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The applicability of sunshine-based global solar radiation models modified with meteorological factors for different climate zones of China

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With the development of renewable energy, the exploitation and utilization of solar energy resources also need continuous progress, but solar radiation data shortage has become a serious concern. A method for estimating global solar radiation has been developed to address this issue. The sunshine-based model is currently the most widely used model due to its high calculation accuracy and few input parameters. This paper will first review 13 subcategories (8 categories in total) of the global solar radiation prediction model based on sunshine. Subsequently, the astronomical factors were introduced to modify empirical coefficients, and 8 new categories of models based on sunshine rate were introduced. The radiation data from 83 meteorological stations in China was used to train and validate the model, and the performance of the model was evaluated by using evaluation indicators, such as coefficient of determination (R^2), root mean square error (RMSE), mean absolute bias error (MABE), mean bias error (MBE), and global performance index (GPI). The results show that the R^2 value of the unmodified empirical model is in a range of 0.82–0.99, and the RMSE value is in a range of 0.018–3.09. In contrast, with the introduction of the astronomical factor, the model accuracy improves significantly, and the modified power function model (N3) gains its best performance. The R^2 of model N3 is in a range of 0.86–0.99, and the RMSE value is in a range of 0.018–2.62. The R^2 increases by 0.49%, while the RMSE value 6.44%. Above all, it does not require the input of other meteorological parameters for predicting the value of global solar radiation.

Abbreviations: *a*, *b*, *c*, *d*, *e*, Regression coefficients; *H*, Daily global radiation on a horizontal surface ($MJm^{-2}d^{-1}$); H_0, Extraterrestrial radiation on a horizontal surface ($MJm^{-2}d^{-1}$); *h*, Altitude (m); *S*, Daily sunshine duration (h); S_0, *CC* Maximum possible daily sunshine duration (h) Cloud cover; T_a, Average daily temperature; T_{max}, maximum daily temperature; T_{min}, minimum daily temperature; V_p, Atmospheric vapor pressure; P_t, Precipitation; *RH*, Relative humidity; R^2, Coefficient of determination; RMSE, Root mean square error ($MJm^{-2}d^{-1}$); MABE, Mean absolute bias error ($MJm^{-2}d^{-1}$); MBE, Mean bias error ($MJm^{-2}d^{-1}$); MPE, Mean percentage error; MRE, Mean relative error; GPI, Global performance index; δ, Solar declination (°); φ, Latitude of the location (°); λ, Longitude of the location (°).

KEYWORDS

global solar radiation, sunshine-based model, predictive modelling, solar declination, China

1 Introduction

Solar radiation is the source of energy for the movements of the earth's atmosphere and the causes of all physical phenomena in the atmosphere. Meanwhile, solar radiation is also the main energy source of the earth's ecosystem and has a significant impact on the development of solar equipment (Sen, 2008). With the continuing depletion of fossil fuels and the aggravation of environmental pollution, the use of renewable energy is becoming important. Therefore, the research and utilization of solar radiation must be expanded (Zhou et al., 2021a). Yet, few ground radiation observation stations have been built in China due to the high costs of solar radiation observation equipment and their maintenance. There are more than 2,000 meteorological data stations in China, but only 122 ground radiation observation stations are found across the country (Chen and Li, 2013). China has a vast land area with various terrains, and the distribution of global solar radiation value varies greatly. Therefore, the observational data from the current stations are insufficient to predict the solar radiation values of other regions.

The commonly used solar radiation prediction methods can be divided into empirical models and data-driven models (Zhou et al., 2021b). Among them, the machine learning model has been widely used to predict solar radiation (Bounoua et al., 2021), and its prediction results are accurate. However, the amount of calculation is large and the calculation process is complicated, making it impossible to predict the radiation data of large-scale stations. The empirical model has become one of the most widely used ones to predict daily global solar radiation due to its relatively high computational accuracy and efficient computational capacity. Hence, it is particularly suitable for large-scale solar radiation calculation tasks (Ustun et al., 2020). Empirical models can be divided into four types according to their input parameters, which include models based on sunshine, temperature, cloud cover, and other meteorological parameters (Mohammadi et al., 2016). The sunshine-based model was the first to be developed among the four types of models. Later, the model based on average daily temperature (T_a) (Sheik and Rao, 2021), cloud cover (*CC*) (Yakoubi et al., 2021), and other meteorological parameters was developed to improve accuracy (Naserpour et al., 2021). The input of multiple meteorological parameters improves the prediction accuracy of the model, but at the cost of the model's complexity (Okundamiya and Emagbetere, 2016). Oyewola et al. (2022) evaluated three groups of 20 models based on sunshine duration, temperature and relative humidity. The results show that the mixed model of temperature and relative humidity has the best prediction accuracy. Quansah et al. (2014) evaluated the performance of various models for estimating global solar radiation in Ghana and other tropical regions, and found that models using S and Ta parameters had the smallest values of MBE, MPE, and RMSE. Benamrou et al. (2018) evaluated 10 prediction models of global solar radiation for sunshine duration and temperature, as well as a newly proposed functional model of Fourier series. The results show that the proposed model is more accurate with smaller errors and the best coefficient of determination.

Several new combination models based on sunshine rate by introducing other meteorological parameters have been developed (T_a, relative humidity (*RH*), *CC*, atmospheric vapor pressure (V_p), etc.) (Chen et al., 2006b). Falayi et al. (2008) proposed a mixed model of the sunshine rate, *RH*, T_a, maximum daily temperature ($T_{\max}$) and minimum daily temperature ($T_{\min}$). Chen and Li (2013) established several models combining sunshine rate, T_a, V_p, *RH*, and precipitation (P_t). The result showed that when the sunshine duration (*S*) is available, the introduction of daily average V_p, *RH*, P_t, and other parameters contributes little to the accuracy of model. The accuracy of the combined model, after the introduction of T_a, has barely improved. Okundamiya and Emagbetere (2016) established a combined model with sunshine rate, T_a, and *CC*. The model prediction accuracy was better, and the R^2 value increased. On the one hand, these models require more input parameters, which significantly increases the difficulty of data acquisition. However, when compared with the sunshine-based model, the accuracy of these models is limited and does not have a significant advantage.

Although different models have advanced significantly, the sunshine-based model has a clear advantage in terms of accuracy and the difficulty of obtaining meteorological parameters. One of the important directions for future large-scale solar radiation prediction tasks is to improve the accuracy of the sunshine-based model without increasing the meteorological parameters (that is, without increasing the difficulty of obtaining meteorological data). Therefore, some researchers proposed to use meteorological factors (including latitude (φ), longitude (λ), and declination angle (δ)) and the number of the day of the year to improve the accuracy of the model. For example, Chen et al. (2006a) introduced parameters such as λ, φ, and altitude (h) to modify experience coefficients. OO Ajayi et al. (2014) introduced the cosine form of the number of the day of the year to improve the accuracy of the model, and the results show that the accuracy of this type of method is better than the combined model based on only the sunshine rate. Prieto and Garcia (2022) introduced the ratio of altitude and distance to the sea as the correction parameter of the empirical coefficient, and established the equation of the coefficient to evaluate the accuracy of the newly-built prediction model. The results show that most of the corrected models have higher accuracy.

