located at about 30 km near from the Three Gorges Dam (TGD), with the altitude of 133.1m. Wanzhou station (30^o 46′N and 108^o 24′ E) lies at 186.7m above sea level located in the middle section of TGRA.

The meteorological observations started from 1961 at the three sites, while the measurements of global solar radiation at Wanzhou are missing since 1991 due to the technical failure [70-71]. Monthly meteorological data for Chongqing and Yichang

(1977-2016) and Wanzhou (1961-1990) were obtained from the Chinese National Meteorological Information Center (NMIC), China Meteorological Administration (CMA). Global solar radiation (MJ m^{-2}) was measured by Pyranometer [72-73]. Sunshine duration (h) was measured by Jordan sunshine recorder. Air temperatures (℃) was measured by mercury and alcohol thermometers. Atmospheric pressure (Kpa) was measured by mercury barometer. Vapor pressure (Kpa) was measured by adjustable cistern barometer. Relative humidity(%) was measured by aspirated psychrometer at 2m height [74-75]. Wind velocity(m/s) was measured by EL wind electric anemometer at 10m height, which was transformed to speed at 2m height by a logarithmic model proposed by FAO56 [76]. All the instruments were calibrated periodically and all the meteorological variables were measured following the standardized procedures recommended by the WMO [73].

2.3 Data check and datasets split

The quality controls were carefully conducted by the CMA, while meteorological measurements can still contain errors due to the occasional voltage instability and equipment errors [77]. Previous studies pointed out that quality control of meteorological data provided by NMIC should be conducted before the usage of these data [78]. Consequently, we further checked the data following the criterions from the quality control scheme presented by Feng et al [79] and Tang et al [80]. First, the records with missing data which were replaced by 32766 were removed. Second, global solar radiations exceeding extra-terrestrial radiation were excluded from the dataset. Then, sunshine duration larger than potential sunshine duration were also deleted. Third, minimum air temperature larger than maximum air temperature were removed. Lastly, the data with evident systematic and operational errors were removed. More details can be found in Feng et al [79] and Tang et al [80].

Two sub-datasets were subsequently built for each station, and the first 75% of the records were used for modelling and the remaining 25% for evaluation. 30-years long modelling data (1977-2006) were used for Chongqing and Yichang sites, and this is because that 30-years long time series is enough to filter out the inter-annual variation or anomalies according to WMO. Thus, the model describing the relationship between solar radiation and meteorological variables based on the 30-years long data would exhibit a higher degree of reliability and confidence. While 22-years long modelling data (1961-1982) were used for Wanzhou site.

2.4 Description of observed meteorological data

Distributions of the monthly meteorological variables of the three stations are presented in Fig.2. Monthly daily solar radiation varied between 4.25MJ m^{-2} in December and 16.03MJ m^{-2} in July, with the average of 9.7 MJ m^{-2}. Monthly daily sunshine duration varied between 1.46 h in January and 6.27h in August, with the average of 3.46h (Fig.2a). Maximum, minimum and average temperatures, which ranged from 9.74 to 33.16℃, from 4.14 to 24.54℃and from 6.51 to 28.17℃, respectively, show similar change patterns with the warmest month in July and the coldest month in January (Fig.2b). Vapor pressure varied between 0.78 kPa in January and 2.93 kPa in July, which was generally opposite to that of atmospheric pressure with the minimum of 97.9 kPa in July and the maximum of 100.09 kPa in December (Fig.2c). Monthly precipitation varied between 18.72cm and 197.32cm, with the maximum in July and the minimum in January (Fig.2d). Relative humidity ranged between 75.98% and 81.66%, and wind velocity ranged between 0.9m/s and 1.24m/s (Fig.2e), without clear seasonal pattern.

2.5 Statistical evaluation and validation

The accuracy and performances of the collected models were evaluated and compared using root mean square error (RMSE) and relative root mean square error (RRMSE) (%). These indicators are widely used to evaluate model performances and thus provide a benchmark to compare models from literatures. Lower values of RMSE and RRMSE indicate a better performance. They were calculated from the following equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_{i,m} - y_{i,p})^2}{n}} \quad (1)$$

$$RRMSE(\%) = 100\sqrt{\frac{\sum_{i=1}^{n}(y_{i,m} - y_{i,p})^2}{n y_{i,m}}} \quad (2)$$

Where n, $y_{i,m}$, and $y_{i,p}$ represent the number of testing data, the measured value and the estimated value, respectively.

3 Model review

A large number of empirical models have been developed for estimation of global solar radiation. The first attempt was conducted by Angstrom [30] who suggested a linear relationship between the ratio of global solar radiation to the corresponding value on a clear day and sunshine fraction. Prescott [31] modified the Angstrom model by replacing the solar radiation on a clear day with the extraterrestrial radiation. The extraterrestrial radiation and potential sunshine duration were calculated using the equations detailed by Allen et al [76].

$$Ra = 37.6d(\omega \sin\sin\delta + \cos\cos\delta\sin\omega) \quad (3)$$

$$d = 1 + 0.033\cos\left(\frac{2\pi}{365}n\right) \quad (4)$$

$$\delta = 0.4093\sin\left(\frac{2\pi}{365}n - 1.39\right) \quad (5)$$

$$\omega = \arccos(-\tan\varphi\tan\delta) \quad (6)$$

$$So = 24\omega/\pi \quad (7)$$

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), and n is the number of the day of year starting from the first of January.

After a comprehensive investigation and review of the literatures, a total of 294 empirical models using different combinations of the meteorological variables and geographic factors were found and presented in Table 1. Meteorological variables employed in the models include sunshine duration, average temperature, maximum temperature, minimum temperature, relative humidity, precipitation, atmospheric pressure, vapor pressure and wind velocity. These variables are routinely measured by CMA and datasets are easily available from the Chinese NMIC (http://data.cma.cn). Besides, geographic factors including the latitude, longitude, and altitude of the site, solar declination angle, and the day of the year are also easily available. These models were classified into 37 groups according to the input variables.

3.1 Group 1: sunshine duration (S) models

Sunshine duration models are the most widely used empirical relationships as the result of their promising performances. 28 S models were collected from literatures and presented in Table 1, and most of these models related the clearness index (ratio of global solar radiation to extraterrestrial radiation) to sunshine fraction. The most well-known one in this group is the A-P model. Many revised versions of the A-P model have been developed by changing the structure of A-P model from linear to quadratic [33], cubic [34], high order [81], exponential [35], logarithmic [36], trigonometric [82] and hybrid forms [83-84]. These models were widely calibrated and evaluated at many locations around the world.

3.2 Group 2: sunshine duration - temperature (ST) models

21 ST models were found in literatures, and most of them were modifications to the A-P model by introducing average temperature [85], maximum temperature [86], minimum temperature [85], temperature range [20] and the combinations of temperatures [20,85]. Some other models were proposed as the exponential [87], quadratic and cubic [88] or hybird functions [89] of the ratio of temperature range to potential sunshine duration.

3.3 Group 3: sunshine duration - relative humidity (SR) models

In this model group, sunshine duration and relative humidity were incorporated with solar radiation or clearness index in the forms of linear [42], quadratic [43] and power [90] functions.

3.4 Group 4: sunshine duration - precipitation (SP) models

Chen and Li [20] introduced precipitation in an additive form to A-P model and presented a SP model in China.

3.5 Group 5: sunshine duration - pressure (SPr) models

Models in this group related the clearness index or solar radiation to the combinations of sunshine duration, atmospheric pressure and vapor pressure [44, 91].

3.6 Group 6: sunshine duration - geographic factors (SG) models

The empirical coefficients of sunshine duration models varied from one site to another. Thus, geographical factors were included to account for the effect of geographical location, and to modify the relationship between solar radiation and meteorological variables. Most of the models in this group are modifications to sunshine duration models by introducing geographical factors in linear [92-94], trigonometric [95] and hyprid function [93-94]. Because the latitude, longitude and altitude are constants for a specific site, they were employed to develop universal models using the pooled data from all the studied sites. A total of 30 SG models were collected and presented in Table 1.

3.7 Group 7: sunshine duration - temperature - relative humidity (STR) models

17 STR models were collected from literatures. Models in this group are modifications to sunshine duration model by introducing the linear [96-97] and nonlinear [98] combinations of temperatures and relative humidity, and most of the modifications are based on the A-P model.

3.8 Group 8: sunshine duration - temperature - precipitation (STP) models

In this group, sunshine duration, temperatures and precipitation were incorporated with clearness index for estimation of solar radiation in the forms of linear [20, 46], quadratic and cubic [99] and hybird [45] functions.

3.9 Group 9: sunshine duration - temperature - pressure (STPr) models

In this group, clearness index or solar radiation was correlated with the combinations of sunshine duration, temperature and pressure in the forms of linear [20], power [54] and hybrid [44] functions.

3.10 Group 10: sunshine duration - relative humidity - precipitation (SRP) models

Saffaripour et al [42] developed a SRP model for estimation of solar radiation using extra-terrestrial solar radiation, sunshine fraction, relative humidity and precipitation.

3.11 Group 11: sunshine duration - temperature - geographic factors (STG) models

Models in this group related solar radiation to the combinations of sunshine fraction, temperature and geographic factors in the form of hybrid function [99].

3.12 Group 12: sunshine duration - temperature - relative humidity - precipitation (STRP) models

In this group, sunshine duration, temperatures, relative humidity and precipitation were incorporated with clearness index for estimation of solar radiation [100].

3.13 Group 13: sunshine duration - temperature - relative humidity - pressure (STRPr) models

Models in this group are modifications to the A-P model by introducing the linear combinations of temperatures, relative humidity and pressure as an additive form [25, 101].

3.14 Group 14: sunshine duration - temperature - precipitation - pressure (STPPr) models

Chen et al [54] presented a hybrid model for estimation of solar radiation using extra-terrestrial solar radiation, sunshine fraction, temperature range, precipitation and vapor pressure deficit.

3.15 Group 15: sunshine duration - temperature - relative humidity - wind (STRW) models

Adeala et al [102] modified the A-P model by introducing the linear combinations of average temperature, relative humidity and wind velocity.

3.16 Group 16: sunshine duration - temperature - relative humidity - geographic factors (STRG) models

In this group, geographic factors were included to modify the relationship between solar radiation and sunshine duration, temperature, and relative humidity. 13 STRG models were collected from literatures and presented in Table 1, and most of them are modifications to STR model by introducing geographical factors in trigonometric [99] and hyprid functions [103].

3.17 Group 17: sunshine duration - temperature - precipitation - geographic factors (STPG) models

Chen et al [99] modified the A-P model using the linear combinations of air temperature, precipitation, latitude, longitude and altitude and suggested 5 STPG models.

3.18 Group 18: sunshine duration - temperature - relative humidity - precipitation - pressure (STRPPr) models

In this group, sunshine duration, temperatures, relative humidity, precipitation and pressure were incorporated with clearness index or solar radiation in the form of hybrid function [45].

3.19 Group 19: sunshine duration - temperature - relative humidity - precipitation - wind (STRPW) models

Ouali and Alkama [104] modified the A-P model by introducing the temperature, relative humidity, precipitation and wind velocity and presented a multivariate linear and a hybrid function.

3.20 Group 20: sunshine duration - temperature - relative humidity - precipitation - geographic factors (STRPG) models

In this group, declination angle and the day of year were used to modify the relationship between solar radiation and sunshine duration, temperature, relative humidity, and precipitation [105].

3.21 Group 21: temperature (T) models

Numerous evaluations showed that the sunshine-based models (sunshine duration models and their modifications) are generally more accurate than temperature-based models (temperature models and their modifications) [2, 21, 47]. However, the sunshine-based models are often limited since sunshine duration data are often not accessible [47-48]. On the contrary, air temperatures data are easily and widely available. In this context, Hargreaves and Samani [49] proposed the H-S model using air temperature range. Using the same data input as by Hargreaves and Samani [49], Bristow and Campbell [55] suggested the B-C model. Both models were widely calibrated and evaluated, and many revised versions of H-S and B-C models were subsequently developed and validated at many places around the world. A total of 64 temperatures models were collected and presented in Table 1.

3.22 Group 22: temperature - relative humidity (TR) models

19 TR models were collected from literatures. In this group, relative humidity was introduced as an additive form [20, 58] and multiplicative form [52, 106] to modify the correlation between solar radiation and air temperatures.

3.23 Group 23: temperature - precipitation (TP) models

In this group, temperature and precipitation were incorporated with clearness index or solar radiation for estimating global solar radiation [56, 107].

3.24 Group 24: temperature-pressure (TPr) models

Models in this group related the clearness index or solar radiation to the combinations of temperature, atmospheric pressure and vapor pressure [20].

3.25 Group 25: temperature - geographic factors (TG) models

In this group, declination angle, the day of year and the altitude were used to modify the correlation between solar radiation and temperatures [105].

3.26 Group 26: temperature - relative humidity - precipitation (TRP) models

In this group, global solar radiation was correlated with the combinations of temperature, relative humidity and precipitation in the forms of quadratic [96], power [108] and hybrid functions [56].

3.27 Group 27: temperature - relative humidity - pressure (TRPr) models

Chen and Li [20] modified the H-S model and Li model [107] by introducing the relative humidity, atmospheric pressure and vapor pressure in an additive form.

3.28 Group 28: temperature - relative humidity - geographic factors (TRG) models

In this group, declination angle and the day of year were included to modify the relationship between solar radiation with temperatures and relative humidity [106].

3.29 Group 29: temperature - precipitation - pressure (TPPr) models

Chen et al [54] modified the H-S model using precipitation and vapor pressure and suggested 4 TPPr models for estimation of solar radiation in China.

3.30 Group 30: temperature - precipitation - wind (TPW) models

Richardson and Reddy [109] proposed an equation to estimate solar radiation using temperature range, precipitation and wind velocity.

3.31 Group 31: temperature - precipitation - geographic factors (TPG) models

In this group, temperature, precipitation and geographic factors were incorporated with clearness index or solar radiation for the estimation of global solar radiation [99].

3.32 Group 32: temperature - relative humidity - precipitation - geographic factors (TRPG) models

Meza and Yebra [110] presented a hybrid function to estimate global solar radiation using temperature range, relative humidity, precipitation and the day of year.

3.33 Group 33: relative humidity (R) models

In this group, clearness index or global solar radiation was correlated with relative humidity in the forms of linear [111], exponential [90], power [58] and high order functions [53].

3.34 Group 34: Precipitation (P) model

Adaramola [59] developed a simple equation to estimate solar radiation using precipitation.

3.35 Group 35: relative humidity - precipitation (RP) model

Akpabio et al [61] proposed a multivariate linear equation using relative humidity, precipitation and extraterrestrial solar radiation for estimation of global solar radiation.

3.36 Group 36: precipitation - geographic factors (PG) model

Reddy [112] developed a model to estimate solar radiation using precipitation and latitude.

3.37 Group 37: pressure (Pr) model

Kamal Skeiker [60] developed a linear equation to estimate solar radiation using extraterrestrial solar radiation and atmospheric pressure.

4. Results and discussion

The collected models were calibrated and evaluated at three stations in the TGRA in China. The performances are presented in Table 2 and Figs.3-10. The calibrated coefficients of the models are presented in Supplementary Data.

Among the sunshine duration models (Fig.3), the model S15 had the lowest RMSE of 1.0863 MJ m^{-2} and RRMSE of 12.16% at Chongqing, the model S28 performed best at Wanzhou, with the RMSE of 0.7759 MJ m^{-2} and RRMSE of 8.47%, and the model S16 was the most accuracy one at Yichang, with the RMSE of 1.3733 MJ m^{-2} and RRMSE of 13.01%. Models S1-S3 showed much higher error indicators (RMSE and RRMSE) than other models, the poor performances of these models were also reported by other literatures [167-168]. Models S4-S7 had similar error indicators, which were slightly higher than those of models S8-S28 (except model S12) that also gave similar performances at the same site for Chongqing and Wanzhou. Except models S12 and S15-16, models S4-S28 also presented similar error indicators at Yichang. These results indicate that revisions of the A-P model by changing the structure from linear to nonlinear forms were generally not effective and yielded little or no improvement, which is similar with the previous studies [37-40, 168-171].

