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A new correlation between global solar radiation and the quality of sunshine duration in China

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ABSTRACT

Accurate and reliable solar radiation models are important in the building energy conservation, solar thermal and photovoltaic utilization, agricultural production and ecological environment, in which the global solar radiation model based on sunshine percentage is the most common model. Sunshine duration only reflects the time accumulation of solar radiation, but cannot reflect its intensity accumulation. Therefore, it is difficult to improve the accuracy of such models. To solve this problem, a new quality of sunshine duration model (QSD model) is proposed, which takes into account both the influence of sunshine duration on solar radiation and the effect of solar radiation intensity on the accumulation of day. The QSD model is simplified from the energy balance equation which is established based on theoretical analysis of the heat transfer process among the Earth's surface layer, air layer and atmospheric layer. Then Meteorological data of 24 stations are utilized to analyze the accuracy of QSD model. The results show that the QSD model is more accurate, and the accuracy of QSD model is best during sunny days, followed by cloudy days, whereas overcast days provide the worst results. Meanwhile, a QSD model is obtained based on data from different regions. Statistical analysis shows that a QSD model has universal applicability in China, and the average value of correlation coefficient (R) is 0.929, Nash-Sutcliffe equation (NSE) is 0.864, and root mean squared error (RMSE) is 0.088.

1. Introduction

The solar radiation model plays a significant role in solar photovoltaic and solar thermal, and is also essential in building energy simulation and evaluation [1]. Because lack of measuring equipment, relocation and maintenance of meteorological stations, many regions have incomplete data or no solar radiation data [2,3].

To solve this problem, many scholars have put forward a series of empirical models to estimate global solar radiation on a horizontal surface. According to different meteorological parameters, global solar radiation empirical models can be divided into four categories. The first kind of models are based on sunshine duration. Angstrom firstly derived a linear relationship between the ratio of average daily global solar radiation to the corresponding value on a completely clear day and the ratio of average daily sunshine duration to the maximum possible sunshine duration [4]. Then Prescott proposed a linear relationship between the clearness index and sunshine percentage based on Angstrom's model [5]; thereafter, many researchers presented a series of modifications by adding relevant meteorological parameters [6–13]. The second kind of proposed models are based on cloud cover. Black firstly proposed this kind of models [9] to estimate global solar radiation by cloud cover data; Paltridge, Badescu and other scholars made further corrections in this kind of models [14,15]. The third kind of models are based on temperature. Hargreaves set up the models to estimate global solar radiation based on temperature difference. Bristow, Campbell and Allen made the furthering exploration based on Hargreaves' research [16–19]. The fourth kind of models are based on other parameters. For instance, Swartman and Ogunlade [20] proposed a composite model based on sunshine percentage and relative humidity, whereas Sabbagh established a new model based on sunshine duration, daily maximum temperature and relative humidity [21]. Moreover, some scholars, such as Bulut and Büyükalaca [22], Li et al. [23], Quej et al. [24], created a new model for ordinal numbers to estimate solar radiation, according to the periodic variation of solar radiation. In addition to the conventional empirical model, satellite imagery and artificial neural network are also used to calculate the global solar radiation [25–28]. For example, through the mathematical processing method, Ramirez Camargo [29] used satellite imagery to obtain the

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Nomenclature

α_1	solar radiation absorption coefficients of the air layers (dimensionless)
α_2	solar radiation absorption coefficients of the soil layers (dimensionless)
H_1	the flux of solar energy incident on the air layers (MJ/m^2)
H_2	the flux of solar energy incident on the soil layers (MJ/m^2)
$a,b,c,d,e,f,g,h,i,j,k,l,m,n$	equation coefficient or constant (dimensionless)
E_{air}	the energy content of the air layers (MJ/m^2)
E_{soil}	the energy content of the soil layers (MJ/m^2)
T_a	the daily instant time temperature (°C)
h_1	the convective heat transfer coefficient between the air layers and the soil layers (W/(m^2·K))
k_1	the heat transfer coefficient between the air layers and the soil layers (W/(m^2·K))
λ	thermal conductivity of interface between the air layers and the soil layers (W/(m^2·K))
δ	thickness of interface between the air layers and the soil layers (m)
Q	quality of sunshine duration (MJ/m^2)
H	daily global solar radiation on horizontal surface (MJ/m^2)
N	daily sunshine duration (h)
α	solar altitude at noon (degree)