This paper reviews more than 100 articles on empirical models for predicting global solar radiation from 1957 to 2021 and divides the models into 13 subcategories (8 categories in total). Based on this, 8 new categories of models have been introduced to explain astronomical factors. By using the radiation data between 1980 and 2016 from 83 meteorological stations in China, we analyzed and studied the global daily solar radiation in different climate zones. The 21 categories of models were trained and validated, and the best model was determined by comparing the evaluation indicators, such as R^2, RMSE, MBE, MABE, and GPI, providing guidance to select the best solar radiation prediction model for a specific region. The conclusion showed that from the perspective of GPI indicators, the power function model with astronomical factors has the highest accuracy, good stability, and best overall performance in different climate regions of China. Therefore, the power function model with astronomical factors can forecast global daily solar radiation.

2 A review of global solar radiation estimation models

As for the sunshine-based model, its *S* measurement is accurate, the data it collects is reliable, and it is easier to compare its meteorological parameters with those of others. Moreover, various studies have shown that *S* has the highest correlation with the value of solar radiation, so the accuracy of global solar radiation based on the sunshine-based model is higher (Nwokolo and Ogbulezie, 2017). Angstrom (1924) was the first to put forward the linear relationship between the ratio of solar radiation to global radiation for clear days and the sunshine rate, and he also established the first monthly average daily global solar radiation calculation model. Prescott (1940) then modified Angstrom's model by replacing clear-sky radiation with average daily extraterrestrial radiation on a horizontal surface and got a new computational model, which is known as the Angstrom-Prescott model. Garg and Garg (1985) developed linear equations by using the data from eleven stations in India. The equation predicts global solar radiation to an accuracy of 0.5%. Bahel et al. (1986) calculated the monthly average daily global radiation from May 1979 to July 1985 in Dhahran city and established the following model, with its prediction error being lower than 7.5%.

Ogelman et al. (1984) developed the quadratic model equation by fitting the radiation data from Adana and Ankara, Turkey and using the *S* data from Adana between 1979 and 1981 and Ankara between 1977 and 1981. The predicted data were then compared with the actual measured data, showing that it had a mean absolute relative error of 4.1%. Akinoglu and Ecevit (1990) established a quadratic model that has better performance in predicting global solar radiation. Togrul et al. (2000a) used the data of the Elazig weather station in Turkey to establish the relationship between sunshine rate and the coefficients a and b, and obtained the best results for the linear and logarithmic equations. Almorox and Hontoria (2004) established linear, quadratic, cubic, logarithmic and exponential equations using data from 16 weather stations in Spain, and found that the cubic model had better performance. Katiyar and Pandey (2010) used 5 years data of India to obtain relevant models for four cities. The results show that compared with the linear model, the accuracy of the quadratic and cubic models has not been significantly improved, and the calculation difficulty has increased. Duzen and Aydin (2012) obtained data from seven weather stations in Turkey and evaluated linear, quadratic, cubic, logarithmic, and exponential models. The conclusion is: The cubic and quadratic regression models are the most suitable regression equations.

Assi and Jama (2010) established the linear, quadratic, cubic, single term exponential, logarithmic, linear logarithmic, and power models for Abu Dhabi and Al Ain. The results show that linear and cubic models perform best in the region. Sekhar et al. (2013) obtained linear and quadratic models by using weather data from different cities in Andhra Pradesh, India, and the results showed that the quadratic model is better than the linear model. Suthar et al. (2014) established linear and quadratic models to estimate the global daily solar radiation in India, and the results showed that the quadratic model was more effective. M. Ozturk (2015) established linear, quadratic, cubic, and power function models for Isparta, Turkey, and the cubic model predicted the best results. Liu et al. (2016) established linear, quadratic, and cubic equations for Zhengzhou, China by using the data between January 1995 and December 2004, and the cubic model predicted better results than other models. Ishola et al. (2019) modified the various model coefficients for Ireland, and the results show that the quadratic model works best.

Ampratwum and Dorvlo (1999) established linear, quadratic, logarithmic, and linear-logarithmic model equations. The estimated results of the quadratic model and the linear logarithmic model were better than that of the logarithmic model, but the logarithmic model was simpler and its error was not significantly higher than that of the quadratic model. Exponential and linear exponential models were newly proposed by Bakirci (2009), and they were compared with other empirical equations. The linear-log and linear-exponential models generally give the best results, while the log and exponential models perform worse than the other models. Pant et al. (2019) built quadratic, cubic, logarithmic, linear-logarithmic models to estimate global solar radiation, and the cubic model was the best of all. Akpootu et al. (2019) evaluated the model and found that exponential and linear exponential models were more suitable for estimating global solar radiation. Nadjem et al. (2020) study found that the best model for estimating global solar radiation in southwestern Algeria was a linear exponential model.

Elagib and Mansell (2000) used the data gathered from 16 stations in four different climatic zones in Sudan to establish

TABLE 1 The existing sunshine-based models.