In group 2 (Fig.4), models ST11-15 and ST20-21 showed higher estimation errors than other models. Models ST16-19 performed similarly at the same station. Models ST2-10 (except ST8) also presented similar error indicators to models ST16-19 at Wanzhou. Models ST10, ST19 and ST9 performed best at Chongqing, Wanzhou and Yichang, with the RMSE of

0.8951 MJ m^{-2}, 0.7898 MJ m^{-2} and 1.2537 MJ m^{-2}, and with the RRMSE of 10.02%, 8.62% and 11.88%, respectively. Modified from the A-P model (group 1) by introducing air temperature, the models ST10 and ST9 had lower error indicators than the A-P model at Chongqing and Yichang, respectively, suggesting that inclusion of air temperature can improve the estimation accuracy of the A-P model. This result agrees well with the result from Chen and Li [20], and Chen et al [121] who found the modification to A-P model by introducing air temperature decreased the estimation error of the A-P model. By incorporating sunshine duration and air temperature models in Nigeria, Boluwaji and Onyedi [172] estimated solar radiation with a new model showing better performance over sunshine duration models. Lee [41] found the newly suggested equation with air temperature generally provided better estimations than the A-P model in Korean. These results further confirm our results at Chongqing and Yichang stations. Model ST19 showing similar performance to the A-P model at Wanzhou is consistent with the result of Wu et al [162] who reported that modification to A-P model by introducing air temperature performed similarly to the A-P model.

Among the sunshine duration - relative humidity models (Table 2), the models SR8, SR7 and SR 6 had the lowest estimation errors at Chongqing, Wanzhou and Yichang, respectively. The model SPr3 in group 5 performed best at Chongqing and Wanzhou. In group 4, only one model (SP1) was collected from literatures, and this model presented similar error indicators to the model SPr3 at the same station. Moreover, the best model at each site of Chongqing and Wanzhou in groups 3-5 performed similarly to the A-P model at the same station, generally indicating that individual inclusion of relative humidity, atmospheric pressure, and precipitation did not increase the estimation accuracy of the A-P model. These results are consist with the result from Chen and Li [20] who found the modifications to A-P model by individually introducing relative humidity, atmospheric pressure and precipitation gave similar performances to the A-P model. Meenal [173] compared 16 empirical models and also reported that exclusion of relative humidity did not affect the estimation accuracy of sunshine duration models in India. While Yildirim et al [13] found both models SR8 and SR7 significantly outperformed A-P model, as well as 14 sunshine duration models in his work.

In group 6 (Fig.5), the model SG7 had the highest error indicators. The model SG16, with similar performance as model SG6, was the most accuracy model at Chongqing and Yichang, with the lowest RMSE of 1.0356 MJ m^{-2} and 1.3861 MJ m^{-2}, and with the RRMSE of 11.59% and 13.13%, respectively. Except models SG6-7 and 16, other models showed similar error indicators at the same site for Chongqing and Yichang. Model SG 28 outperformed other models at Wanzhou, with the RMSE of 0.7893 MJ m^{-2} and RRMSE of 8.62%, while models SG1-2, SG4-5, SG7, SG10-11, SG15 and SG 17 had higher error indicators than other models that present similar error indicators at this site.

Among the sunshine duration - temperature - relative humidity models (Fig.6), models STR3 and STR10 showed much higher estimation errors than other models. Models STR15, STR4 and STR16 performed best at Chongqing, Wanzhou and Yichang, with the RMSE of 0.8893 MJ m^{-2}, 0.7954 MJ m^{-2} and 1.2207 MJ m^{-2}, and with the RRMSE of 9.96%, 8.68% and 11.57%, respectively. While the error indicators of the models STR15 and STR16 were similar to those of models STR7-8 and STR14-16 at the same site for Chongqing and Yichang. At Wanzhou station, the best model STR4 showed very similar error indicators to the models

STR4-5, STR7-9, STR11-12 and STR 14-17. Emad [174] compared the performances of model STR7 and some sunshine duration models in Egypt, and found that the model STR7 yielded better results over others. Falayi et al [85] observed that incorporating sunshine duration, temperature and relative humidity models yielded better precision than other models in Nigeria. These results are consistent with ours at Chongqing and Yichang where model STR7 showed lower estimation errors than the sunshine duration models.

In group 8 (Fig.7), the model STP9, which shows slightly lower error indicators than others at the same site for Chongqing and Yichang, had the lowest RMSE of 0.8952 MJ m^{-2} and 1.2267 MJ m^{-2}, and the lowest RRMSE of 10.06% and 11.62%, respectively. Model STP10 performeds best at Wanzhou where all the STP models showed very similar performances. Fan et al [45] compared the performances of models STP4-6 against other 10 models and found that model STP6 had higher accuracy than others in South China. While models STP9 and STP10 performed better than the STP6 in our study.

In groups 10 and 14-15 (Table2), only one model was collected for each group. Model STRW1 was superior to STPPr1 and SRP1 at the same site for Chongqing and Yichang, while model STPPr1 outperformed STRW1 and SRP1 at Wanzhou. In groups 9, 11-13 and 17-19, all the models in each group were found similar error indicators at the same site for Chongqing and Wanzhou. On average, model groups 9,11,12,14 and 17-18 had similar performances at Chongqing, and the error indicators were higher than those of groups 15 and 19-20 that also performed similarly at this station. At Wenzhou station, groups 9, 11-15, 17 and 19 presented similar average error indicators, which were slightly higher than those of group 18. Model groups 9, 10, 12-14 and 17 performed similarly at Yichang where groups 11, 15 and 18-20 also showed similar error indicators. Compared the performance of the model STRPr1 against the A-P model, Chen and Li [25] reported that air temperature, atmospheric pressure and relative humidity, as introduced in an additive form, accounted less for the improvement in accuracy of the A-P model. This result is consistent with our results at Wanzhou where both models had similar error indicators. However, the model STRPr1, as well as other STRPr models in group 13, showed better performances than the A-P model at Chongqing and Yichang. Ouali and Alkama [104] evaluated the performances of models STRP1, STRPW1, STRPW2 and STR7, and found that addition of precipitation and wind velocity increased the accuracy of the model employing sunshine fraction, temperature and relative humidity in Nigeria. Such models were found performing similarly in our study. Coulibaly and Ouedraogo [175] revised the A-P model using air temperature and sin of solar declination, and found this new model outperformed sunshine duration models in Africa. This agrees with our result at Chongqing and Yichang where group 11 had lower error indicators than A-P model. Adeala et al [102] compared the performances of models STRW1, S9, SR5 and STR7 in South Africa, and reported that STRW1 was the best one. This is confirmed by our results at Chongqing and Yichang, while all these models had similar error indictors at Wanzhou.

Among the sunshine duration - temperature - relative humidity - geographic factors models (Fig.8), models STRG12 and STRG4 performed best at Chongqing and Wanzhou, with the RMSE of 0.8973 MJ $m^{-2}$and 0.8623 MJ m^{-2}, and with the RMSE of 10.05% and 9.41%, respectively. Models TRG1-3 showed larger error indicators than STRG 4-13 that presented similar error indicators at the same site for the two stations. Model STRG7 was superior to other models at Yichang, with the RMSE of 1.2221 MJ m^{-2} and RMSE of 11.58%. Models STRG1-4 had higher error indicators than STRG 5-13 that performed similarly at this station.

In group 21(Fig.9), models T64 and T59 were the most accuracy ones for Chongqing and Wanzhou, with the RMSE of 1.0179 MJ m^{-2} and 1.2081 MJ m^{-2}, and with the RMSE of 11.39% and 13.18%, respectively. The error indicators of the two models were similar to those of T38, T52 and T54 at the same site for the two stations. Models T2-8, T18-19, T28, T35, T37, T39, T47-51, T53 and T61 performed similarly at the same site for Chongqing and Wanzhou, while models T1, T22-23, T45-46 and T57 presented larger error indicators than other models. At Yichang station, model T40 had the lowest RMSE of 1.3176 m^{-2} and RMSE of 12.48%, which were similar to T26, T30-31, T33-34, T40-41, T52, T55-56 and T58-59. Models T2, T4-8, T10, T18-19, T28, T35, T37, T39, T49-51, T53, T61 and T63 also showed similar error indicators at this site, while models T23 and T25 presented higher error indicators than other models.

Among the temperature - relative humidity models (Fig.10), model TR11 outperformed other models at Chongqing, Wanzhou and Yichang, with the RMSE of 1.0897 MJ m^{-2}, 1.2757 MJ m^{-2}, 1.3531 MJ m^{-2}, and with the RMSE of 12.20%, 13.92% and 12.82%, respectively. Models TR1, TR4, TR7-8 and TR19 presented higher error indicators than other models. In group 23 (Table 2), the model TP7 was superior to TP1-6 that perform similarly at the same site. Models TPr3 and TG4 performed best in group 24 and 25, respectively. Modified from T41, T49, T5 and T19 by introducing relative humidity, precipitation, vapor pressure and geographic factor, respectively, the models TR11, TP7, TPr3 and TG4 showed smaller error indicators than the corresponding models T41, T49, T5 and T19. This result indicates that inclusion of relative humidity, precipitation, vapor pressure and geographic factor can increase estimation accuracy of the temperature models. Chen and Li [20] evaluated some modifications to the H-S model by introducing relative humidity and vapor pressure and reported similar conclusion to ours. Ouali and Alkama [104] discovered that the application of precipitation enhanced the performance of temperature models in Algeria, which is in agreement with our results. While Chen and Li [20] found the modification to the H-S model by introducing precipitation gave similar performance to the H-S model.

Models TRP5, TRPr4, TRG4, TPPr4 and TPG1 performed best in groups 26, 27, 28, 29 and 31, respectively. While these models showed similar performances at Yichang, and their error indicators were similar to those of the model TRPG1 in group 32. Models TPG1 and TRG4, which had similar error indicators at Chongqing, outperformed models TRP5, TRPr4 and TPPr4 that also performed similarly at this site. Models TRP5, TRG4 and TRPG1 gave the similar estimations at Wanzhou. In group 30, only one model (TPW1) was collected from literatures, and this model presented higher error indicators than TRP5, TRPr4, TRG4, TPPr4, TPG1 and TRPG1 at the same site.

In group 33(Table 2), models R1-3 had much higher error indicators than R4-7. The model R6 had the lowest error indicators at Chongqing and Wanzhou, while the model R7 performed better than other models at Yichang. In groups 34-37, only one model was collected for each group, the model RP1 in group 35 was superior to P1(group 34), PG1(group 36) and Pr1(group 37) at the same site for Chongqing and Yichang, while the model Pr1 outperformed other models at Wanzhou. However, all these models presented higher error indicators than the models in groups 1-32.

In order to give an overview of the best model in each group, the top three models with the smallest average error indicators of the three stations in each group are selected and presented in Table 3. If the number of the model in group is less than 3, all the models are selected. Overall, the model STP10 was the most accuracy one followed by STP9 and STRPG2, while their error indicators were similar to many models as shown in Table 3. This result is in agreement with the conclusions from Evrendilek and Ertekin [64], and Sonmete et al [65] who evaluated many empirical equations in Turkey, and the results showed that model STP10 was the most accuracy one. Besharat et al [2] reviewed 78 empirical models and concluded that the model S1 performed best for Iran. Yao et al [32] compared 118 equations and reported that the model S24 was superior to other models at Shanghai in China, while both models S1 and S24 were inferior to many models reviewed in our study. Despotovic et al [5] evaluated 101 equations using long term sunshine duration data throughout the world and concluded that the model presented by Khogali et al [176] gave the best estimations. Similar to Despotovic and his colleagues's work [5], Bayrakçı et al [9] compared 105 sunshine duration equations and found that the models presented by Veeran and Kumar [177] and Chegaar and Chibani [178] performed best in Turkey. In fact, the most accuracy equations reported by Despotovic et al [5], Bayrakçı et al [9] and Yao et al [32] were A-P model just with different coefficients. While the A-P model was inferior to many models according our results. However, it is noteworthy that many equations in their works had the same formulas just with different coefficients rather than locally calibrated. We do not support such comparisons because the empirical coefficients are site-dependent [2, 5, 19, 22] and greatly affected by topographical characteristics and local climate [10, 13], and thus unconditional utilizations are not appropriate. When sunshine duration data are not available, the model TPG1 performed best followed by TRG4 and TG4. Sonmete et al [65] found the model TPG2 was the best temperature-based model in Turkey, while this model was inferior to many temperature-based models in our study. Models TPG1, TRG4 and TG4 showed higher error indicators than STP10, STP9 and STRPG2, as well as many other models in groups1-20, indicating that the sunshine-based models outperform the temperature-based models and the empirical models employing other meteorological variables, which has been confirmed by many studies [2, 20-21, 47].

5 Concludings

Empirical model is the most widely used method to estimate global solar radiation. This paper comprehensively reviewed the empirical models using the commonly measured meteorological variables and geographic factors. In total, 294 different types of empirical models were collected from literatures. These models were classified into 37 groups according to the input meteorological variables, 162 models with the corresponding 20 groups accounting for 55.1% were reported for the sunshine-based models; 121 models with 12 groups representing 41.2% for the temperature-based models; and 11 models with 5 groups resulting to 3.7% for other models. Furthermore, these models were calibrated and evaluated at three meteorological stations in Three Gorges Reservoir Area in China to identify the most appropriate one for the specific applications.

The results suggest that the sunshine-based models are generally more accurate than the temperature-based models and the empirical models employing other meteorological variables. Overall, the model STP10 gave the best performance followed by STP9 and STRPG2, while the model TPG1 performed best followed by TRG4 and TG4 when sunshine duration data are unavailable.

The main novelty of this study is that, to our best knowledge, this is so far the most comprehensively review on empirical models for estimation of solar radiation using the commonly measured meteorological variables and geographic factors. Remarkable efforts have been made to estimate solar radiation with empirical models. However, it is still a challenging task to develop better accuracy models due to the complex process of radiation. Numerous evaluations seem to indicate that empirical models have far overreached their predictive limits. Thus, it is more convenient to select an appropriate one from literatures rather than developing new models. This comprehensive review has built an empirical model library providing an overall overview of the developed empirical models in literatures. Moreover, the collected models are evaluated and compared to assist the governments, scientists and engineers in selecting the most appropriate one for specific applications in agriculture, climate, ecology and energy studies.

The collected and reviewed model formulas were based on the long term meteorological data at thousands of stations throughout the world. Thus, these formulas have a large potential for applications on global scale. However, the main difficulty in limiting the universal applicability of the most accuracy models in our study to other regions is the empirical coefficients which are site-dependent [19, 22]. Thus, it is clear from many literatures and our results that selecting a most accuracy model for estimation of solar radiation at any location of interest is not a viable work. This is as a result of its complexity, intrinsic quality of equipments, the topographical and the local climate characteristics [10, 13]. Nevertheless, it is reasonable that our conclusions are applicable to the regions with similar climatic conditions and topography. For other regions, the interested models can be collected from the empirical model library and evaluated to select the best model following the scheme of this study without having to check and review a large number of literatures, making our study would be a benchmark to select empirical models for estimating global solar radiation.

Due to the simplicity and operability yet reasonable accuracy, the empirical models are extensively studied and applied. While the commonly employed judgments criterions identifying the best model neglect the intrinsic quality of estimations [22]. Thus, the slight improvement of accuracy of the models with complex structure and more number of empirical coefficients is unable to prove the superiority to simple models yet satisfactory accuracy. This has been stressed by several studies [18, 179]. Accordingly, it is necessary to explore the optimal trade-off between the accuracy and the complexity, which is mainly depended on the application of the estimation and the data availability. Therefore, it is crucial to cooperate each other for developing a universal framework to guide the selection of the optimal empirical model.

