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New combined models for estimating daily global solar radiation based on sunshine duration in humid regions: A case study in South China

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A R T I C L E I N F O

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A B S T R A C T

In the present study, two single (T1 and T2) and eight combined (C1–C8) sunshine-based empirical models for estimating daily horizontal global solar radiation were compared, and four new combined sunshine-based models (P1–P4) were developed. The accuracy and applicability of these models were further evaluated in South China with humid subtropical and tropical climates influenced by the Asian monsoon as a case study. For this purpose, daily meteorological data during 1966–2000 from 20 radiation stations were used for model calibration and the data from 2001 to 2015 were used to validate the models. These models were evaluated and compared based on coefficient of determination (R^2), root mean square error (RMSE), normalized root mean square error (NRMSE), mean bias error (MBE) and a global performance index (GPI). The single sunshine-based model T2 was recommended for R_s estimation with acceptable accuracy when using only sunshine duration data. In terms of combined sunshine-based models, the newly proposed model P3 was the optimum model for daily global solar radiation estimation when sunshine duration, air temperature and precipitation were available. The proposed complex model P4 was recommended for estimating daily global solar radiation with an excellent accuracy when vapor pressure deficit and relatively humidity were further available. Generally, the proposed combined models based on sunshine duration can be applied for daily global solar radiation estimation with high accuracy in humid regions of China and maybe elsewhere with similar climate.

1. Introduction

Global solar radiation (R_s) arriving on the Earth's surface is a fundamental input for the optimum design and use of solar energy conversion systems [1–3]. However, unlike other routinely observed meteorological variables (e.g. sunshine duration, air temperature, precipitation and relative humidity), global solar radiation measurements are not readily available at many worldwide sites due to the high costs and the difficulty in maintenance and calibration of the recording equipment [4]. Thus, different methods have been developed to indirectly estimate R_s as a result of the lack of measured global solar radiation data, such as empirical models [5], artificial intelligence-based models [6–8] and satellite-based methods [9]. Among the above mentioned methods, empirical models are more commonly used due to their readily available inputs and low computational costs [4,10].

Over the past few decades, different types of empirical models have been established to predict global solar radiation, e.g. sunshine-based models [11–13], temperature-based models [10,14,15] and complex models which estimate R_s by combing various meteorological variables [5,11,16]. The single sunshine-based empirical models have been reported to generally give better R_s estimates than those based on air temperature or other single meteorological variables [17,18]. The Angström–Prescott correlation [19,20] was the first and most commonly used sunshine-based model for its simplicity and acceptable performance [21]. The modified quadratic and cubic forms of Angström–Prescott model by Rietveld [22] and Bahel et al. [23] were also widely applied under various climatic conditions [24–26]. Other forms of Angström–Prescott model (e.g. logarithmic and exponential) have also been proposed and applied around the world [27,28]. Duzen and Aydin [29] evaluated all these single sunshine-based models by using data from seven meteorological stations in the Eastern Anatolia region of Turkey. They have identified the best performances of cubic model for four stations and quadratic model for the other three stations. Al-Mostafa et al. [30] and Yao et al. [31] also reviewed and compared

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different forms of single sunshine-based models. The Angström–Prescott model was found to be best suited for estimating global solar radiation for Jouf, Saudi Arabia, while the polynomial models were the most accurate models for estimating global solar radiation for Shanghai, China.

In addition, the accuracy of R_s estimations can be largely improved by combining the sunshine duration data with other meteorological data, e.g. maximum and minimum air temperature, precipitation, relative humidity, vapor pressure deficit and dew point temperature [4,24,32]. However, different input forms of meteorological variables (e.g., linear, logarithmic and power) have various effects on the accuracy improvement of the complex sunshine-based models. Chen et al. [24] corrected Angström–Prescott model by considering a logarithmic relationship between the daily global radiation and the diurnal temperature difference and this revised model was better than the Angström–Prescott model and the Bahel model. Chen et al. [32] established combined models for estimating daily solar radiation at 45 stations in China as a function of relative sunshine duration, a power form of diurnal temperature range, average air temperature, precipitation, vapor pressure deficit and relative humidity. Kirmani et al. [33] also proposed combined models to obtain global solar radiation in New Delhi, India based on relative sunshine duration, average air temperature, precipitation and relative humidity. Jahani et al. [4] corrected the Angström–Prescott model for global radiation estimation in Iran by adding a power form of diurnal temperature range, precipitation and dew point temperature. They found that their newly proposed combined models were the top ranked models.