Model	Functional form	Main studies which developed or discussed the models
S1	$H = H_0[a + b(\frac{S}{S_0})]$	Angstrom (1924), Prescott (1940), Rietveld (1978), Hay (1979), Lewis (1981), Andretta et al. (1982), Khogali et al. (1983), Benson et al. (1984), Garg and Garg (1985), Bahel et al. (1986), Jain (1986), Jain and Jain (1988), Newland (1989), Luhanga and Andringa (1990), Jain (1990), Raja and Twidell (1990a), Alsaad (1990), Louche et al. (1991), Gopinathan and Soler (1992), Lewis (1992), Veeran and Kumar (1993), Rehman and Halawani (1997), Elagib et al. (1999), Togrul et al. (2000b), Akpabio and Etuk (2003), Rensheng et al. (2006), Ulgen and Hepbasil (2004), Almorox and Hontoria (2004), Jin et al. (2005), El-Metwally (2005), El-Sebaii and Trabea (2005), Aras et al. (2006), Rensheng et al. (2006), Bakirci (2009), Katiyar and Pandey (2010), Assi and Jama (2010), Duzen and Aydin (2012), Srivastava and Harsha (2013), Suthar et al. (2014), Ouali and Alkama (2014), Yao et al. (2014), Onyango and Ongoma (2015), Gbadebo and Adeleke, 2015, Adeala et al. (2016), Ozturk (2015), Poudyal (2016), Akinnawo et al. (2016), Okundamiya and Emagbetere (2016), Sarkar and Sifat (2016), Mohammadi et al. (2016), Coulibaly and Ouedraogo. (2016), Liu et al. (2016), Gong et al. (2016), Yang et al. (2016), Olomiyesan and Oyedum (2016), Namrata et al. (2016), Ayodele and Ogynjuyigbe (2017), Soulouknga et al. (2017a), Achour et al. (2017), Soulouknga et al. (2017b), Bakirci (2017), Kalogirou et al. (2017), Cao et al. (2017), Yaniktepe et al. (2017), Aoun and Bouchouicha (2017), Benamrou et al. (2018), Yıldırım et al. (2018), Kaplan (2018), Siva Krishna Rao et al. (2018), Gouda et al. (2018), Chala (2018), Uckan and Khudhur (2018), Kada et al. (2018), Pereira and Schiebelbein (2018), Zhang et al. (2018), Mbiaké et al. (2018), Akpootu et al. (2019), Ishola et al. (2019), Khan and Ahmad (2019), Makade et al. (2019), Manju and Sandeep (2019), Monteiro et al. (2019), Samanta et al. (2019), Shahrukh Anis et al. (2019), Tsung et al. (2019), Woldegiyorgis (2019), Argungu et al. (2020), Kaplan and Kaplan. (2020), Nadjem et al. (2020), Saud et al. (2020)
S2	$H = H_0[a + b(\frac{S}{S_0}) + c(\frac{S}{S_0})^2]$	Ogelman et al. (1984), Rietveld (1978), Akinoğlu and Ecevit (1990), Layi Fagbenle (1993), Aksoy (1997), Elagib et al. (1999), Togrul et al. (2000b), Toğrul and Toğrul, 2002, Almorox and Hontoria (2004), Jin et al. (2005), Aras, Balli, and Hepbasli (2006), Bakirci (2009), Katiyar and Pandey (2010), Duzen and Aydin (2012), Assi and Jama (2010), Sekhar et al. (2013), Suthar et al. (2014), Onyango and Ongoma (2015), Ozturk (2015), Akinnawo et al. (2016), Sarkar and Sifat (2016), Liu et al. (2016), Gong et al. (2016), Yang et al. (2016), Ayodele and Ogynjuyigbe (2017), Achour et al. (2017), Bakirci (2017), Cao et al. (2017), Aoun and Bouchouicha (2017), Kaplan (2018), Benamrou et al. (2018), Siva Krishna Rao et al. (2018), Olatona (2018), Uckan and Khudhur (2018), Kada et al. (2018), Zhang et al. (2018), Akpootu et al. (2019), Ishola et al. (2019), Khan and Ahmad (2019), Manju and Sandeep (2019), Pant et al. (2019), Samanta et al. (2019), Shahrukh Anis et al. (2019), Kaplan and Kaplan. (2020), Nadjem et al. (2020), Saud et al. (2020), Xiao et al. (2020)
S3	$H = H_0[a + b(\frac{S}{S_0}) + c(\frac{S}{S_0})^2 + d(\frac{S}{S_0})^3]$	Bahel et al. (1987), Samuel (1991), Lewis (1992), Togrul et al. (2000b), Toğrul and Toğrul, 2002, Rensheng et al. (2006), Ulgen and Hepbasli (2004), Almorox and Hontoria (2004), Jin et al. (2005), Aras et al. (2006), Rensheng et al. (2006), Katiyar and Pandey (2010), Duzen and Aydin (2012), Assi and Jama (2010), Ouali and Alkama (2014), Onyango and Ongoma (2015), Ozturk (2015), Akinnawo et al. (2016), Sarkar and Sifat (2016), Liu et al. (2016), Gong et al. (2016), Yang et al. (2016), Ayodele and Ogynjuyigbe (2017), Kaplan (2018), Achour et al. (2017), Bakirci (2017), Cao et al. (2017), Benamrou et al. (2018), Gouda et al. (2018), Uckan and Khudhur (2018), Kada et al. (2018), Zhang et al. (2018), Siva Krishna Rao et al. (2018), Akpootu et al. (2019), Khan and Ahmad (2019), Manju and Sandeep (2019), Pant et al. (2019), Samanta et al. (2019), Feng et al. (2020), Kaplan and Kaplan. (2020), Nadjem et al. (2020), Saud et al. (2020)
S4	$H = H_0[a + b\log(\frac{S}{S_0} + 1)]$	Ampratwum and Dorvlo (1999), Almorox and Hontoria (2004), Togrul et al. (2000a), Bakirci (2009), Duzen and Aydin (2012), Assi and Jama (2010), Yao et al. (2014), Onyango and Ongoma (2015), Sarkar and Sifat (2016), Ayodele and Ogynjuyigbe (2017), Kaplan and Kaplan (2020), Achour et al. (2017), Cao et al. (2017), Aoun Bouchouicha (2017), Benamrou et al. (2018), Uckan and Khudhur (2018), Kada et al. (2018), Akpootu et al. (2019), Khan and Ahmad (2019), Manju and Sandeep (2019), Pant et al. (2019), Saud et al. (2020)
S5	$H = H_0[a + b(\frac{S}{S_0}) + c\log(S/S_0 + 1)]$	Newland (1989), Bakirci (2009), Assi and Jama (2010), Ouali and Alkama (2014), Cao et al. (2017), Akpootu et al. (2019), Pant et al. (2019), Nadjem et al. (2020), Saud et al. (2020)
S6	$H = H_0[a + b\exp(\frac{S}{S_0})]$	Almorox and Hontoria (2004), Elagib et al. (1999), Toğrul and Toğrul, 2002, Bakirci (2009), Duzen and Aydin (2012), Assi and Jama (2010), Yao et al. (2014), Onyango and Ongoma (2015), Ayodele and Ogynjuyigbe (2017), Achour et al. (2017), Cao et al. (2017), Aoun and Bouchouicha (2017), Siva Krishna Rao et al. (2018), Akpootu et al. (2019), Ishola et al. (2019), Khan and Ahmad (2019), Manju and Sandeep (2019), Monteiro et al. (2019), Shahrukh Anis et al. (2019), Argungu et al. (2020), Nadjem et al. (2020), Saud et al. (2020)
S7	$H = H_0[a(\frac{S}{S_0})^b]$	Bakirci (2009), Elagib et al. (1999), Togrul et al. (2000a), Assi and Jama (2010), Yao et al. (2014), Sarkar and Sifat (2016), Achour et al. (2017), Aoun and Bouchouicha (2017), Benamrou et al. (2018), Siva Krishna Rao et al. (2018), Uckan and Khudhur (2018), Akpootu et al. (2019), Khan and Ahmad (2019), Manju and Sandeep (2019), Shahrukh Anis et al. (2019), Argungu et al. (2020)
S8	$H = H_0[a + b(\frac{S}{S_0})^c]$	El-Sebaii et al. (2009), Ozturk (2015), Cao et al. (2017), Uckan and Khudhur (2018), Saud et al. (2020)
S9	$H = H_0[a + b(\frac{S}{S_0}) + c\varphi]$	Achour et al. (2017), Glover and McCulloch (1958), Raja and Twidell (1990b), Achour et al. (2017), Uckan and Khudhur (2018), Awasthi and Poudyal (2018), Zhang et al. (2018), Pereira and Schiebelbein (2018)
S10	$H = H_0[a + b(\frac{S}{S_0}) + cZ]$	Lewis (1992)
S11	$H = H_0[a + b(\frac{S}{S_0}) + c\sin\delta]$	Toğrul et al. (2000b)
S12	$H = H_0[a + b(\frac{S}{S_0}) + c\varphi + dZ]$	Elagib and Mansell (2000), Jin et al. (2005), Rensheng et al. (2006), Zhang et al. (2018)
S13	$H = H_0[a + b(\frac{S}{S_0}) + c\cos\varphi + dZ]$	Gopinathan (1988), Jin et al. (2005), Rensheng et al. (2006), Zhang et al. (2018), Makade et al. (2019)