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Table 1 Empirical models for estimation of global solar radiation in literatures

Model group	Model ID	Equation	Input variables	Reference
Group 1	S1	$Rs/Ra = b_1^{S/S0}$	Ra, S, S_0	El-Metwally [113]
Group 1	S2	$Rs = b_1 exp(b_2 S)$	S	Lewis [90]
Group 1	S3	$Rs/Ra = b_1 S/S_0$	Ra, S, S_0	Gana and Akpootu [114]
Group 1	S4	$Rs/Ra = b_1(S/S_0)^{b2}$	Ra, S, S_0	Elagib and Mansell [92]
Group 1	S5	$Rs/Ra = e^{b1}(S/S_0)^{b2}$	Ra, S, S_0	Coppolino [115]
Group 1	S6	$Rs/Ra = b_1(S/Sn)^{b2}$ $1/Sn = 0.8706/S_0 + 0.0003$	Ra, S, S_0	Togrul and Togrul [84]
Group 1	S7	$Rs/Ra = b_1 exp(b_2 S/S_0)$	Ra, S, S_0	Elagib and Mansell [92]
Group 1	S8	$Rs/Ra = b_1 exp(-((S/S_0-b_2)/b_3)^2)$	Ra, S, S_0	Yildirim et al [1]
Group 1	S9	$Rs/Ra = a + b_1 S/S_0$	Ra, S, S_0	Prescott [31]
Group 1	S10	$Rs/Ra = a + b_1 S/Sn$	Ra, S, S_0	Louche et al [116]
Group 1	S11	$Rs/Ra = a + b_1(S/S_0)^{b2}$	Ra, S, S_0	Elagib and Mansell [92]
Group 1	S12	$Rs/Ra = a + b_1 log(S/S_0)$	Ra, S, S_0	Ampratwum and Dorvio [36]
Group 1	S13	$Rs/Ra = a + b_1 exp(S/S_0)$	Ra, S, S_0	Almorox Hontoria [35]
Group 1	S14	$Rs/Ra = b_1 sin(b_2 S/S_0 + b_3)$	Ra, S, S_0	Yildirim et al [1]
Group 1	S15	$Rs = a + a_1 Ra + b_2 S$	Ra，S	Li et al [52]
Group 1	S16	$Rs = a + a_1 Ra + b_2 S/S_0$	Ra, S, S_0	Togrul and Onat [95]
Group 1	S17	$Rs/Ra = a + b_1 S/S_0 + b_2 exp(S/S_0)$	Ra, S, S_0	BakiRci [83]
Group 1	S18	$Rs/Ra = a + b_1 S/S_0 + b_2 log(S/S_0)$	Ra, S, S_0	Newland [117]
Group 1	S19	$Rs/Ra = a + b_1 S/S_0 + b_2(S/S_0)^2$	Ra, S, S_0	Ögelman et al [33]
Group 1	S20	$Rs/Ra = a + b_1 S/Sn + b_2(S/Sn)^2$	Ra, S, S_0	Togrul and Togrul [84]

Group 1	S21	$Rs/Ra = a + b_1\ln(S/S_0) + (b_2 + b_3\ln(S/S_0))S/S_0$	Ra, S, S_0	Togrul and Togrul [84]
Group 1	S22	$Rs/Ra = a + b_1S/S_0 + b_2(S/S_0)^2 + b_3(S/S_0)^3$	Ra, S, S_0	Bahel et al [34]
Group 1	S23	$Rs/Ra = a + b_1S/Sn + b_2(S/Sn)^2 + b_3(S/Sn)^3$	Ra, S, S_0	Togrul and Togrul [84]
Group 1	S24	$Rs/Ra = a + b_1S/S_0 + b_2(S/S_0)^2 + b_3(S/S_0)^3 + b_4(S/S_0)^4$	Ra, S, S_0	Togrul and Togrul [84]
Group 1	S25	$Rs/Ra = a + b_1\cos(S/S_0) + b_2\sin(S/S_0) + b_3\cos(2S/S_0) + b_4\sin(2S/S_0)$	Ra, S, S_0	Behrang et al [82]
Group 1	S26	$Rs/Ra = a + b_1S/S_0 + b_2(S/S_0)^2 + b_3(S/S_0)^3 + b_4(S/S_0)^4 + b_5(S/S_0)^5$	Ra, S, S_0	BakirciK [118]
Group 1	S27	$Rs/Ra = a + b_1S/S_0 + b_2(S/S_0)^2 + b_3(S/S_0)^3 + b_4(S/S_0)^4 + b_5(S/S_0)^5 + b_6(S/S_0)^6$	Ra, S, S_0	Katiyar et al [81]
Group 1	S28	$Rs/Ra = a + b_1\cos(S/S_0) + b_2\sin(S/S_0) + b_3\cos(2S/S_0) + b_4\sin2(S/S_0) + b_5\cos(3S/S_0) + b_6\sin(3S/S_0)$	Ra, S, S_0	Behrang et al [82]
Group 2	ST1	$Rs = a + b_1S + c_1T$	S, T	Pu [91]
Group 2	ST2	$Rs/Ra = a + b_1S/S_0 + c_1T$	Ra, S, S_0, T	Falayi et al [85]
Group 2	ST3	$Rs/Ra = a + b_1S/S_0 + c_1Tmin$	Ra, S, S_0, Tmin	Falayi et al [85]
Group 2	ST4	$Rs/Ra = a + b_1S/S_0 + c_1Tmax$	Ra, S, S_0, Tmax	Olayinka [86]
Group 2	ST5	$Rs/Ra = a + b_1S/S_0 + c_1(Tmax/65)$	Ra, S, S_0, Tmax	Mubiru et al [111]
Group 2	ST6	$Rs/Ra = a + b_1S/S_0 + c_1Tmin/Tmax$	Ra, S, S_0, Tmax, Tmin	Falayi et al [85]
Group 2	ST7	$Rs/Ra = a + b_1S/S_0 + c_1T(Tmin/Tmax)$	Ra, S, S_0, Tmax, Tmin, T	Sambo [119]
Group 2	ST8	$Rs = a + a_1Ra + b_1S/S_0 + c_1Tmax$	Ra, S, S_0, Tmax	Saffaripour et al [42]
Group 2	ST9	$Rs/Ra = a + b_1S/S_0 + c_1Tmin + c_2Tmax$	Ra, S, S_0, Tmax, Tmin	Chen and Li [20]
Group 2	ST10	$Rs/Ra = a + b_1S/S_0 + c_1T + c_2Tmin/Tmax$	Ra, S, S_0, Tmax, Tmin, T	Falayi et al [85]
Group 2	ST11	$Rs/Ra = a + b_1(\triangle T/S_0)$	Ra, S_0, Tmax, Tmin	Garcia [88]
Group 2	ST12	$Rs/Ra = a + \exp(b_1\triangle T/S_0)$	Ra, S_0, Tmax, Tmin	Garcia [88]
Group 2	ST13	$Rs/Ra = a + b_1\log(\triangle T/S_0)$	Ra, S_0, Tmax, Tmin	Garcia [88]

Group 2	ST14	$Rs/Ra = b_1(1\text{-}exp(d_2(\triangle T)^{c1}/S_0))$	Ra, S_0, Tmax, Tmin	Donatelli and Marletto [89]
Group 2	ST15	$Rs/Ra = 0.75(1\text{-}exp(b_1(\triangle T)^2/S_0))$	Ra, S_0, Tmax, Tmin	Weiss et al [87]
Group 2	ST16	$Rs/Ra = a + b_1 S/S_0 + c_1\triangle T$	Ra, S, S_0, Tmax, Tmin	Abdallah [120]
Group 2	ST17	$Rs/Ra = a + b_1 S/S_0 + c_1(\triangle T)^{0.5}$	Ra, S, S_0, Tmax, Tmin	Chen and Li [20]
Group 2	ST18	$Rs/Ra = a + b_1(S/S_0)^{b2} + c_1 ln(\triangle T)$	Ra, S, S_0, Tmax, Tmin	Chen et al [121]
Group 2	ST19	$Rs/Ra = a + b_1(S/S_0)^{b2} + c_1(\triangle T)^{c2}$	Ra, S, S_0, Tmax, Tmin	Khil-Ha Lee [41]
Group 2	ST20	$Rs/Ra = a + b_1(\triangle T/S_0) + b_2(\triangle T/S_0)^2$	Ra, S, S_0, Tmax, Tmin	Garcia [88]
Group 2	ST21	$Rs/Ra = a + b_1(\triangle T/S_0)+ b_2(\triangle T/S_0)^2+ b_3(\triangle T/S_0)^3$	Ra, S, S_0, Tmax, Tmin	Garcia [88]
Group 3	SR1	$Rs = b_1(S)^{b2}(Rh)^{d1}$	S, Rh	Lewis [90]
Group 3	SR2	$Rs = b_1(S/S_0)^{b2} (Rh)^{d1}$	S, S_0, Rh	Lewis [90]
Group 3	SR3	$Rs = a + b_1(Rh\text{-}S)$	S, Rh	Elagib et al [121]
Group 3	SR4	$Rs = a + b_1 S/S_0 + d_1 Rh$	S, S_0, Rh	Lewis [90]
Group 3	SR5	$Rs/Ra = a + b_1 S/S_0 + d_1 Rh$	Ra, S, S_0, Rh	Swartman and Ogunlade [123]
Group 3	SR6	$Rs = a + a_1 Ra + b_1 S/S_0 + d_1 Rh$	Ra, S, S_0, Rh	Saffaripour et al [42]
Group 3	SR7	$Rs/Ra = a + b_1 S/S_0 + b_2(S/S_0)^2 + d_1 Rh$	Ra, S, S_0, Rh	Bakirci Kadir [43]
Group 3	SR8	$Rs/Ra = a + b_1 S/S_0 + b_2(S/S_0)^2 + b_3(S/S_0)^3 + d_1 Rh$	Ra, S, S_0, Rh	Yıldırım et al [13]
Group 4	SP1	$Rs/Ra = a + b_1 S/S_0 + e_1 P$	Ra, S, S_0, P	Chen and Li [20]
Group 5	SPr1	$Rs/Ra = a + b_1 S/S_0 + f_1 Ap$	Ra, S, S_0, Ap	Chen and Li [20]
Group 5	SPr2	$Rs = a + b_1 S+ f_1 Vp$	S, S_0, Vp	Pu [91]
Group 5	SPr3	$Rs/Ra = a + (a_1 + f_1 Vp)S/S_0$	Ra, S, S_0, Vp	Liu et al [44]
Group 6	SG1	$Rs/Ra = e^{a1}(S/S_0)^{b1}(sin(90\text{-}\delta\text{-}\varphi))^{g1}$	Ra, S, S_0, φ, δ	Coppolino [115]
Group 6	SG2	$Rs/Ra = b_1 S/S_0 + g_1 cos\varphi$	Ra, S, S_0, φ	Glower and McGulloch [124]
Group 6	SG3	$Rs/Ra = a + b_1 S/S_{04}$ $S_{04} = 2/15cos^{-1}((sin4^{\circ} - sin\varphi sin\delta)/cos\varphi cos\delta)$	Ra, S, φ, δ	Bennett [125]

Group 6	SG4	$Rs/Ra = a + b_1 S/S_0 + g_1 \varphi$	Ra, S, S_0, φ	Elagib and Mansell [92]
Group 6	SG5	$Rs/Ra = a + b_1 S/S_0 + g_1 Z$	Ra, S, S_0, Z	Elagib and Mansell [92]
Group 6	SG6	$Rs/Ra = a + b_1 S/S_0 + g_1 \sin(\delta)$	Ra, S, S_0, δ	Togrul and Togrul [84]
Group 6	SG7	$Rs = b_1 S^{1.24} \delta^{-0.19} + g_1 (\sin\delta)^{2.1} + g_2 (\sin\delta)^3$	S, δ	Barbaro et al [125]
Group 6	SG8	$Rs/Ra = a + b_1 S/S_0 + g_1 \varphi + g_2 Z$	Ra, S, S_0, φ, Z	Elagib and Mansell [92]
Group 6	SG9	$Rs/Ra = a + b_1 S/S_0 + g_1 \cos\varphi + g_2 Z$	Ra, S, S_0, φ, Z	Elagib and Mansell [92]
Group 6	SG10	$Rs/Ra = a + (a_1 + g_1 \varphi) S/S_0 + g_2 \varphi$	Ra, S, S_0, φ	Dogniaux Lemoine [127]
Group 6	SG11	$Rs/Ra = a + (a_1 + g_1 \cos(\varphi-\delta)) S/S_0 + g_2 \cos(\varphi-\delta) + g_3 Z$	Ra, S, S_0, Z, φ, λ	Kilic and Ozturk [128]
Group 6	SG12	$Rs/Ra = a + b_1 S/S_0 + g_1 \cos\varphi + g_2 \cos\lambda + g_3 Z$	Ra, S, S_0, Z, φ, λ	Rehman [129]
Group 6	SG13	$Rs/Ra = a + b_1 S/S_0 + g_1 \varphi + g_2 \lambda + g_3 Z$	Ra, S, S_0, Z, φ, λ	Chen et al [93]
Group 6	SG14	$Rs/Ra = a + b_1 S/S_0 + g_1 \cos\varphi + g_2 \lambda + g_3 Z$	Ra, S, S_0, Z, φ, λ	Chen et al [93]
Group 6	SG15	$Rs/Ra = a + b_1 S/S_0 + b_2 Z(S/S_0) + b_3 (S/S_0)^2 + g_1 Z$	Ra, S, S_0, Z	Gopinathan [130]
Group 6	SG16	$Rs/Ra = a + b_1 S/S_0 + b_2 (a_1 + S/S_0)(n-a_2)^2$	Ra, S, S_0, n	Klabzuba et al [131]
Group 6	SG17	$Rs/Ra = a + ((a_1 + g_1 \cos(\varphi-\delta)) S/S_0 + g_2 \cos(\varphi-\delta) + g_3 Z$	Ra, S, S_0, Z, φ	Kilic and Ozturk [125]
Group 6	SG18	$Rs/Ra = a + (a_1 + g_1 \varphi + g_2 Z) S/S_0 + g_3 \varphi + g_4 Z$	Ra, S, S_0, Z, φ	Jin et al [94]
Group 6	SG19	$Rs/Ra = a + (a_1 + g_1 \cos\varphi + g_2 Z) S/S_0 + g_3 \cos\varphi + g_4 Z$	Ra, S, S_0, Z, φ	Jin et al [94]
Group 6	SG20	$Rs/Ra = a + b_1 S/S_0 + b_2 (S/S_0)^2 + b_3 (S/S_0)^3 + g_1 \varphi + g_2 Z$	Ra, S, S_0, Z, φ	Chen et al [93]
Group 6	SG21	$Rs/Ra = a + b_1 S/S_0 + b_2 (S/S_0)^2 + b_3 (S/S_0)^3 + g_1 \cos\varphi + g_2 Z$	Ra, S, S_0, Z, φ	Chen et al [93]
Group 6	SG22	$Rs/Ra = a + b_1 S/S_0 + b_2 S/S_0 (\cos\varphi) + b_3 Z(S/S_0) + b_4 (S/S_0)^2 + g_1 \cos\varphi + g_2 Z$	Ra, S, S_0, Z, φ	Gopinathan [130]
Group 6	SG23	$Rs/Ra = a + (a_1 + g_1 \varphi + g_2 \lambda + g_3 Z) S/S_0 + g_4 \varphi + g_5 \lambda + g_6 Z$	Ra, S, S_0, Z, φ, λ	Chen et al [93]
Group 6	SG24	$Rs/Ra = a + (a_1 + g_1 \cos\varphi + g_2 \lambda + g_3 Z) S/S_0 + g_4 \cos\varphi + g_5 \lambda + g_6 Z$	Ra, S, S_0, Z, φ, λ	Chen et al [93]
Group 6	SG25	$Rs/Ra = a + b_1 S/S_0 + b_2 (S/S_0)^2 + b_3 (S/S_0)^3 + g_1 \varphi + g_2 \lambda + g_3 \lambda^2 + g_4 Z$	Ra, S, S_0, Z, φ, λ	Chen et al [93]