Previous studies have indicated that the low values of global solar radiation were closely related to the negative meteorological conditions such heavy clouds during rainy days, low vapor pressure deficit and high relative humidity in humid regions [3], which perfectly apply to the case in South China characterized by humid subtropical and tropical climates. Thus, the objectives of the present study were to: (1) assess the applicability and performance of two commonly applied empirical models that use only sunshine duration data and eight existing models that combine sunshine duration with air temperature, precipitation, relative humidity and vapor pressure deific for daily global solar radiation estimation based on four statistical indicators and a global performance index; and (2) develop four new combined model that employ sunshine duration and other readily available meteorological data for estimating R_s in the humid regions and further evaluated the proposed models in South China as a case study.

2. Materials and methods

2.1. Study area

The humid subtropical and tropical regions in South China (Fig. 1) are characterized by a mean annual precipitation of 1323 mm (mainly occurred from June to September) and a mean annual pan evaporation of 1545 mm. The mean annual air temperature is 18.3 °C and the relative air humidity is 76.0%.

2.2. Data collection and analysis

Continuous and long-time series of observed daily global solar radiation on horizontal surface, sunshine duration, air temperature, precipitation, vapor pressure deficit and relative humidity during 1966–2015 were collected from 20 radiations in the humid subtropical and tropical regions of China (Fig. 1). A detailed description of the selected radiation stations can be found in Table 1. The weather data were provided and quality examined by the National Meteorological Information Center (NMIC) of China Meteorological Administration (CMA). These daily data were excluded if any of the above meteorological data was missing or the ration between the measured radiation and the extra-terrestrial radiation or the ratio of the actual sunshine duration and the potential sunshine duration was higher than 1. The measured data during 1966–2015 were then divided into two datasets. The first dataset (1966–2000) were used to develop empirical correlations, while the second dataset (2001–2015) were used to validate and evaluate the calibrated empirical models.

2.3. Selection of sunshine-based models

Table 2 presents the two single sunshine-based empirical models (T1 and T2), eight existing (C1–C8) and four proposed (P1–P4) complex sunshine-based models in the present study. These models were selected on the basis of their wide applicability in different climates and regions.

(1) Single sunshine-based models

The first and commonly used sunshine-based model for predicting global solar radiation was developed by Angström [19] and further revised by Prescott [20], who obtained a linear relation between the ratio of global solar radiation to the daily extra-terrestrial solar radiation and the ratio of daily sunshine duration to maximum possible sunshine duration (relative sunshine duration). The Angstrom-Prescott model (represented here by T1) is as follows:

$$R_s = R_a\left(a + b\frac{n}{N}\right) \quad (1)$$

where R_s is the global solar radiation (J m^{-2} d^{-1}); R_a is the daily extra-terrestrial solar radiation (J m^{-2} d^{-1}), which can be determined as per the procedures described by Allen et al. [34] as a function of site latitude, solar declination angle and Julian day of the year; n is the daily sunshine duration (hr); N is the maximum possible sunshine duration (hr).

Bahel et al. [23] derived a polynomial worldwide correlation based on monthly average daily global solar radiation and sunshine duration data of 48 radiation stations (shown here as T2):

$$R_s = R_a\left[a + b\frac{n}{N} + c\left(\frac{n}{N}\right)^2 + d\left(\frac{n}{N}\right)^3\right] \quad (2)$$

(2) Combined sunshine-based models

Chen et al. [24] developed a combined model based on a power form of relative sunshine duration and a logarithmic form of diurnal temperature range (shown here as C1):

$$R_s = R_a\left[a + b\left(\frac{n}{N}\right)^c + d\ln(\Delta T)\right] \quad (3)$$

where T is the diurnal temperature range (°C), which is calculated as the difference of daily maximum temperature (T_{max}, °C) and minimum temperature (T_{min}, °C).

Two combined models have been recently proposed by Jahani et al. [4] for estimating daily R_s, as a function of relative sunshine duration, a power form of diurnal temperature range, precipitation and dew point temperature (shown here as C2 and C3, respectively):

$$R_s = R_a\left(a + b\frac{n}{N} + cP + d\Delta T_{dw}\right) \quad (4)$$

$$R_s = R_a\left(a + b\frac{n}{N} + c\Delta T^{0.5} + d\Delta T_{dw}\right) \quad (5)$$

where P is the precipitation (mm); ΔT_{dw} is the dew point temperature and determined as the difference of dry (T_{dry}, °C) and wet (T_{wet}, °C) bulb temperature.

Kirmani et al. [33] also proposed a combined model to obtain global solar radiation based on relative sunshine duration, average air temperature, precipitation and relative humidity (shown here as C4):

$$R_s = R_a\left(a + b\frac{n}{N} + cT + dP + eH_r\right) \quad (6)$$

where H_r is the relative humidity.