several new models. The results show that adding geographic parameters to the classical predictors improves global solar radiation estimation. Siva Krishna Rao et al. (2018) used the solar radiation data measured in India from August 2015 to July 2016 to build various models. The results show that the model with the input latitude parameter produces more accurate results. Rensheng et al. (2006) corrected the linear and cubic models by using factors such as longitude, latitude, and altitude. The results show that the latitude can effectively improve the accuracy of the model, and the cos φ results are better. Awasthi and Poudyal (2018) corrected the coefficients of the daily global solar radiation model at Simara Airport in India. The results proved that the model was more accurate after the latitude is introduced.

Researchers have done a lot of research on empirical models and proposed models based on different parameters such as S, T_a, and CC. However, due to the advantages of the simple acquisition of sunshine data, less computation, and high model accuracy, the empirical model based on sunshine duration is still the most widely used empirical model. And a large number of studies have shown that the introduction of other meteorological parameters on the basis of the sunshine model can improve the accuracy of the model, but the performance is not obvious. Because of the multi-parameter input, it is difficult to obtain meteorological data, and the complexity of the model also increases. How to use the least meteorological parameters and improve the accuracy of the model is one of the focuses of the research. On the basis of the sunshine-based model, the introduction of known parameters such as astronomy and geography to improve the accuracy of the model is lacking in current research.

According to the above model introduction, the current empirical models based on sunshine rate can be divided into the following 13 categories. They have been reviewed, and the review results are summarized in Table 1. The detailed introduction of the model is shown in the Supplementary Material.

3 Data acquisition and quality control

The research data in this paper is from the daily radiation data dataset of the National Meteorological Data Sharing Center of China and the daily dataset of China's surface climate data of the National Scientific Meteorological Data Center. The covering period is between 1981 and 2016 while the period records varied from 6 to 35 years. Data includes Daily global radiation on a horizontal surface (H), Daily sunshine duration (S), T_a, $T_{\max}$, $T_{\min}$, daily maximum pressure, daily minimum pressure, daily average pressure, etc. The theory is used to calculate Maximum possible daily sunshine duration (S_0) and extraterrestrial radiation on a horizontal surface (H_0) values. The data set is divided into two parts. Two-thirds of them are used for model training, and the rest of them are used for model testing.

Radiation data may have abnormal values due to random errors and instrument errors, which may easily lead to large errors in global radiation calculation. Therefore, the quality of radiation data must be ensured. The data quality control process is as follows: 1) Missing data. If a piece of data is missing, delete it along with all data of that day; 2) If the H is greater than H_0 or less than 0.03 time of H_0, then remove all data for that day.

China has a vast land expanse from east to west, so it has different climates in different areas. Based on the data of 660 meteorological stations, Liu et al. (2017) proposed a two-step solar radiation zoning method based on support vector machines and k-means clustering, dividing the whole country into five climate zones: zone I: strong radiation and semi-arid zone; zone II: long-sun and arid zone; zone III: semi-humid zone; zone IV: humid zone; zone V: high-humidity and low-sun zone. This paper analyzes the data of 83 meteorological stations in China. Then, according to the climatic zone of each station, the evaluation indicators of each model in different climatic zones are statistically analyzed (Figure 1).

4 Model development and evaluation method

Liu et al. (2015) analyzed the changing rules of the empirical coefficient of the A-P model and found that the coefficient value changes dynamically. This paper firstly takes Mohe data as an example, calculates the empirical coefficients a, b of the A-P model of the site in 1 year, and plots the results in Figures 2, 3. It can be seen from the figure that the empirical coefficients a and b of this site change in a trigonometric function, with the characteristics of fluctuation, which is similar to the change law of astronomical factors. This paper proposes a hypothesis to modify the empirical coefficient of the model to make it more in line with the actual change law, no matter whether it affects the improvement of the model accuracy or not. Therefore, this paper introduces the declination angle to dynamically correct the empirical coefficient of the A-P model, that is, the coefficient a in the original empirical model is corrected to $a_0+a_1\sin\delta$, and the coefficient b is corrected to $b_0+b_1\sin\delta$. Similarly, this process is extended to other models, and 8 new models as shown in Table 2 are proposed.

In this paper, the least square method (Zhou et al., 2019) was used to calculate the model coefficients. The mathematical principles of the least square method are as follows: given a set of data (x_i, y_i), $(i = 1, 2, \ldots, n)$, the empirical function is $F(x) = a_0 + a_1 x_i + \ldots + a_k x_i^k$, the experience coefficient is constant a_k. The squared formula to get the standard error is:

$$\boldsymbol{E}^2 = \sum_{i=1}^{n} \left(\boldsymbol{y}_i - \boldsymbol{F}(\boldsymbol{x}_i)\right)^2 \tag{1}$$

Minimize the value of Eq. 1, solve the coefficient a_k, and get the following equation:

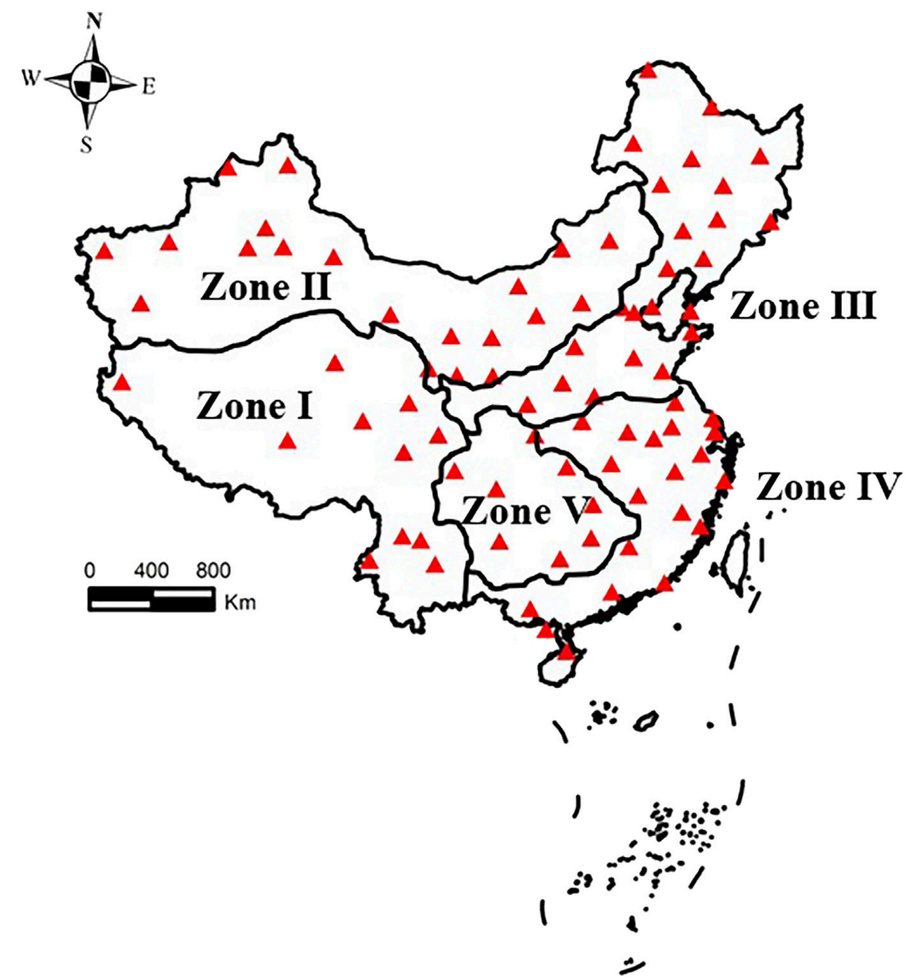

FIGURE 1
Station distribution and radiation zones.

$$\begin{bmatrix} 1 & x_1 & \cdots & x_1^k \\ 1 & x_2 & \ldots & x_2^k \\ \vdots & \vdots & \ddots & \vdots \\ 1 & x_n & \cdots & x_n^k \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_k \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \tag{2}$$

The equation of the coefficient matrix A is as follows:

$$A = X^{-1}Y \tag{3}$$

This paper compares the new model with the original one and computes the results by using the least square fitting method. All models are evaluated by using various indicators, and the most suitable model equations for various climate regions in China are obtained. This paper uses the R^2, RMSE, MABE, MBE, and GPI methods for data evaluation. The calculation methods are as follows:

(1) determination coefficient

$$R^2 = \frac{\left[\sum_{i=1}^{n} (Y_{i,c} - \bar{Y}_{i,c})(Y_{i,m} - \bar{Y}_{i,m})\right]^2}{\sum_{i=1}^{n} (Y_{i,c} - \bar{Y}_{i,c})^2 \sum_{i=1}^{n} (Y_{i,m} - \bar{Y}_{i,m})^2} \tag{4}$$

(2) root mean square error

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Y_{i,m} - Y_{i,c})^2}{n}} \tag{5}$$

(3) mean absolute bias error

$$MABE = \frac{1}{n}\sum_{i=1}^{n} \left(\left|Y_{i,m} - Y_{i,c}\right|\right) \tag{6}$$

(4) mean bias error

$$MBE = \frac{1}{n}\sum_{i=1}^{n} (Y_{i,m} - Y_{i,c}) \tag{7}$$

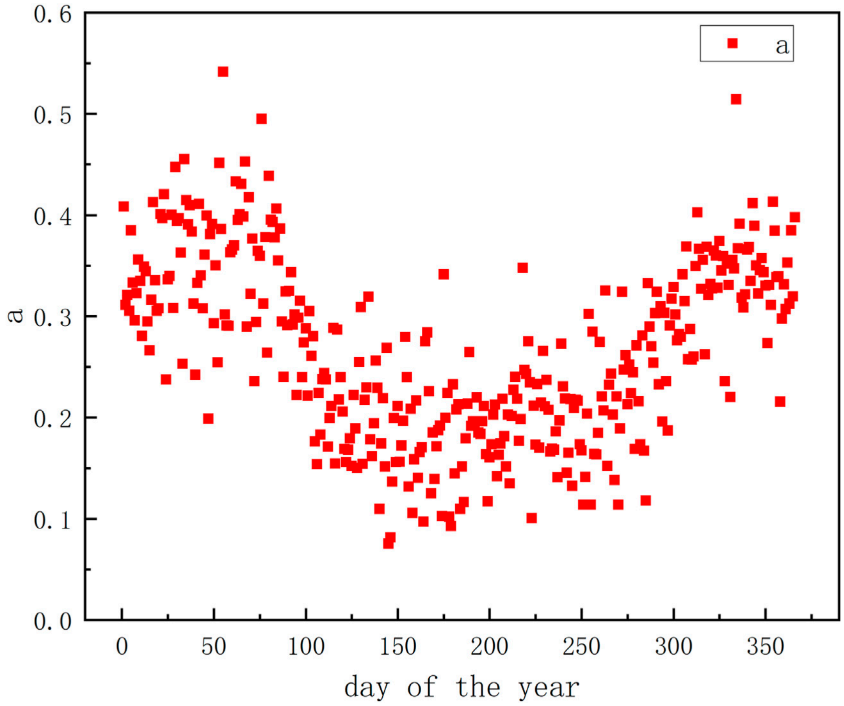

FIGURE 2
Annual change distribution of empirical coefficient a.

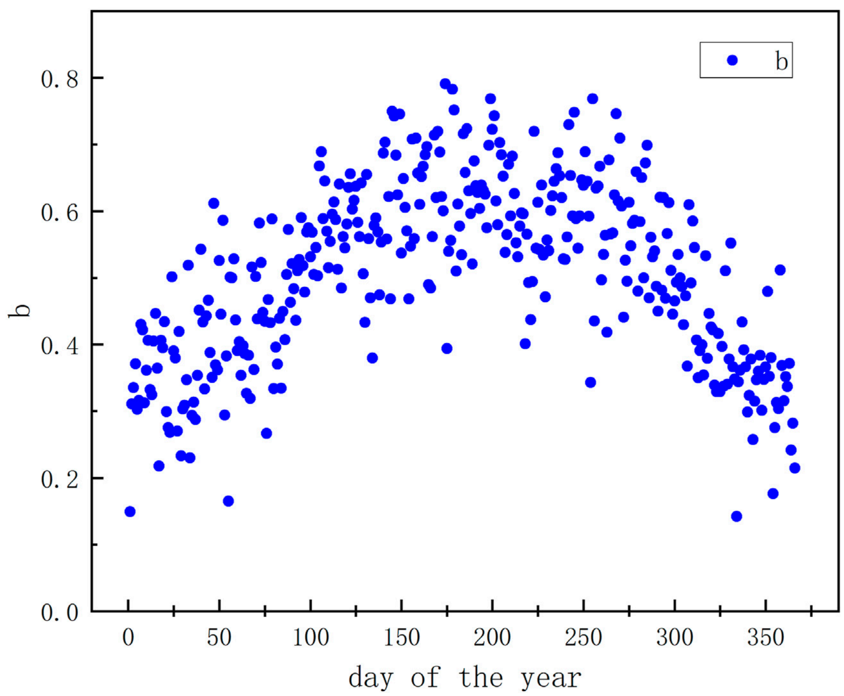

FIGURE 3
Annual change distribution of empirical coefficient b.