Group 6	SG26	$Rs/Ra = a + b_1S/S_0 + b_2(S/S_0)^2 + b_3(S/S_0)^3 + g_1\cos\varphi + g_2\lambda + g_3\lambda^2 + g_4Z$	Ra, S, S_0, Z, φ, λ	Chen et al [93]
Group 6	SG27	$Rs/Ra = a + (a_1 + g_1\varphi + g_2Z)S/S_0 + (a_2 + g_3\varphi + g_4Z)(S/S_0)^2 + g_5\varphi + g_6Z$	Ra, S, S_0, Z, φ	Jin et al[94]
Group 6	SG28	$Rs/Ra = a + (a_1 + g_1\cos\varphi + g_2Z)S/S_0 + (a_2 + g_3\cos\varphi + g_4Z)(S/S_0)^2 + g_5\cos\varphi + g_6Z$	Ra, S, S_0, Z, φ	Jin et al [94]
Group 6	SG29	$Rs/Ra = a + (a_1 + g_1\cos\varphi + g_2Z)S/S_0 + (a_2 + g_3\cos\varphi + g_4Z)(S/S_0)^2 + (a_3 + g_5\cos\varphi + g_6Z)(S/S_0)^3 + g_7\cos\varphi + g_8Z$	Ra, S, S_0, Z, φ	Chen et al [93]
Group 6	SG30	$Rs/Ra = a + (a_1 + g_1\cos\varphi + g_2Z + g_3\lambda + g_4\lambda^2)S/S_0 + (a_2 + g_5\cos\varphi + g_6Z + g_7\lambda + g_8\lambda^2)(S/S_0)^2 + (a_3 + g_9\cos\varphi + g_{10}Z + g_{11}\lambda + g_{12}\lambda^2)(S/S_0)^3 + g_{13}\cos\varphi + g_{14}Z + g_{15}\lambda + g_{16}\lambda^2$	Ra, S, S_0, Z, φ, λ	Chen et al [93]
Group 7	STR1	$Rs/Ra = b_1(S/S_0)^{b2} (Tmax)^{c1} (Rh)^{d1}$	Ra, S, S_0, Tmax, Rh	Ododo et al [98]
Group 7	STR2	$Rs/Ra = \exp(b_1S/S_0 - d_1Rh - c_1/Tmax)$	Ra, S, S_0, Tmax, Rh	Onyango [132]
Group 7	STR3	$Rs = a + b_1(Rh - T - S)$	S, T, Rh	Elagib et al [121]
Group 7	STR4	$Rs/Ra = a + b_1S/S_0 + d_1Wa1$ $Wa1 = Rh (4.7923 + 0.3647T + 0.0055T^2 + 0.0003T^3)$	Ra, S, S_0, T, Rh	Garg and Garg [133]
Group 7	STR5	$Rs/Ra = a + b_1S + d_1Wa2$ $Wa2 = 0.0049Rh(\exp(26.23-5416/T)/T)$	Ra, S, S_0, T, Rh	Garg and Garg [133]
Group 7	STR6	$Rs = a + b_1S + c_1T + d_1Rh$	S, T, Rh	Lin and Gao [134]
Group 7	STR7	$Rs/Ra= a + b_1S/S_0 + c_1T + d_1Rh$	Ra, S, S_0, T, Rh	Abdallah [120]
Group 7	STR8	$Rs/Ra= a + b_1S/S_0 + c_1Tmax+ d_1Rh$	Ra, S, S_0, Tmax, Rh	Al-Salihi et al [97]
Group 7	STR9	$Rs/Ra = a + b_1S/S_0 + c_1\triangle T+ d_1Rh$	Ra, S, S_0, Tmax, Tmin, Rh	Abdalla [120]
Group 7	STR10	$Rs = a + b_1S/S_0 + c_1T/Tmax + d_1Rh/Rhmax$	S, S_0, T, Tmax, Rh	Kuye and Jagtap [135]
Group 7	STR11	$Rs/Ra = a + b_1S/S_0 + c_1Tmin/Tmax + c_2Rh/Rhmax$	Ra, S, S_0, Tmax, Tmin, Rh	Ojosu and Komolafe [136]
Group 7	STR12	$Rs/Ra = a + b_1S/S_0 + c_1Tmin/Tmax+ d_1Rh$	Ra, S, S_0, T, Tmax, Rh	Falayi et al [85]
Group 7	STR13	$Rs = a + a_1Ra + b_1S/S_0 + c_1T + d_1Rh$	Ra, S, S_0, T, Tmax, Rh	Thornton and Running [96]
Group 7	STR14	$Rs/Ra = a + b_1S/S_0 + c_1Tmin + c_2Tmax+ d_1Rh$	Ra, S, S_0, Tmax, Tmin, Rh	Chen and Li [20]

Group 7	STR15	$Rs/Ra = a + b_1S/S_0 + c_1T + c_2Tmin/Tmax + d_1Rh$	Ra, S, S_0, Tmax, Tmin, T, Rh	Falayi et al [85]
Group 7	STR16	$Rs/Ra = a + b_1S/S_0 + c_1Tmax + b_2Tmax(S/S_0) + d_1Rh$	Ra, S, S_0, Tmax, Rh	Ododo et al [98]
Group 7	STR17	$Rs/Ra = a + b_1S/S_0 + b_2(S/S_0 - Rh - Tmin/Tmax) + b_3(S/S_0)(Tmin/Tmax)$	Ra, S, S_0, Tmax, Tmin, T	Sambo [119]
Group 8	STP1	$Rs/Ra = a + b_1S/S_0 + c_1T + e_1P$	Ra, S, S_0, T, P	Chen et al [99]
Group 8	STP2	$Rs/Ra = a + b_1S/S_0 + c_1Tmin + e_1P$	Ra, S, S_0, Tmin, P	Okonkwo and Nwokoye [46]
Group 8	STP3	$Rs/Ra = a + b_1S/S_0 + c_1Tmin + c_2Tmax + e_1P$	Ra, S, S_0, Tmax, Tmin, P	Chen and Li [20]
Group 8	STP4	$Rs/Ra = a + b_1S/S_0 + c_1\ln\triangle T + e_1\ln(P+1)$	Ra, S, S_0, Tmax, Tmin, P	Fan et al [45]
Group 8	STP5	$Rs/Ra = a + b_1S/S_0 + c_1T + c_2\ln\triangle T + e_1\ln(P+1)$	Ra, S, S_0, Tmax, Tmin, T, P	Fan et al [45]
Group 8	STP6	$Rs/Ra = a + b_1(S/S_0)^{b2} + c_1T + c_2\ln\triangle T + e_1\ln(P+1)$	Ra, S, S_0, Tmax, Tmin, T, P	Fan et al [45]
Group 8	STP7	$Rs/Ra = a + (a_1 + c_1T + e_1P)S/S_0 + c_2T + e_2P$	Ra, S, S_0, T, P	Chen et al [99]
Group 8	STP8	$Rs/Ra = a + (a_1 + c_1T + e_1P + e_2P^2)S/S_0 + c_2T + e_3P + e_4P^2$	Ra, S, S_0, T, P	Chen et al [99]
Group 8	STP9	$Rs/Ra = a + (a_1 + c_1T + c_2T^2 + e_1P + e_2P^2)S/S_0 + c_3T + c_4T^2 + e_3P + e_4P^2$	Ra, S, S_0, T, P	Chen et al [99]
Group 8	STP10	$Rs/Ra = a + (a_1 + c_1T + c_2T^2 + c_3T^3 + e_1P + e_2P^2)S/S_0 + c_4T + c_5T^2 + c_6T^3 + e_3P + e_4P^2$	Ra, S, S_0, T, P	Chen et al [99]
Group 9	STPr1	$Rs/Ra = a + (a_1+f_1/Vp)S/S_0 + c_1\ln\triangle T$	Ra, S, S_0, Tmax, Tmin, Vp	Liu [44]
Group 9	STPr2	$Rs/Ra = a + b_1S/S_0 + c_1Tmin + c_2Tmax + f_1Ap$	Ra, S, S_0, Tmax, Tmin, Ap	Chen and Li [20]
Group 9	STPr3	$Rs = a + Ra(a_1 + b_1S/S_0 + c_1(\triangle T)^{0.5}) + f_1D$ $D = 0.6108 \exp(17.27T/(T+273.3)) - Vp$	Ra, S, S_0, Tmax, Tmin, T, Vp	Chen et al [54]
Group 10	SRP1	$Rs = a + a_1Ra + b_1S/S_0 + d_1Rh + e_1P$	Ra, S, S_0, Rh, P	Saffaripour et al [42]
Group 11	STG1	$Rs = a + b_1S/S_0 + c_1T + g_1\sin\delta$	S, S_0, T, δ	Togrul and Onat [95]
Group 11	STG2	$Rs = a + b_1S/S_0 + c_1Tmax + g_1\sin\delta$	S, S_0, Tmax, δ	Chen et al [99]
Group 12	STRP1	$Rs/Ra = a + b_1S/S_0 + c_1T + d_1Rh + e_1P$	Ra, S, S_0, T, Rh, P	Kirmani et al [100]
Group 12	STRP2	$Rs/Ra = a + b_1S/S_0 + c_1Tmin/Tmax + d_1Rh + e_1P$	Ra, S, S_0, Tmax, Tmin, Rh, P	Okonkwo and Nwokoye [46]

Group 13	STRPr1	$Rs/Ra = a + b_1S/S_0 + c_1(\triangle T)^{0.5} + d_1Rh + f_2Ap$	Ra, S, S_0, Tmax, Tmin, Rh, Ap	Chen and Li [25]
Group 13	STRPr2	$Rs/Ra = a + b_1S/S_0 + c_1T + d_1Rh + f_1Ap/Aps$	Ra, S, S_0, T, Rh, Ap	Abdalla [120]
Group 13	STRPr3	$Rs/Ra = a + b_1S/S_0 + c_1\triangle T + d_1Rh + f_1Ap/Aps$	Ra, S, S_0, T, Rh, Ap	Abdalla [120]
Group 13	STRPr4	$Rs/Ra = a + b_1S/S_0 + c_1Tmax+ d_1Rh + f_1Ap/Aps+ f_2Vp$	Ra, S, S_0, T, Rh, Ap, Vp	Trabea [101]
Group 14	STPPr1	$Rs = a + Ra(a_1 + b_1S/S_0 + c_1(\triangle T)^{0.5}) + e_1P + c_2D$	Ra, S, S_0, Tmax, Tmin, T, P, Vp	Chen et al [54]
Group 15	STRW1	$Rs/Ra = a + b_1S/S_0 + c_1T + d_1Rh + h_1Wv$	Ra, S, S_0, T, Rh, Wv	Adeala et al [102]
Group 16	STRG1	$Rs = a_1K_\varphi exp(\varphi(S/S_0 -Rh /15 -1/Tmax)$ $K_\varphi = 4.18(\varphi1*S_0 + cos\varphi) *10^6, \varphi1 = 0.2/(1 + 0.2\varphi)$	S, S_0, Tmax, Rh, φ	Sayigh [137]
Group 16	STRG2	$Rs = a_1K_\varphi exp(\varphi(S/S_0 - Rh^{1/3} - 1/Tmax))$	S, S_0, Tmax, Rh, φ	Sabbagh [138]
Group 16	STRG3	$Rs = K_\varphi (a_1 + b_1S/S_0 + c_1Tmin/Tmax+ b_2S/S_0 (Tmin/Tmax)) /(Rh)^{0.5}$	S, S_0, Tmin, Tmax, Rh, φ	Reddy [139]
Group 16	STRG4	$Rs = K_\varphi(a_1 + b_1S/S_0*T + d_1Rh^{0.5} + d_2Rh/K_\varphi + c_1Rh (T)^{0.5}/K_\varphi)$	S, S_0, T, Rh, φ	Reddy [139]
Group 16	STRG5	$Rs = a + b_1S/S_0 + c_1T + d_1Rh + g_1sin\delta$	S, S_0, T, Rh, δ	Togrul and Onat [95]
Group 16	STRG6	$Rs = a + a_1R_a + b_1S/S_0+ c_1T + d_1Rh + g_1sin\delta$	Ra, S, S_0, T, Rh, δ	Togrul and Onat [95]
Group 16	STRG7	$Rs = a + a_1Ra + b_1S/S_0 + c_1Tmax+ d_1Rh + g_1sin\delta$	Ra, S, S_0, Tmax, Rh, δ	Chen et al [99]
Group 16	STRG8	$Rs/Ra = a + b_1S/S_0 + c_1T + d_1Rh + g_1cos\varphi + g_2Z$	Ra, S, S_0, T, Rh, φ, Z	Gopinathan [130]
Group 16	STRG9	$Rs = a + a_1Ra + b_1S/S_0 + c_1T + c_2Tmin/Tmax + d_1Rh + g_1\delta$	Ra, S, S_0, T, Tmax, Tmin Rh, δ	Akpabio et al [61]
Group 16	STRG10	$Rs/Ra = a + b_1S/S_0 + c_1Tmax+ c_2Tmax/Rh + c_3(Tmax/Rh)^2 + g_1cos\varphi + g_2cosn + g_3(cos\varphi)(cosn)$	Ra, S, S_0, Tmax, Rh, φ, n	Ajayi et al [103]
Group 16	STRG11	$Rs/Ra = a + b_1S/S_0 + c_1Tmax+ c_2Tmax/Rh + c_3(Tmax/Rh)^2 + c_4Tmax/cos\varphi + g_1cos\varphi + g_2cosn + g_3(cos\varphi)(cosn)$	Ra, S, S_0, Tmax, Rh, φ, n	Ajayi et al [103]
Group 16	STRG12	$Rs/Ra = a + b_1S/S + c_1Tmax + d_1Rh + c_2Tmax/Rh + c_3(Tmax/Rh)^2 + g_1cos\varphi + g_2cosn + g_3(cos\varphi)(cosn)+ g_4(cosn)^2$	Ra, S, S_0, Tmax, Rh, φ, n	Ajayi et al [103]
Group 16	STRG13	$Rs/Ra = a + b_1S/S + b_2(S/S_0)^2 + c_1Tmax+ c_2Tmax/Rh +$	Ra, S, S_0, Tmax, Rh, φ, n	Ajayi et al [103]