TABLE 2 The modified empirical model proposed in this paper.

Model ID	Model equation
N1	$H = H_0[a_0 + a_1 \sin\delta + (b_0 + b_1 \sin\delta)S/S_0]$
N2	$H = H_0[a_0 + a_1 \sin\delta + (b_0 + b_1 \sin\delta)\ln\ (S/S_0 + 1)]$
N3	$H = H_0[a_0 + a_1 \sin\delta + (b_0 + b_1 \sin\delta)(S/S_0)^c]$
N4	$H = H_0[a_0 + a_1 \sin\delta + (b_0 + b_1 \sin\delta)(S/S_0)^{1.5}]$
N5	$H = H_0[a + b(S/S_0)^{c+d\sin\delta}]$
N6	$H = H_0[a_0 + a_1 \sin\delta + (b_0 + b_1 \sin\delta)(S/S_0)^2]$
N7	$H = H_0[a + b(S/S_0) + c(S/S_0)^2 + d\sin\delta]$
N8	$H = H_0[a + b(S/S_0) + c(S/S_0)^2 + d(S/S_0)^3 + e\sin\delta]$

(5) global performance index

$$\mathbf{GPI}_i = \sum_{j=1}^{4} \alpha_j\left(\overline{y_j} - y_{ij}\right) \tag{8}$$

Where y_{ij} is the standardized value of the j-th index of the i-th model, $\overline{y_j}$ is the median of y_{ij}, $y_{i,m}$ is the measured value, $y_{i,c}$ the is calculated value, and n is the number of observations. For $j = 1(R^2)$, α_j is equal to -1, whereas for other indicators, α_j is equal to 1.

R^2 is the ratio of the regression sum of squares to the total sum of squares. The model's performance improves as R^2 gets closer to 1. The degree of dispersion between the calculated and measured values is represented by the RMSE, which is always greater than 0, and the smaller the value, the better the result. MABE is a statistic that describes the degree of data dispersion, which can be used to better reflect the actual situation of the predicted error. The smaller the value, the better the result. Models with higher accuracy have higher GPI values.

5 Results and discussion

In this paper, the least squares method is used to fit the solar radiation data of 83 stations under 21 equations, and various evaluation indicators are obtained. The boxplots of each indicator under 21 equations are drawn, and the different results of each indicator in 5 radiation zones, as well as the graphs of the global performance indicators, are also drawn.

As can be seen from the Figure 4, the values of R^2, RMSE, MABE, and MBE for these models range from 0.82 to 0.99, 0.018–3.09 $MJm^{-2}d^{-1}$, 0.014–1.74 $MJm^{-2}d^{-1}$, −0.71–1.31 $MJm^{-2}d^{-1}$, the average values are 0.97, 1.34 $MJm^{-2}d^{-1}$, 0.67 $MJm^{-2}d^{-1}$, −0.028 $MJm^{-2}d^{-1}$. Among them, the model S7 and N4 have poorer performances, and the values of the evaluation indicators of the model S7 are all the last digits in each model. The S7 model is in the form of a power function, so it can be seen that the empirical equation in the form of a power

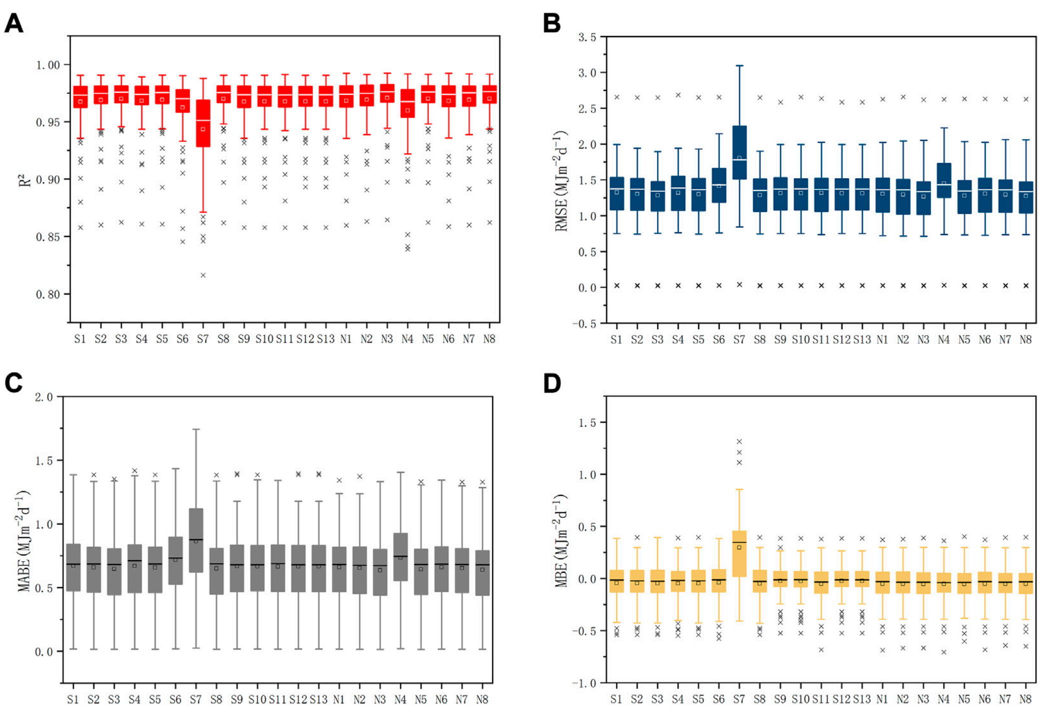

FIGURE 4
Boxplots of evaluation indicators for each model. **(A)**Boxplots for each model R^2; **(B)**Boxplots for each model RMSE; **(C)**Boxplots for each model MABE; **(D)**Boxplots for each model MBE.