		$c_3(Tmax/Rh)^2 + c_4(Tmax/Rh)^3 + c_5Tmax/\cos\varphi + g_1\cos\varphi + g_2\cos n + g_3(\cos\varphi)(\cos n) + g_4(\cos n)^2$		
Group 17	STPG1	$Rs/Ra = a + b_1S/S_0 + c_1T + e_1P + g_1\varphi + g_2Z + g_3\lambda$	Ra, S, S_0, T, P, φ, Z, λ	Chen et al [99]
Group 17	STPG2	$Rs/Ra = a + b_1S/S_0 + c_1T + e_1P + e_2P^2 + g_1\varphi + g_2Z + g_3\lambda$	Ra, S, S_0, T, P, φ, Z, λ	Chen et al [99]
Group 17	STPG3	$Rs/Ra = a + b_1S/S_0 + c_1T + c_2T^2 + c_3T^3 + e_1P + g_1\varphi + g_2Z + g_3\lambda$	Ra, S, S_0, T, P, φ, Z, λ	Chen et al [99]
Group 17	STPG4	$Rs/Ra = a + b_1S/S_0 + c_1T + c_2T^2 + c_3T^3 + e_1P + e_2P^2 + g_1\varphi + g_2Z + g_3\lambda$	Ra, S, S_0, T, P, φ, Z, λ	Chen et al [99]
Group 17	STPG5	$Rs/Ra = a + (a_1 + g_1\varphi + g_2Z + g_3\lambda)S/S_0 + c_1T + e_1P+ g_4\varphi + g_5Z + g_6\lambda$	Ra, S, S_0, T, P, φ, Z, λ	Chen et al [99]
Group 18	STRPP1	$Rs = a + Ra(a_1 + b_1S/S_0) + c_1(\triangle T)^{0.5} + c_2T + d_1Rh + e_1P + c_3D$	Ra, S, S_0, Tmax, Tmin, T, Rh, P, Vp	Chen et al [99]
Group 18	STRPP2	$Rs/Ra = a + b_1(S/S_0)^{b2} + c_1\ln\triangle T + c_2T + d_1Rh + e_1\ln(P+1) +c_3D$	Ra, S, S_0, Tmax, Tmin, T, Rh, P, Vp	Fan et al [45]
Group 19	STRPW1	$Rs/Ra = a + b_1S/S_0 + c_1T + d_1Rh + e_1P + h_1Wv$	Ra, S, S0, T, Rh, P, Wv	Ouali and Alkama [104]
Group 19	STRPW2	$Rs/Ra = a + b_1S/S_0 + c_1T + d_1Rh + e_1P + h_1Wv + b_2(S/S_0 * P * Wv * Rh * T)$	Ra, S, S0, T, Rh, P, Wv	Ouali and Alkama [104]
Group 20	STRPG1	$Rs = a + a_1Ra + b_1S/S_0 + c_1T + c_2Tmin /Tmax + d_1Rh + e_1P + g_1\delta$	Ra, S, S_0, T, Tmax, Tmin, Rh, P, δ	Akpabio et al [61]
Group 20	STRPG2	$Rs/Ra = (a_1 + g_1\sin M + g_2\cos M + b_1S + d_1Rh + e_1P) (1 – \exp(c_2(\triangle T)^{c3})), M = 2\pi n/365$	Ra, S, Tmax, Tmin, Rh, P, n	Zou et al [105]
Group 21	T1	$Rs/Ra = c_1(\triangle T)^{0.5}$	Ra, Tmax, Tmin	Hargreaves and Samani [49]
Group 21	T2	$Rs/Ra = c_1(\triangle T)^{c2}$	Ra, Tmax, Tmin	Richardson [140]
Group 21	T3	$Rs/Ra = c_1\exp(c_2T^{c3})$	Ra, T	Hassan et al [51]
Group 21	T4	$Rs/Ra = a + c_1\triangle T$	Ra, Tmax, Tmin	Chen and Li [20]
Group 21	T5	$Rs/Ra = a + c_1(\triangle T)^{0.5}$	Ra, Tmax, Tmin	Hargreaves et al [141]
Group 21	T6	$Rs/Ra = a + c_1(\triangle T)^{c2}$	Ra, Tmax, Tmin	Hassan et al [51]

Group 21	T7	$Rs/Ra = a + c_1 \ln(\triangle T)$	Ra, Tmax, Tmin	Chen et al 2004 [121]
Group 21	T8	$Rs/Ra = (a_1 + c_1 \triangle T)(\triangle T)^{c2}$	Ra, Tmax, Tmin	Hassan et al [51]
Group 21	T9	$Rs/Ra = (a_1 + c_1 T)(\triangle T)^{c2}$	Ra, Tmax, Tmin	Hassan et al [51]
Group 21	T10	$Rs = a + c_1 Ra(\triangle T)^{0.5}$	Ra, Tmax, Tmin	Hunt et al 139 [145]
Group 21	T11	$Rs = a + c_1 Ra(\triangle T)^{0.25}$	Ra, Tmax, Tmin	Benghanem and Mellit [50]
Group 21	T12	$Rs/Ra = a + c_1 Ra(T)^{c2}$	Ra, Tmax, Tmin	Hassan et al [51]
Group 21	T13	$Rs/Ra = a + c_1 T$	Ra, T	Falayi et al [85]
Group 21	T14	$Rs/Ra = a + c_1 Tmax$	Ra, Tmax,	Awachie and Okeke [143]
Group 21	T15	$Rs/Ra = a + c_1(Tmax/65)$	Ra, Tmax,	Mubiru et al [111]
Group 21	T16	$Rs/Ra = a + c_1 Tmin$	Ra, Tmin	Falayi et al [85]
Group 21	T17	$Rs/Ra = a + c_1 Tmin*Tmax$	Ra, Tmax, Tmin	Pandey and Katiyar [144]
Group 21	T18	$Rs/Ra =1 - \exp(c_1(\triangle T)^{c2})$	Ra, Tmax, Tmin	Thornton and Running [96]
Group 21	T19	$Rs/Ra = c_1(1 - \exp(c_2(\triangle T)^{c3}))$	Ra, Tmax, Tmin	Bristow and Campbell [55]
Group 21	T20	$Rs/Ra = 0.75(1 - \exp(c_1(\triangle T)^2))$	Ra, Tmax, Tmin	Meza [145]
Group 21	T21	$Rs/Ra = c_1(1 - \exp(c_2(\Delta T)^{c3}/Ra))$	Ra, Tmax, Tmin	Goodin et al. [57]
Group 21	T22	$Rs/Ra = c_1(1 - \exp(c_2(\triangle T)^{c3}/T))$	Ra, T, Tmax, Tmin	Donatelli and Campbell [146]
Group 21	T23	$Rs/Ra = 0.75(1 - \exp(c_1(\triangle T)^2/T))$	Ra, T, Tmax, Tmin	Abraha and Savage [147]
Group 21	T24	$Rs/Ra = c_1(1- \exp(c_2(\triangle T)^{c3} f(T))$, $f(T) = 0.017\exp(\exp(-0.053T))$	Ra, T, Tmax, Tmin	Donatelli and Campbell [146]
Group 21	T25	$Rs/Ra = 0.75(1 - \exp(c_1(\triangle T)^2 f(T))$	Ra, T, Tmax, Tmin	Weiss et al [87]
Group 21	T26	$Rs/Ra = c_1(1 - \exp(c_2(\triangle T)^{c3} f(T)f(Tmin))$ $f(Tmin) = \exp(Tmin/24.2807)$	Ra, T, Tmax, Tmin	Weiss et al [87]
Group 21	T27	$Rs/Ra = 0.75(1 - \exp(c_1(\triangle T)^2 f(T)f(Tmin))$	Ra, T, Tmax, Tmin	Abraha and Savage [147]
Group 21	T28	$Rs/Ra = c_1(1 - \exp(c_2(\triangle T)^{0.5} - c_3 \triangle T - c_4(\triangle T)^2)$	Ra, Tmax, Tmin	Hunt et al [142]
Group 21	T29	$Rs/Ra = c_1(1- c_2 Es(Tmin)/Es(Tmax))$	Ra, Tmax, Tmin	Winslow et al [148]

		$Es(T) = 0.6108 \exp(17.27T/(T+273.3))$		
Group 21	T30	$Rs/Ra = c_1(\triangle T)^{c2}(1 - \exp(c_3(Es(Tmin))^{c4})$	Ra, Tmax, Tmin	Almorox et al [149]
Group 21	T31	$Rs/Ra = c_1(\triangle T)^{c2}(1 - \exp(c_3(Es(Tmin)/Es(Tmax))^{c4})$	Ra, Tmax, Tmin	Almorox et al [149]
Group 21	T32	$Rs = a + a_1Ra + c_1T$	Ra, T	Ertekin and Yaldiz [150]
Group 21	T33	$Rs/Ra = a + (a_1 + c_1T)(\triangle T)^{0.5}$	Ra, T, Tmax, Tmin	Li et al [151]
Group 21	T34	$Rs/Ra = a + (a_1 + c_1T)(\triangle T)^{c2}$	Ra, T, Tmax, Tmin	Hassan et al [51]
Group 21	T35	$Rs/Ra = a + c_1(\triangle T)^{0.5} + c_2(\triangle T)$	Ra, T, Tmax, Tmin	Ohunakin et al [152]
Group 21	T36	$Rs/Ra = a + c_1T + c_2T^2$	Ra, T	Ohunakin et al [152]
Group 21	T37	$Rs/Ra = (a_1 + c_1\triangle T + c_2(\triangle T)^2)(\triangle T)^{c3}$	Ra, Tmax, Tmin	Hassan et al [51]
Group 21	T38	$Rs/Ra = (a_1 + c_1T + c_2T^2)(\triangle T)^{c3}$	Ra, T, Tmax, Tmin	Hassan et al [51]
Group 21	T39	$Rs/Ra = (a_1 + c_1\triangle T + c_2(\triangle T)^2)(\triangle T)^{0.5}$	Ra, T, Tmax, Tmin	Samani [153]
Group 21	T40	$Rs = a + (c_1Tmax + c_2Tmin)Ra$	Ra, Tmax, Tmin	Li et al [154]
Group 21	T41	$Rs/Ra = a + c_1Tmax + c_2Tmin$	Ra, Tmax, Tmin	Li et al [107]
Group 21	T42	$Rs/Ra = a + c_1Tmin/Tmax + c_2Tmax$	Ra, Tmax, Tmin	Okundamiya and Nzeako [155]
Group 21	T43	$Rs/Ra = a + c_1Tmin + c_2Tmin^2$	Ra, Tmin	Okundamiya and Nzeako [155]
Group 21	T44	$Rs/Ra = a + c_1Tmax + c_2Tmax^2$	Ra, Tmax	Okundamiya and Nzeako [155]
Group 21	T45	$Rs/ Ra = (a_1 + c_1Tmin/Tmax)(Tmin/Tmax)^{c2}$	Ra, Tmax, Tmin	Richardson and Reddy [109]
Group 21	T46	$Rs/Ra = a + c_1Tmin/Tmax + c_2(Tmin/Tmax)^2$	Ra, Tmax, Tmin	Pandey and Katiyar [144]
Group 21	T47	$Rs/Ra = a + c_1Tmin*Tmax + c_2(Tmin*Tmax)^2$	Ra, Tmax, Tmin	Okonkwo and Nwokoye [46]
Group 21	T48	$Rs/Ra = a + c_1T + c_2T^2 + c_2T^3$	Ra, T	Hassan et al [50]
Group 21	T49	$Rs/Ra = a + c_1(\triangle T)^{0.25} + c_2(\triangle T)^{0.5} + c_3\triangle T$	Ra, Tmax, Tmin	Fan et al [56]
Group 21	T50	$Rs/Ra = a + c_1(\triangle T)^{0.5} + c_2(\triangle T)^{1.5} + c_3(\triangle T)^{2.5}$	Ra, Tmax, Tmin	Jahani et al [157]
Group 21	T51	$Rs/Ra = a + c_1\triangle T + c_2(\triangle T)^2 + c_3(\triangle T)^3$	Ra, Tmax, Tmin	Jahani et al [156]
Group 21	T52	$Rs/Ra = a + (a_1 + c_1T + c_2T^2)(\triangle T)^{c3}$	Ra, T, Tmax, Tmin	Hassan et al [51]

Group 21	T53	$Rs/Ra = a + (a_1 + c_1\triangle T + c_2(\triangle T)^2)(\triangle T)^{c3}$	Ra, Tmax, Tmin	Hassan et al [51]
Group 21	T54	$Rs/Ra = (a_1 + c_1T + c_2T^2 + c_3T^3)(\triangle T)^{c4}$	Ra, T, Tmax, Tmin	Hassan et al [51]
Group 21	T55	$Rs = a + a_1Ra + c_1Tmax + c_2Tmin$	Ra, Tmax, Tmin	Almorox et al [157]
Group 21	T56	$Rs/ Ra = a + c_1Tmax + c_2Tmin + c_3Tmin*Tmax$	Ra, Tmax, Tmin	Chen and Li [20]
Group 21	T57	$Rs/Ra = a + c_1Tmax/Tmin + c_2(Tmax/Tmin)^2 + c_3(Tmax/Tmin)^3$	Ra, Tmax, Tmin	Pandey and Katiyar [144]
Group 21	T58	$Rs = Ra (a_1 + c_1(\triangle T)^{0.25} + c_2(\triangle T)^{0.5} + c_3\triangle T) + c_4T$	Ra, T, Tmax, Tmin	Fan et al [56]
Group 21	T59	$Rs/Ra = a + (a_1 + c_1\triangle T + c_2(\triangle T)^2 + c_3(\triangle T)^3)(\triangle T)^{c4}$	Ra, Tmax, Tmin	Hassan et al [51]
Group 21	T60	$Rs = a + c_1T + c_2T^2 + c_3T^3 + c_4T^4 + c_5T^5$	T	Dincer et al [158]
Group 21	T61	$Rs/Ra = a + c_1\triangle T + c_2(\triangle T)^2 + c_3(\triangle T)^3 + c_4(\triangle T)^4 + c_5(\triangle T)^5 + c_6(\triangle T)^6 + c_7(\triangle T)^7 + c_8(\triangle T)^8 + c_9(\triangle T)^9 + c_{10}(\triangle T)^{10}$	Ra, Tmax, Tmin	Korachagaon and Bapat [53]
Group 21	T62	$Rs = a + c_1Tmin + c_2Tmin^2 + c_3Tmin^3 + c_4Tmin^4 + c_5Tmin^5 + c_6Tmin^6 + c_7Tmin^7 + c_8Tmin^8 + c_9Tmin^9 + c_{10}Tmin^{10}$	Tmin	Korachagaon and Bapat [53]
Group 21	T63	$Rs = a + c_1Tmax+ c_2Tmax^2 + c_3Tmax^3 + c_4Tmax^4 + c_5Tmax^5 + c_6Tmax^6 + c_7Tmax^7 + c_8Tmax^8 + c_9Tmax^9 + c_{10}Tmax^{10}$	Tmax	Korachagaon and Bapat [53]
Group 21	T64	$Rs = a + c_1Tmax + c_2\triangle T+ c_3Tmax^2 + c_4(\triangle T)^2 + c_5Tmax*\triangle T + c_6Tmax^3 + c_7(\triangle T)^3 + c_8Tmax*(\triangle T)^2 + c_9Tmax^2*\triangle T$	Tmax, Tmin	Korachagaon and Bapat [53]
Group 22	TR1	$Rs = a + c_1(Rh - T)$	T , Rh	Elagib et al [121]
Group 22	TR2	$Rs/Ra = c_1(1 + d_1Rh)\triangle T$	Ra, Tmax, Tmin, Rh	Li et al [106]
Group 22	TR3	$Rs = a + Ra(c_1\triangle T + d_1Rh)$	Ra, Tmax, Tmin, Rh	Li et al [52]
Group 22	TR4	$Rs/Ra = a + c_1Tmin/Tmax*Rh$	Ra, Tmax, Tmin, Rh	Adaramola [59]
Group 22	TR5	$Rs/Ra = a + c_1T + d_1Rh$	T , Rh	El-Sebaii et al [159]
Group 22	TR6	$Rs/Ra = a + c_1(\triangle T)^{0.5} + d_1Rh$	Ra, Tmax, Tmin, Rh	Chen and Li [20]
Group 22	TR7	$Rs/Ra = a + c_1Tmin/Tmax + d_1Rh$	Ra, Tmax, Tmin, Rh	Richardson and Reddy [109]
Group 22	TR8	$Rs = a + c_1(Rh - \triangle T - Ra)$	Ra, Tmax, Tmin, Rh	Elagib et al [121]
Group 22	TR9	$Rs = a + c_1(Rh - T - Ra)$	Ra, T, Rh	Elagib et al [121]

Group 22	TR10	$Rs/Ra = c_1(1 + d_1Rh)(1- \exp(c_2(\triangle T)^{c3}))$	Ra, Tmax, Tmin, Rh	Li et al [106]
Group 22	TR11	$Rs = a + Ra(c_1Tmax + c_2Tmin + d_1Rh)$	Ra, Tmax, Tmin, Rh	Li et al [52]
Group 22	TR12	$Rs = a + Ra(c_1Tmax + c_2Tmin) + d_1Rh$	Ra, Tmax, Tmin, Rh	Li et al [52]
Group 22	TR13	$Rs/Ra = a + c_1Tmax + c_2\triangle T + d_1Rh$	Ra, Tmax, Tmin, Rh	Iranna and Bapat [53]
Group 22	TR14	$Rs/Ra = a + c_1\triangle T + c_2Tmin/Tmax + d_1Rh$	Ra, Tmax, Tmin, Rh	Kolebaje et al [58]
Group 22	TR15	$Rs/Ra = a + c_1T + c_2Tmin/Tmax + d_1Rh$	Ra, Tmax, Tmin, T, Rh	Falayi et al [85]
Group 22	TR16	$Rs/Ra = a + c_1Tmax + c_2Tmin + c_3\triangle T + d_1Rh$	Ra, Tmax, Tmin, Rh	Iranna and Bapat [53]
Group 22	TR17	$Rs/Ra = a + c_1Tmax + c_2Tmax^2 + d_1Rh + c_3Rh*Tmax + d_2Rh^2$	Ra, Tmax, Rh	Ododo [160]
Group 22	TR18	$Rs = a + c_1Tmax + c_2Tmax^2 + c_3Tmax^3 + c_4Tmax^4 + c_5Tmax^5 + d_1Rh + d_2Rh^2 + d_3Rh^3 + d_4Rh^4 + d_5Rh^5$	Ra, Tmax, Rh	Iranna and Bapat [53]
Group 22	TR19	$Rs = a + c_1\ln\triangle T + d_1Rh + c_2\ln(\triangle T)^2 + d_2Rh^2 + c_3\ln(\triangle T)*Rh + c_4\ln(\triangle T)^3 + d_3Rh^3 + c_5(\ln\triangle T)(Rh)^2 + c_6\ln(\triangle T)^2*Rh$	Tmax, Tmin, Rh	Iranna and Bapat [53]
Group 23	TP1	$Rs/Ra = a + c_1(\triangle T)^{0.5} + e_1P$	Ra, Tmax, Tmin, P	Chen and Li [20]
Group 23	TP2	$Rs/Ra = a_1(\triangle T)^{c1}(1 + e_1P + e_2P^2)$	Ra, Tmax, Tmin, P	De Jong and Stewart [161]
Group 23	TP3	$Rs/Ra = a + c_1Tmax + c_2Tmin + e_1P$	Ra, Tmax, Tmin, P	Li et al [104]
Group 23	TP4	$Rs/Ra = a + c_1(\triangle T)^{0.5} + c_2T + e_1Pa$ $P > 0, Pa = 1; P = 0, Pa = 0$	Ra, Tmax, Tmin, T, P	Wu et al [162]
Group 23	TP5	$Rs = a + c_1Ra(\triangle T)^{0.5} + c_2Tmax + e_1P + e_2P^2$	Ra, Tmax, Tmin, T, P	Hunt et al [142]
Group 23	TP6	$Rs/Ra = a + c_1T + c_2T^2 + c_3T^3 + e_1P + e_1P^2$	Ra, T, P	Chen et al [99]
Group 23	TP7	$Rs/Ra = (a_1 + c_1\triangle T + c_2(\triangle T)^{0.25} + c_3(\triangle T)^{0.5})(1 + c_4T + e_1f(p)), f(p) = \ln(P+1)$	Ra, Tmax, Tmin, T, P	Fan et al [56]
Group 24	TPr1	$Rs/Ra = c_1(\triangle T)^{0.5}(Ap/Aps)^{0.5}$	Ra, Tmax, Tmin, Ap	Allen [163]
Group 24	TPr2	$Rs/Ra = a + c_1(\triangle T)^{0.5} + f_1Ap$	Ra, Tmax, Tmin, Ap	Chen and Li [20]
Group 24	TPr3	$Rs/Ra = a + c_1(\triangle T)^{0.5} + c_2D$	Ra, Tmax, Tmin, T, Vp	Chen et al [54]
Group 24	TPr4	$Rs = a + a_1Ra + c_1(\triangle T)^{0.5} + c_2D$	Ra, Tmax, Tmin, T, Vp	Chen et al [54]

Group 24	TPr5	$Rs = a + Ra (a_1 + c_1(\triangle T)^{0.5}) + c_2\log(D)$	Ra, Tmax, Tmin, T, Vp	Chen et al [54]
Group 24	TPr6	$Rs = a + Ra (a_1 + c_1(\triangle T)^{0.5}) + c_2D$	Ra, Tmax, Tmin, T, Vp	Chen et al [54]
Group 25	TG1	$Rs/Ra = c_1(1 + 2.7*10^{-5}Z) (\triangle T)^{0.5}$	Ra, Tmax, Tmin, Z	Annandale et al [164]
Group 25	TG2	$Rs/Ra = a + c_1Tmin/Tmax + g_1\delta$	Ra, Tmax, Tmin, δ	Akpabio et al [61]
Group 25	TG3	$Rs = (c_1(\triangle T)^{c2}(L)^{c3} - c_4)/c_5$ $L = 0.8 + 0.12((182-n)/183)^{1.5}$	Tmax, Tmin, n	Mahmood and Hubbard [165]
Group 25	TG4	$Rs/Ra = a_1(1 + g_1\cos(g_2n\pi/180 + a_2))(1-\exp(c_1(\triangle T)^{c2}))$	Tmax, Tmin, n	Li et al [106]
Group 26	TRP1	$Rs = a + Ra(a_1 + c_1T + d_1Rh + e_1P)$	Ra, T, Rh, P	Chen et al [54]
Group 26	TRP2	$Rs = a + Ra(a_1 + d_1Rh) + c_1T + e_1P$	Ra, T, Rh, P	Chen et al [54]
Group 26	TRP3	$Rs = a + Ra(a_1 + d_1Rh) + c_1\exp(T) + e_1P$	Ra, T, Rh, P	Chen et al [54]
Group 26	TRP4	$Rs = Ra(a_1+(\triangle T)^{c1})(1 + d_1Rh) + e_1Pa$	Ra, Tmax, Tmin, Rh, P	Quej et al [108]
Group 26	TRP5	$Rs = Ra(a_1 + c_1\triangle T + c_2(\triangle T)^{0.25} + c_3(\triangle T)^{0.5})(1 + c_4T + e_1f(p)) + d_1Rh$	Ra, Tmax, Tmin, T, Rh, P	Fan et al [56]
Group 27	TRPr1	$Rs/Ra = a + c_1(\triangle T)^{0.5} + d_1Rh + f_1Ap$	Ra, Tmax, Tmin, Rh, Ap	Chen and Li [20]
Group 27	TRPr2	$Rs/Ra = a + c_1(\triangle T)^{0.5} + d_1Rh + f_1Vp$	Ra, Tmax, Tmin, Rh, Vp	Chen and Li [25]
Group 27	TRPr3	$Rs/Ra = a + c_1Tmax + c_2Tmin + d_1Rh + f_1Ap$	Ra, Tmax, Tmin, Rh, Ap	Chen and Li [20]
Group 27	TRPr4	$Rs/ Ra = a + c_1Tmax + c_2Tmin + c_3Tmin*Tmax + d_1Rh + f_1Ap$	Ra, Tmax, Tmin, Rh, Ap	Chen and Li [20]
Group 28	TRG1	$Rs/Ra = a + c_1Wa2 + g_1\delta$	Ra, T, Rh, δ	Garg and Garg [133]
Group 28	TRG2	$Rs = a + c_1Tmin/Tmax + d_1Rh + g_1\delta$	Tmax, Tmin, Rh, δ	Akpabio et al [61]
Group 28	TRG3	$Rs/Ra = a_1(1 + g_1\cos(g_2n\pi/180 + a_2) + d_1Rh)\triangle T$	Tmax, Tmin, Rh, n	Li et al [106]
Group 28	TRG4	$Rs/Ra = a_1(1 + g_1\cos(g_2n\pi/180 + a_2) + d_1Rh)(1-\exp(c_1(\triangle T)^{c2}))$	Tmax, Tmin, Rh, n	Li et al [106]
Group 29	TPPr1	$Rs/Ra= a + c_1(\triangle T)^{0.5} + e_1P + c_2D$	Ra, Tmax, Tmin, T, P, Vp	Chen et al [54]
Group 29	TPPr2	$Rs = a + Ra(c_1(\triangle T)^{0.5} + a_1) + e_1P + c_2D$	Ra, Tmax, Tmin, T, P, Vp	Chen et al [54]

Group 29	TPPr3	$Rs = a + Ra((c_1(\triangle T)^{0.5} + a_1) + a_2) + e_1P + c_2D$	Ra, Tmax, Tmin, T, P, Vp	Chen et al [54]
Group 29	TPPr4	$Rs = a + Ra(a_1 + c_1(\triangle T)^{0.5} + e_1Pr) + c_2T + c_3log(D) + e_2P$	Ra, Tmax, Tmin, T, P, Vp	Chen et al [54]
Group 30	TPW1	$Rs = a + c_1Tmax + c_2Tmin + e_1P + h_1Wv$	Tmax, Tmin, P, Wv	Richardson and Reddy [1009]
Group 31	TPG1	$Rs/Ra = a + c_1T+ c_2T^2 + c_3T^3+ e_1P + e_2P^2 + g_1\varphi + g_2\lambda+ g_3Z$	Ra, T, P, φ, Z, λ	Chen et al [99]
Group 31	TPG2	$Rs = a + c_1Tmax+ c_2Tmax^2 + c_3Tmin + c_4Tmin^2+ c_5Tmax*Tmin + e_1P + e_2P^2 + c_6Tmax*P + c_7Tmin*P + g_1n + c_8Tmaxn$	Tmax, Tmin, P, n	Ball et al [166]
Group 32	TRPG1	$Rs/Ra = (a + g_1sinM + g_2cosM + d_1Rh + e_1Pa) (1 - exp(c_1(\triangle T)^{c2}))$	Ra, Tmax, Tmin, Rh, P, n	Meza and Yebra [110]
Group 33	R1	$Rs = d_1Rh^{d2}$	Rh	Lewis [90]
Group 33	R2	$Rs = d_1exp(d_2Rh)$	Rh	Lewis [90]
Group 33	R3	$Rs = a + d_1Rh$	Rh	Ertekin and Yaldiz [150]
Group 33	R4	$Rs/Ra = a + d_1Rh$	Ra, Rh	Mubiru et al [111]
Group 33	R5	$Rs = a + d_1(Rh-Ra)$	Ra, Rh	Elagib et al [122]
Group 33	R6	$Rs/Ra = a + d_1Rh + d_2Rh^{d3}$	Ra, Rh	Kolebaje e al [58]
Group 33	R7	$Rs/Ra = a + d_1Rh + d_2Rh^2 + d_3Rh^3 + d_4Rh^4 + d_5Rh^5 + d_6Rh^6 + d_7Rh^7 + d_8Rh^8 + d_9Rh^9 + c_{10}Rh^{10}$	Ra, Rh	Iranna and Bapat [53]
Group 34	P1	$Rs/Ra = a + e_1P$	Ra, P	Adaramola [59]
Group 35	RP1	$Rs = a + a_1Ra + d_1Rh + e_1P$	Ra, P, Rh	Akpabio et al [61]
Group 36	PG1	$Rs/Ra = a + e_1P^{0.33}+ g_1\varphi$	Ra, P, φ	Reddy [112]
Group 37	Pr1	$Rs = a + a_1Ra + e_1Ap$	Ra, Ap	Kamal [60]

Table 2 RMSE (MJ m^{-2}) and RRMSE of the empirical models for solar radiation estimation

Model group	Model ID	Chongqing		Wanzhou		Yichang	
		RMSE	RRMSE	RMSE	RRMSE	RMSE	RRMSE
Group 3	SR1	1.533	17.16%	1.242	13.55%	2.684	25.43%
Group 3	SR2	1.823	20.41%	1.610	17.58%	3.257	30.86%
Group 3	SR3	3.186	35.66%	2.859	31.21%	3.899	36.94%
Group 3	SR4	1.816	20.33%	1.581	17.25%	3.287	31.15%
Group 3	SR5	1.094	12.25%	0.808	8.81%	1.602	15.18%
Group 3	SR6	1.164	13.03%	0.953	10.40%	1.380	13.08%
Group 3	SR7	1.089	12.19%	0.800	8.73%	1.597	15.14%
Group 3	SR8	1.088	12.18%	0.800	8.73%	1.599	15.15%
Group 4	SP1	1.079	12.08%	0.801	8.74%	1.550	14.69%
Group 5	SPr1	1.049	11.75%	0.798	8.71%	1.488	14.10%
Group 5	SPr2	1.233	13.81%	1.076	11.75%	1.870	17.72%
Group 5	SPr3	1.039	11.63%	0.785	8.57%	1.502	14.24%
Group 9	STPr1	0.950	10.64%	0.805	8.79%	1.347	12.77%
Group 9	STPr2	0.965	10.81%	0.807	8.81%	1.255	11.89%
Group 9	STPr3	1.008	11.28%	0.791	8.63%	1.386	13.13%
Group 10	SRP1	1.151	12.89%	0.956	10.43%	1.359	12.87%
Group 11	STG1	1.053	11.79%	0.905	9.88%	1.284	12.17%
Group 11	STG2	1.045	11.70%	0.905	9.88%	1.272	12.05%
Group 12	STRP1	0.964	10.79%	0.809	8.84%	1.249	11.84%
Group 12	STRP2	1.013	11.34%	0.806	8.80%	1.364	12.92%
Group 13	STRPr1	0.972	10.88%	0.812	8.86%	1.356	12.84%
Group 13	STRPr2	0.930	10.42%	0.812	8.86%	1.252	11.86%
Group 13	STRPr3	0.969	10.85%	0.810	8.84%	1.362	12.90%
Group 13	STRPr4	0.911	10.20%	0.788	8.61%	1.246	11.80%
Group 14	STPPr1	1.006	11.26%	0.788	8.60%	1.381	13.09%
Group 15	STRW1	0.930	10.41%	0.808	8.82%	1.234	11.69%
Group 17	STPG1	1.027	11.50%	0.849	9.27%	1.381	13.09%
Group 17	STPG2	0.999	11.18%	0.842	9.19%	1.379	13.07%
Group 17	STPG3	0.977	10.94%	0.842	9.19%	1.379	13.07%
Group 17	STPG4	0.963	10.78%	0.839	9.16%	1.377	13.05%

Table 2 RMSE (MJ m^{-2}) and RRMSE of the empirical models for solar radiation estimation (continued)