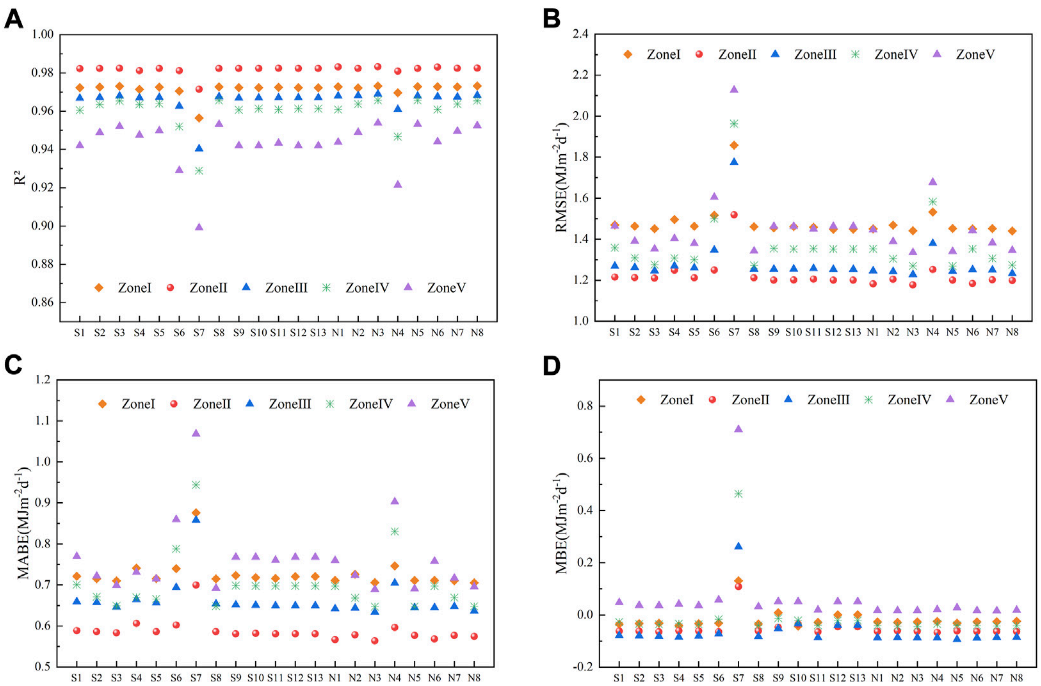

FIGURE 5
The average evaluation index of the models in each climate zone. **(A)** R^2 values of different models in each climate zone; **(B)** RMSE values of different models in each climate zone; **(C)** MABE values of different models in each climate zone; **(D)** MBE values of different models in each climate zone.

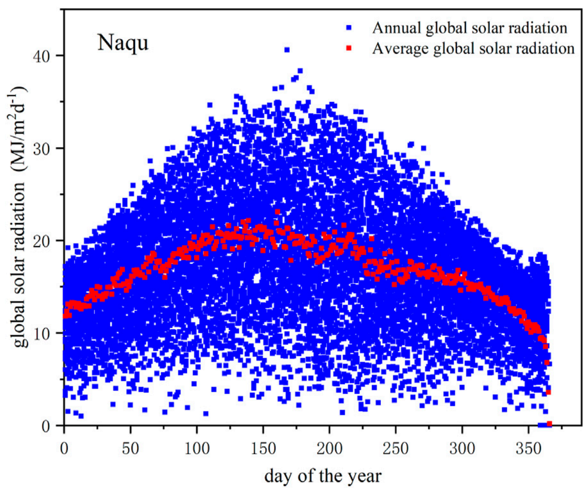

FIGURE 6
The distribution of *H* in Naqu over 37 years.

function is used to estimate the total solar radiation with poor results. The N4 model is a 1.5th power function model after the correction of the empirical coefficient, and the result is not good. Except for the N4 model, the prediction accuracy of the rest of the new models, after the correction of the empirical coefficients, has improved. Therefore, for the traditional empirical models, the use of the declination angle δ to correct the empirical coefficients can effectively improve the model accuracy.

Among all the models, the N3 model in the new model has the best performance. The R^2, RMSE, MABE, MBE values of this model range from 0.86 to −0.99, 0.018–2.62 $MJm^{-2}d^{-1}$, 0.014–1.33 $MJm^{-2}d^{-1}$, −0.67–0.39 $MJm^{-2}d^{-1}$. The N3 model is a power function model after correcting the empirical coefficients. Compared with the S8 model, it can be seen that the accuracy of the exponential model including the constant term, after the correction of the declination angle δ, has improved. Compared with the N4 model, it can be seen that limiting the exponential value of the exponential model will reduce the prediction accuracy of the model. Different from the value improvements of the uncorrected individual models, the R^2 value improvement ranges from 0.076% to 2.89%, and the RMSE value reduction is between 1.36% and 29.8%.

When model S7 is used to predict the *H*, if it is under cloudy conditions, *S* equals zero, and the predicted *H* by the model is also zero. However, in fact, the *H* must be greater than zero. Therefore, the prediction accuracy of S7 is limited. It can be only used to predict the *H* on clear days, and it is not applicable in

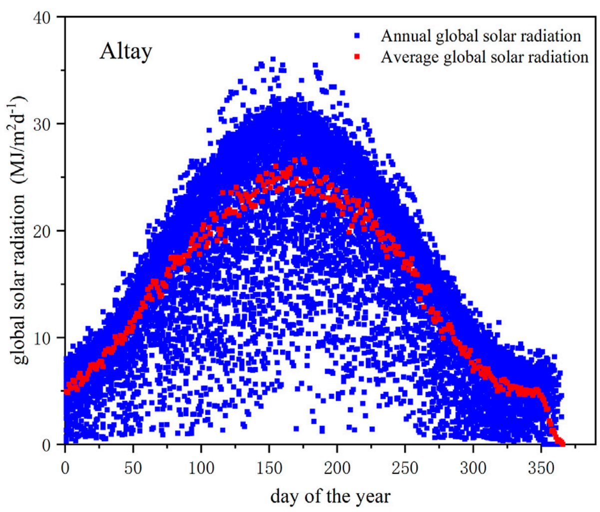

FIGURE 7
The distribution of *H* in Altay over 37 years.

cloudy conditions. As for the yearly *H*, it produces poor results. In terms of model N4, due to the influence of aerosol concentration and other factors, the variation law between the *H* and the *S* of each station is not a definite value. Therefore, the deterministic coefficients of the model reduce the prediction accuracy of the model. As for N3, the constant term of the model is not zero, and it also has the fluctuating characteristics of coefficient changes, which is suitable for prediction under various climatic conditions. The coefficients in N3 can be changed with the change of the station data, which improves the flexibility of the model and makes its prediction result the best among all the models.