Model group	Model ID	Chongqing		Wanzhou		Yichang	
		RMSE	RRMSE	RMSE	RRMSE	RMSE	RRMSE
Group 17	STPG5	1.010	11.30%	0.843	9.20%	1.345	12.74%
Group 18	STRPP1	1.024	11.46%	0.760	8.29%	1.378	13.06%
Group 18	STRPP2	1.023	11.45%	0.741	8.09%	1.200	11.37%
Group 19	STRPW1	0.930	10.41%	0.811	8.86%	1.248	11.83%
Group 19	STRPW2	0.906	10.14%	0.803	8.77%	1.255	11.89%
Group 20	STRPG1	0.928	10.39%	0.915	9.99%	1.231	11.66%
Group 20	STRPG2	0.873	9.77%	0.810	8.84%	1.228	11.64%
Group 23	TP1	1.531	17.14%	1.514	16.53%	1.519	14.40%
Group 23	TP2	1.515	16.96%	1.505	16.42%	1.543	14.62%
Group 23	TP3	1.363	15.26%	1.387	15.14%	1.419	13.44%
Group 23	TP4	1.392	15.58%	1.411	15.40%	1.416	13.42%
Group 23	TP5	1.447	16.20%	1.479	16.15%	1.423	13.48%
Group 23	TP6	1.490	16.68%	1.489	16.25%	1.593	15.09%
Group 23	TP7	1.216	13.62%	1.317	14.37%	1.363	12.91%
Group 24	TPr1	2.152	24.09%	1.850	20.20%	1.603	15.18%
Group 24	TPr2	1.567	17.54%	1.508	16.46%	1.540	14.60%
Group 24	TPr3	1.419	15.88%	1.469	16.03%	1.502	14.23%
Group 24	TPr4	1.538	17.22%	1.738	18.97%	1.551	14.69%
Group 24	TPr5	1.594	17.84%	1.489	16.26%	1.529	14.49%
Group 24	TPr6	1.463	16.38%	1.523	16.62%	1.509	14.29%
Group 25	TG1	1.631	18.26%	1.561	17.03%	1.562	14.80%
Group 25	TG2	2.413	27.01%	2.223	24.26%	1.862	17.64%
Group 25	TG3	1.294	14.48%	1.321	14.42%	1.327	12.57%
Group 25	TG4	1.089	12.19%	1.216	13.27%	1.264	11.97%
Group 26	TRP1	1.299	14.54%	1.532	16.72%	1.621	15.36%
Group 26	TRP2	1.390	15.57%	1.666	18.18%	1.634	15.48%
Group 26	TRP3	1.695	18.97%	1.674	18.27%	1.949	18.46%
Group 26	TRP4	1.463	16.38%	1.604	17.50%	1.495	14.17%
Group 26	TRP5	1.138	12.74%	1.248	13.62%	1.318	12.49%
Group 27	TRPr1	1.396	15.63%	1.506	16.43%	1.541	14.60%

Table 2 RMSE (MJ m^{-2}) and RRMSE of the empirical models for solar radiation estimation (continued)

Model group	Model ID	Chongqing		Wanzhou		Yichang	
		RMSE	RRMSE	RMSE	RRMSE	RMSE	RRMSE
Group 27	TRPr2	1.202	13.45%	1.370	14.95%	1.476	13.98%
Group 27	TRPr3	1.244	13.93%	1.387	15.14%	1.448	13.72%
Group 27	TRPr4	1.104	12.35%	1.186	12.94%	1.369	12.97%
Group 28	TRG1	1.652	18.49%	1.516	16.54%	1.862	17.64%
Group 28	TRG2	1.815	20.32%	2.073	22.62%	1.749	16.57%
Group 28	TRG3	1.047	11.72%	1.227	13.39%	1.311	12.42%
Group 28	TRG4	1.039	11.63%	1.220	13.32%	1.296	12.28%
Group 29	TPPr1	1.365	15.29%	1.508	16.46%	1.501	14.22%
Group 29	TPPr2	1.395	15.61%	1.507	16.45%	1.506	14.27%
Group 29	TPPr3	1.179	13.19%	1.363	14.88%	1.323	12.53%
Group 29	TPPr4	1.175	13.15%	1.362	14.87%	1.311	12.42%
Group 30	TPW1	1.365	15.28%	1.473	16.08%	1.525	14.45%
Group 31	TPG1	1.026	11.48%	1.145	12.49%	1.379	13.07%
Group 31	TPG2	1.555	17.41%	1.467	16.01%	1.910	18.10%
Group 32	TRPG1	1.046	11.71%	1.243	13.57%	1.285	12.17%
Group 33	R1	3.607	40.38%	3.878	42.33%	3.923	37.17%
Group 33	R2	3.589	40.18%	3.854	42.06%	3.923	37.17%
Group 33	R3	3.591	40.20%	3.749	40.92%	3.923	37.17%
Group 33	R4	2.084	23.33%	2.324	25.36%	2.058	19.50%
Group 33	R5	2.167	24.26%	2.298	25.08%	2.139	20.27%
Group 33	R6	2.074	23.22%	2.298	25.08%	2.061	19.52%
Group 33	R7	2.075	23.23%	2.302	25.12%	2.035	19.28%
Group 34	P1	3.254	36.43%	2.290	24.99%	2.001	18.96%
Group 35	RP1	1.917	21.47%	2.139	23.35%	1.799	17.04%
Group 36	PG1	3.174	35.54%	2.416	26.37%	2.105	19.94%
Group 37	Pr1	2.299	25.74%	1.755	19.16%	1.994	18.89%

Table 3 RMSE (MJ m^{-2}) and RRMSE of the top three empirical models in each group

Model group	Model ID	RMSE	RRMSE	Model group	Model ID	RMSE	RRMSE
Group 1	S15	1.1005	11.45%	Group 12	STRP2	1.0608	11.02%
Group 1	S16	1.1464	11.96%	Group 13	STRPr4	0.9818	10.20%
Group 1	S27	1.1559	11.96%	Group 13	STRPr2	0.9980	10.38%
Group 2	ST10	0.9934	10.31%	Group 13	STRPr1	1.0462	10.86%
Group 2	ST9	1.0065	10.47%	Group 14	STPPr1	1.0584	10.98%
Group 2	ST4	1.0257	10.65%	Group 15	STRW1	0.9908	10.31%
Group 3	SR7	1.1621	12.02%	Group 16	STRG7	1.0403	10.86%
Group 3	SR6	1.1658	12.17%	Group 16	STRG6	1.0443	10.90%
Group 3	SR5	1.1677	12.08%	Group 16	STRG9	1.0456	10.88%
Group 4	SP1	1.1434	11.84%	Group 17	STPG4	1.0600	11.00%
Group 5	SPr1	1.1115	11.52%	Group 17	STPG5	1.0657	11.08%
Group 5	SPr2	1.3931	14.42%	Group 17	STPG3	1.0659	11.06%
Group 5	SPr3	1.1088	11.48%	Group 18	STRPP1	1.0539	10.94%
Group 6	SG16	1.0727	11.14%	Group 18	STRPP2	0.9878	10.30%
Group 6	SG6	1.0895	11.31%	Group 19	STRPW1	0.9964	10.36%
Group 6	SG27	1.1643	12.04%	Group 19	STRPW2	0.9882	10.27%
Group 7	STR15	0.9762	10.14%	Group 20	STRPG1	1.0247	10.68%
Group 7	STR16	0.9832	10.23%	Group 20	STRPG2	0.9701	10.08%
Group 7	STR8	0.9918	10.32%	Group 21	T59	1.2202	12.74%
Group 8	STP10	0.9655	10.03%	Group 21	T54	1.2300	12.84%
Group 8	STP9	0.9655	10.03%	Group 21	T52	1.2387	12.95%
Group 8	STP5	0.9916	10.32%	Group 22	TR11	1.2395	12.98%
Group 9	STPr1	1.0344	10.73%	Group 22	TR12	1.3398	14.07%
Group 9	STPr2	1.0093	10.50%	Group 22	TR16	1.3654	14.33%
Group 9	STPr3	1.0616	11.02%	Group 23	TP7	1.2985	13.63%
Group 10	SRP1	1.1552	12.06%	Group 23	TP3	1.3897	14.61%
Group 11	STG1	1.0807	11.28%	Group 23	TP4	1.4064	14.80%
Group 11	STG2	1.0738	11.21%	Group 24	TPr3	1.4633	15.38%
Group 12	STRP1	1.0077	10.49%	Group 24	TPr6	1.4982	15.76%

Table 3 RMSE (MJ m^{-2}) and RRMSE of the top three empirical models in each group (continued)

Model group	Model ID	RMSE	RRMSE	Model group	Model ID	RMSE	RRMSE
Group 24	TPr5	1.5375	16.20%	Group 29	TPPr3	1.2880	13.53%
Group 25	TG4	1.1896	12.48%	Group 29	TPPr1	1.4581	15.32%
Group 25	TG3	1.3138	13.82%	Group 30	TPW1	1.4542	15.27%
Group 25	TG1	1.5844	16.70%	Group 31	TPG1	1.1831	12.35%
Group 26	TRP5	1.2346	12.95%	Group 31	TPG2	1.6440	17.17%
Group 26	TRP1	1.4840	15.54%	Group 32	TRPG1	1.1914	12.48%
Group 26	TRP4	1.5208	16.02%	Group 33	R7	2.1370	22.54%
Group 27	TRPr4	1.2194	12.76%	Group 33	R6	2.1442	22.61%
Group 27	TRPr2	1.3492	14.13%	Group 33	R4	2.1553	22.73%
Group 27	TRPr3	1.3597	14.26%	Group 34	P1	2.5150	26.79%
Group 28	TRG4	1.1850	12.41%	Group 35	RP1	1.9518	20.62%
Group 28	TRG3	1.1947	12.51%	Group 36	PG1	2.5649	27.28%
Group 28	TRG1	1.6765	17.56%	Group 37	Pr1	2.0160	21.26%
Group 29	TPPr4	1.2825	13.48%				

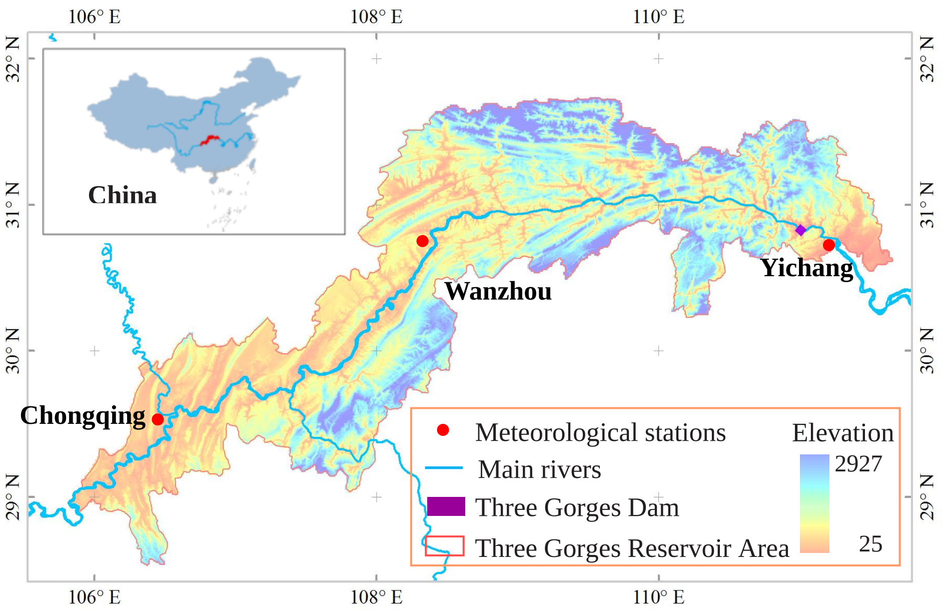

Fig.1 Location of Three Gorges Reservoir Area and theree studied meteorological sites

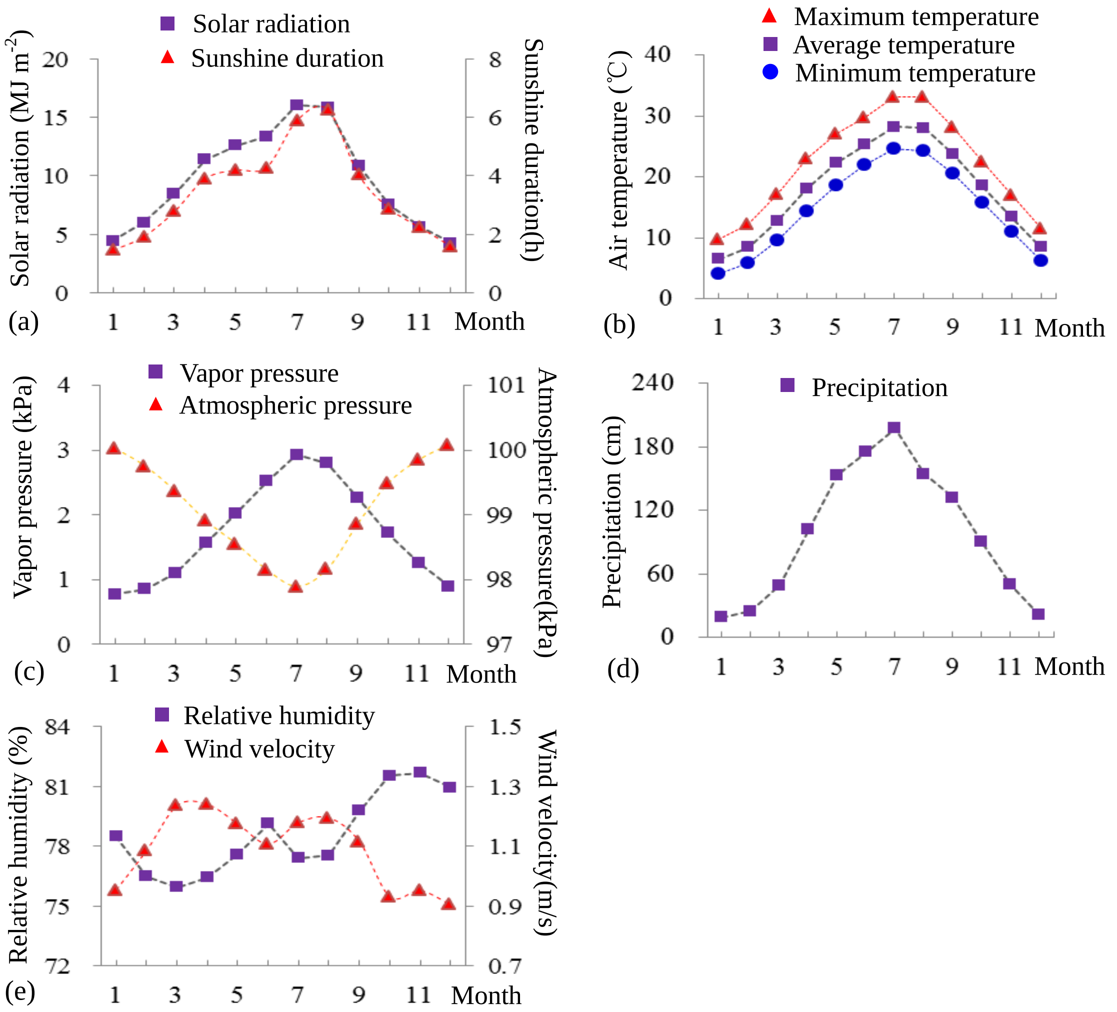

Fig.2 Temporal variations of the meteorological variables in Three Gorges Reservoir Area