It can be seen from Figure 5 that for all models in different partitions, the indicators R^2, RMSE, and MABE have the best performance in zone II, and their ranges are 0.95–0.99, 0.72–2.06 $MJm^{-2}d^{-1}$, and 0.27–1.01 $MJm^{-2}d^{-1}$ respectively. Zone V has the worst performance, with the ranges of 0.85–0.98, 0.018–3.09 $MJm^{-2}d^{-1}$, and 0.014–1.74 $MJm^{-2}d^{-1}$, respectively. For the indicator MBE, the performance of zone I is the best, and its range is −0.41–0.44 $MJm^{-2}d^{-1}$, and the performance of zone III is the worst, and its range is −0.53–0.71 $MJm^{-2}d^{-1}$. The newly-built model N3 has the best evaluation performance in each region, while the R^2 evaluation model ranks second in Zone I and first in the remaining regions. The average values of R^2 are 0.97, 0.98, 0.97, 0.97, and 0.95 in the I-V zones, respectively. The average values of RMSE of I–V zones are 1.44 $MJm^{-2}d^{-1}$, 1.18 $MJm^{-2}d^{-1}$, 1.23 $MJm^{-2}d^{-1}$, 1.27 $MJm^{-2}d^{-1}$, and 1.34 $MJm^{-2}d^{-1}$ respectively. The average MABE values of I-V zones are 0.71 $MJm^{-2}d^{-1}$, 0.56 $MJm^{-2}d^{-1}$, 0.63 $MJm^{-2}d^{-1}$, 0.65 $MJm^{-2}d^{-1}$, and 0.69 $MJm^{-2}d^{-1}$, and the mean values of MBE are −0.027 $MJm^{-2}d^{-1}$, −0.063 $MJm^{-2}d^{-1}$, −0.087 $MJm^{-2}d^{-1}$, −0.045 $MJm^{-2}d^{-1}$, and 0.016 $MJm^{-2}d^{-1}$ respectively. Model S7 has the worst adaptation performance of each evaluation index in the five climatic zones. The average R^2 and RMSE values in each zone are 0.96, 0.97, 0.94, 0.93, and 0.90, and 1.86 $MJm^{-2}d^{-1}$, 1.52 $MJm^{-2}d^{-1}$, 1.77 $MJm^{-2}d^{-1}$, 1.96 $MJm^{-2}d^{-1}$, and 2.13 $MJm^{-2}d^{-1}$, respectively. The average MABE values of I-V zones are 0.88 $MJm^{-2}d^{-1}$, 0.70 $MJm^{-2}d^{-1}$, 0.86 $MJm^{-2}d^{-1}$, 0.94 $MJm^{-2}d^{-1}$, and 1.07 $MJm^{-2}d^{-1}$, and the mean values of MBE are 0.13 $MJm^{-2}d^{-1}$, 0.11 $MJm^{-2}d^{-1}$, 0.26 $MJm^{-2}d^{-1}$, 0.46 $MJm^{-2}d^{-1}$, and 0.71 $MJm^{-2}d^{-1}$, respectively.

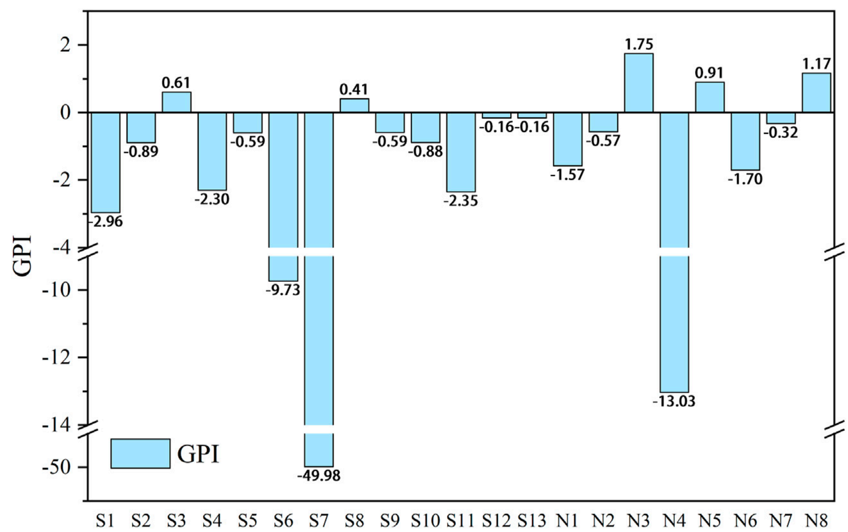

FIGURE 8
Global performance indicators of each model.

Comprehensive analysis. The performance of all models in zone II is generally higher than those in other regions, and their performance in zone V is the worst. Figure 6 shows the distribution of *H* in Naqu over 37 years. Naqu belongs to zone I (high radiation zone). The reason that the radiation in zone I is high is due to the high atmospheric transparency. As a result, the *H* on clear and cloudy days varies greatly, as shown in Figure 6, and the distribution of *H* is much more discrete. Therefore, the prediction accuracy of models decreases. In comparison, zone II belongs to the long sunshine duration zone. The reason why the radiation in zone II is high is because of the long sunshine duration. Take Altay as an example. Figure 7 shows *H* distribution. It is can be easily found that the distribution of *H* is much more concentrated. Therefore, the prediction accuracy of the model in zone II is the best. The difference in solar radiation between clear and cloudy conditions is large. We can see from the figure that the distribution of global solar radiation values is more discrete, resulting in the accuracy of each prediction model being lower than that of the stations in zone II. Area II has a long-day and arid area with enough solar radiation and long sunshine duration, and the environment is less affected by other meteorological conditions. As can be seen from Figure 7, the global solar radiation value at the Altay site is more concentrated, so the performance of each model in this zone is the best. Zone V has high humidity and a low solar radiation area. Precipitation, cloud cover, and other factors influence the relationship between global solar radiation and sunshine rate, so each model's performance in zone V is the worst.

This paper uses four evaluation indicators, but the comprehensive performance of the model cannot be judged by a single evaluation indicator. Therefore, the GPI value is used to rank the model. It can be seen from Figure 8 that model N3 has the best performance with a GPI value of 1.75; model S7 has the worst performance with a GPI value of −49.98. The comprehensive evaluation results are consistent with the above model analysis and regional evaluation results.

6 Conclusion

This article reviews more than 100 papers on prediction models of global solar radiation based on sunshine rate. By introducing the astronomical factors to modify the empirical coefficients, eight new categories of daily global solar radiation models have been proposed. The radiation data from 83 meteorological stations in China is used to train and validate models of 21 categories. The main conclusions of this study are as follows:

(1) Although different combined models have been developed, the model performances have not improved that much. Furthermore, the difficulties of the acquisition of required meteorological data have increased sharply. Therefore, the sunshine-based models should be the best model for global solar radiation prediction, which yields higher accuracy and less meteorological data.
(2) The power function model with declination angle outperforms all other models. The R^2 value is the highest in long-sunshine and arid areas (~0.98), and the smallest in high-humidity areas (~0.95). The average value of RMSE is in a range of 1.15–1.44 $MJm^{-2}d^{-1}$. The maximum and minimum average values of MABE are 0.71 $MJm^{-2}d^{-1}$ and 0.54 $MJm^{-2}d^{-1}$ respectively. The minimum and maximum MBE values are -0.091 $MJm^{-2}d^{-1}$ and—0.027 $MJm^{-2}d^{-1}$ respectively.
(3) A method is proposed to modify the empirical models by using astronomical factors. The modified models improve R^2 by 0.076%–2.89%, and the RMSE value decreases by 1.36%–29.8%, allowing it to predict the more accurate value of daily global solar radiation.

To improve the accuracy of sunshine-based models, this paper introduces the astronomical factor to modify the empirical coefficient, but the changes of empirical coefficients in other kinds of models have not been discussed yet. In the future research, more models will be discussed, such as temperature-based models. Concurrently, this paper only focuses on the influence of the sun's declination angle. In fact, more astronomical, meteorological, and geographical parameters should be covered, such as the day of the year.

Author contributions

All authors contributed to this work. Methodology, KL and LW; software, LW and YZ; investigation, KL, ZZ, and SF; resources, KL; writing—original draft preparation, LW; writing—review and editing, YZ; supervision, SF and PC All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.1010745/full#supplementary-material

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