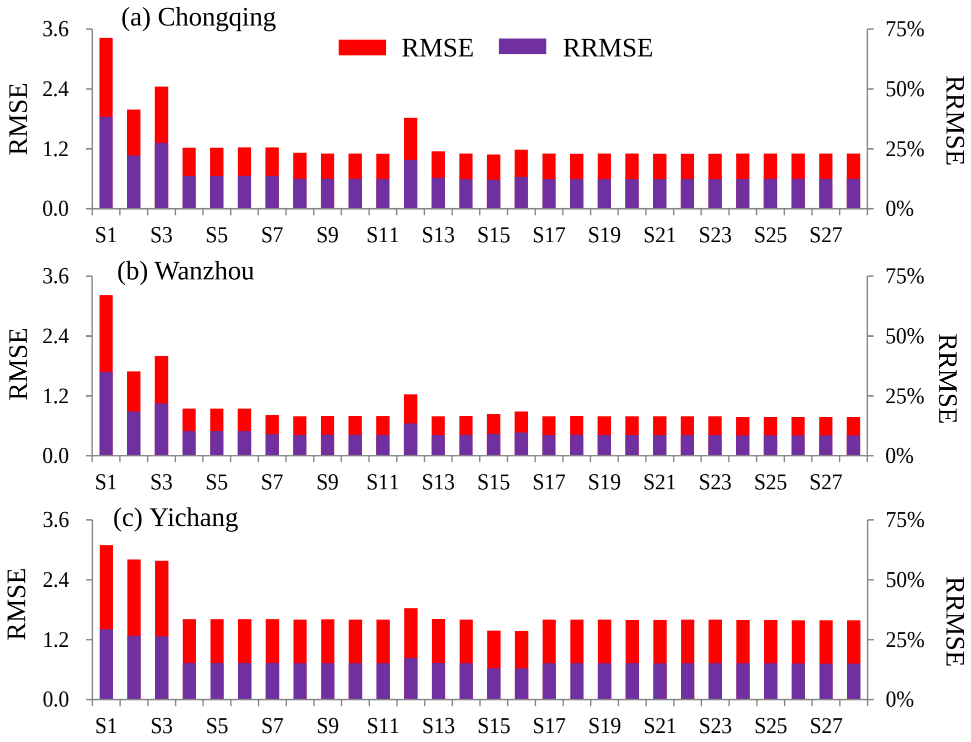

Fig.3 RMSE (MJ m^{-2}) and RRMSE of the sunshine duration (S) models

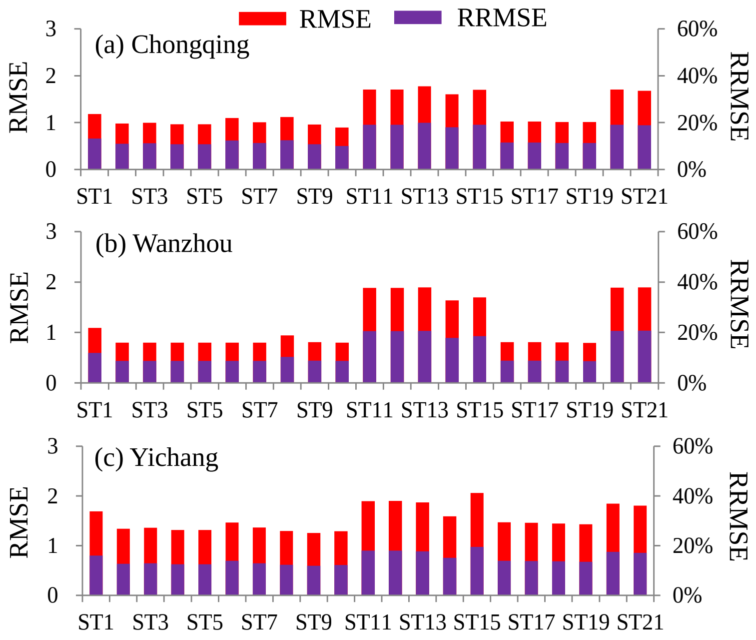

Fig.4 RMSE (MJ m^{-2}) and RRMSE of the sunshine duration - temperature (ST) models

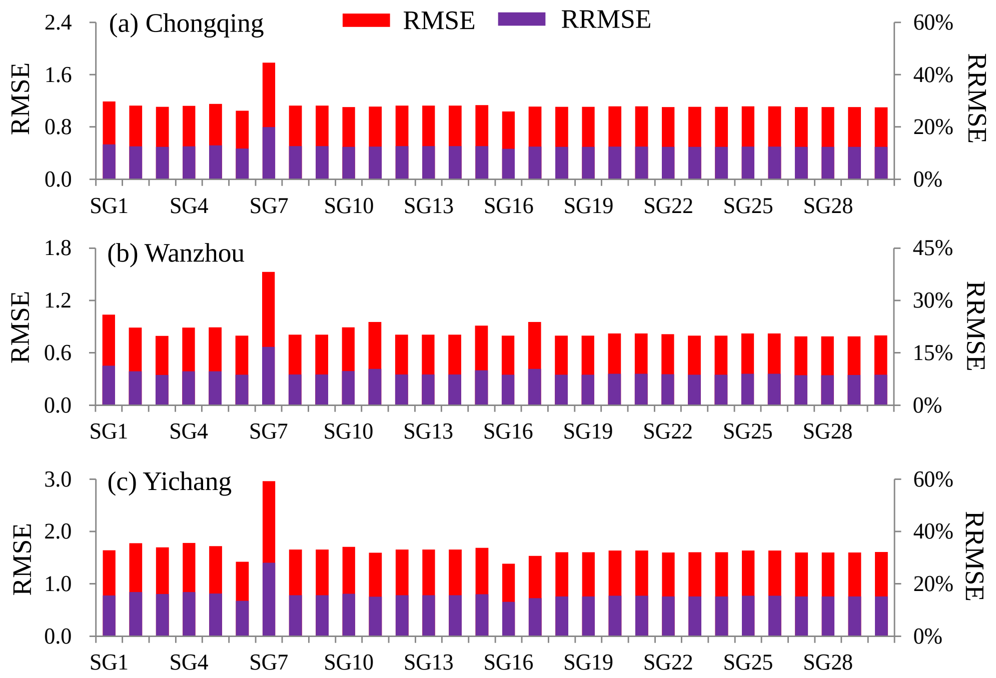

Fig.5 RMSE (MJ m^{-2}) and RRMSE of the sunshine duration - geographic factors (SG) models

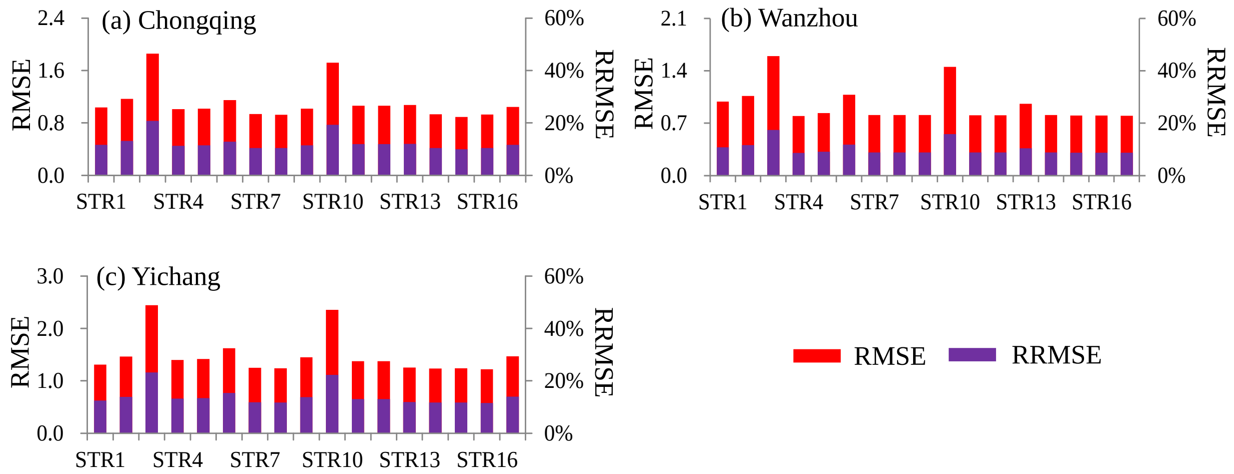

Fig.6 RMSE (MJ m^{-2}) and RRMSE of the sunshine duration - temperature - relative humidity (STR) models

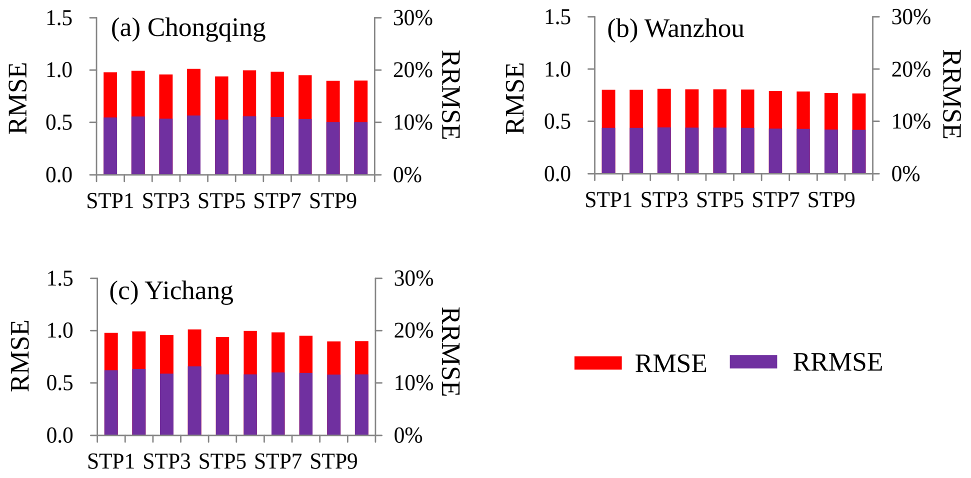

Fig.7 RMSE (MJ m^{-2}) and RRMSE of the sunshine duration - temperature - precipitation (STP) models

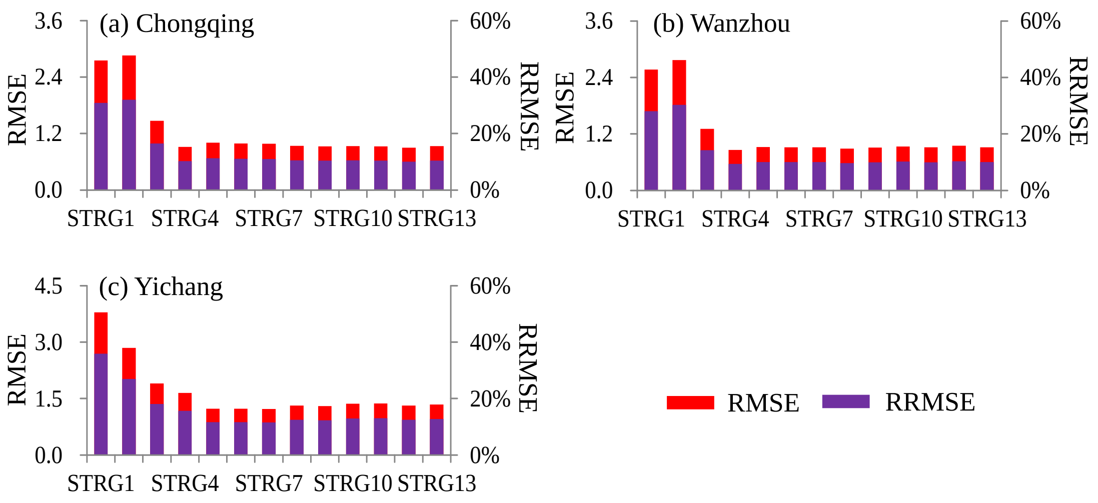

Fig.8 RMSE (MJ m^{-2}) and RRMSE of the sunshine duration - temperature - relative humidity - geographic factors (STRG) models

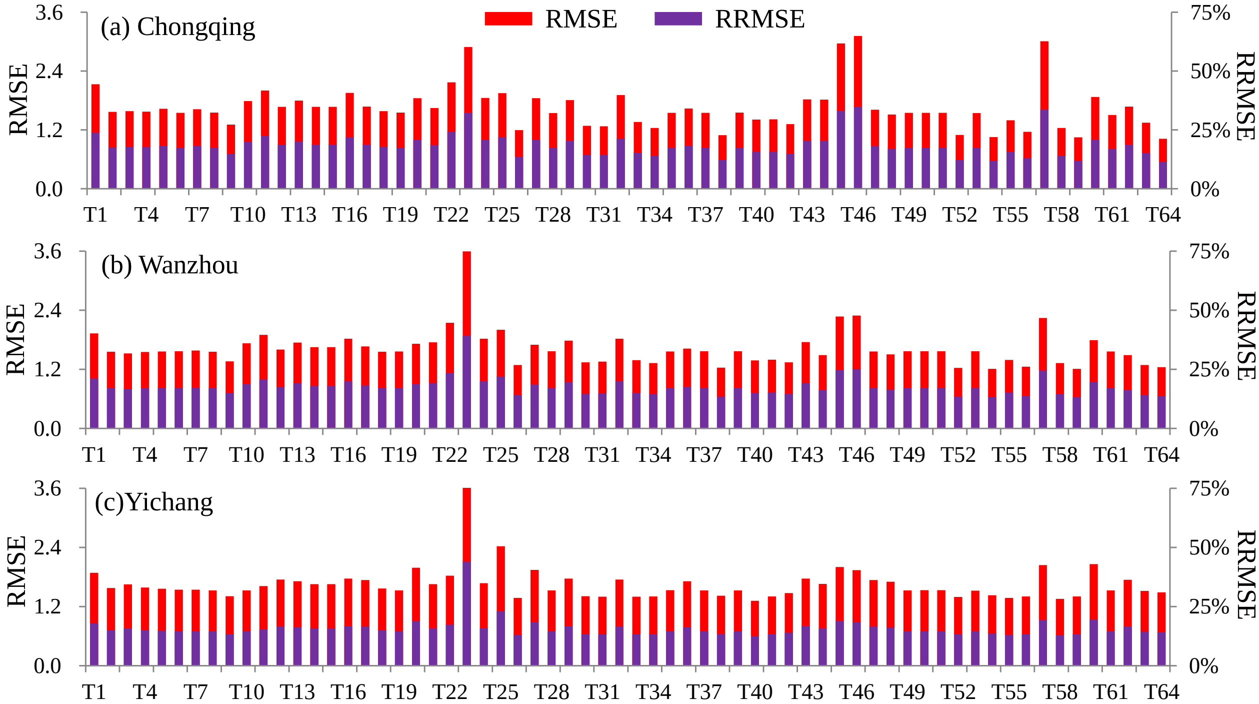

Fig.9 RMSE (MJ m^{-2}) and RRMSE of the temperature (T) models

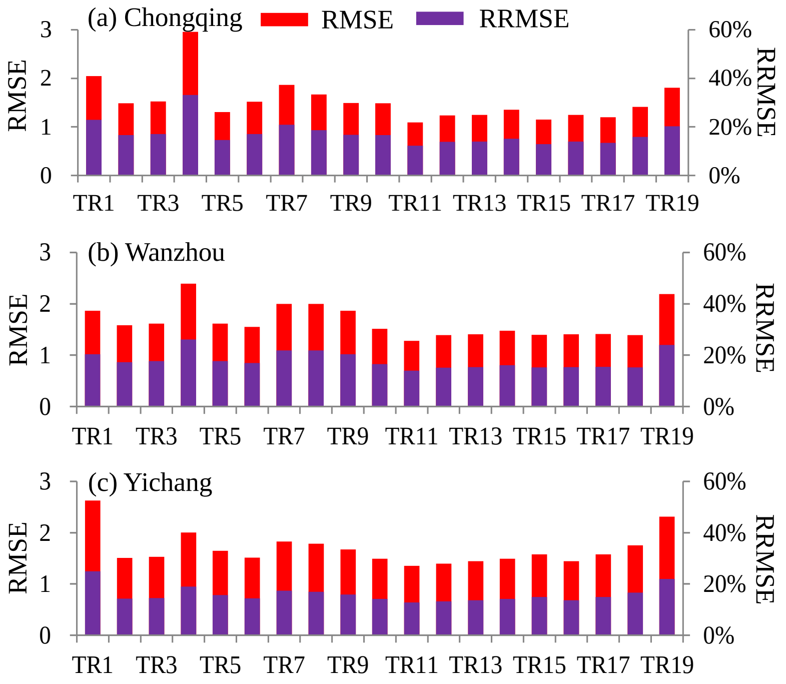

Fig.10 RMSE (MJ m^{-2}) and RRMSE of the temperature - relative humidity (TR) models