global solar radiation. Baser and Demirhan [30] presented a fuzzy regression using the support vector machine approach to estimate solar radiation for Lerma Valley in Argentina. Ibrahim [31] proposed a novel hybrid model for the prediction of hourly global solar radiation using the random forest techniques and firefly algorithms.

There are some empirical models in the literature, in which cloud cover, temperature and relative humidity are not direct factors influencing solar radiation. Therefore, the accuracy of solar radiation models based on these parameters is generally not high. Sunshine duration is a straightforward factor of solar radiation, but daily global solar radiation does not only depend on sunshine duration, but also on solar radiation intensity (especially in different seasons). As shown in Fig. 1, global solar radiation measured in the same region at different times across a two-day period varies greatly even though sunshine duration was the same.

In this paper, energy balance equation among the Earth's surface layer, air layer and atmospheric layer is established based on theoretical analysis of the heat transfer process. By simplifying it, a new model based on a linear relationship between daily global solar radiation and the quality of sunshine duration (QSD) is proposed. In addition, compared with existing models in literature, the performance of the QSD model is discussed. Finally, measured data from 24 stations in the last 24 years is utilized to verify the applicability of the new QSD models in China.

Compared with the Angstrom-Prescott type models, the proposed model not only takes into account the time cumulative effect of global solar radiation (sunshine duration), but considers the cumulative effect of global solar radiation intensity. So it is significant to further improve the accuracy of global solar models. For the countries or regions which are lack of testing station or testing equipment, the daily global solar radiation can only be estimated by sunshine duration and some geographical parameters. The results of this study can improve the accuracy of global solar radiation in these regions, and it has a great significance to the evaluation, utilization and transformation of solar resources.

2. Theoretical analysis

Solar energy is scattered into the environment in the form of solar radiation, and is absorbed by plants and transformed into different form of energy. This is the primary source of energy stored by fossil fuels on the Earth [32]. Solar energy utilization is directly related to the solar radiation received by the ground layer, which can be reflected by the energy balance of the air layer near the ground layer [33]. In fact, for a certain range in space, only the Earth's surface and the atmospheric layer have direct impacts on the air layer near the ground. Consequently, this paper takes the air layer near the ground as a research object, and analyzes the influence of solar radiation on its energy variation.

For a system consisting of the Earth's surface and a layer of atmosphere, it is assumed that there is only one energy input (solar energy), which means that the system does not produce energy. This system is composed of the Earth's surface layer (surface layer for short), air layer and atmospheric layer. Based on the above analysis, the following assumptions are proposed: (1) In the unit area above the Earth's surface, the surface layer, air layer and atmospheric layer are parallel to each other; (2) The direction of the temperature gradient is perpendicular to each layer; (3) The air layer is transparent and it does not generate heat.

Based on the above assumptions, the instantaneous energy balance equation of the unit air layer is as follows.

$$\frac{\partial E_{air}}{\partial t} = \alpha_1 H_1 + h_1(T_s - T_a) + \lambda(T_s - T_a)/\delta + k_1(T_u - T_a) + R_1 + R_2 \quad (1)$$

In Eq. (1), $\frac{\partial E_{air}}{\partial t}$ is the energy variation of unit air layer per unit time. $h_1(T_s - T_a)$, $\lambda(T_s - T_a)/\delta$ and R_1 are the convective heat transfer, conduction heat transfer and radiation heat transfer between the air layer and surface layer respectively. $k_1(T_u - T_a)$ and R_2 are the convective heat exchange (including convective heat transfer and conduction heat transfer) and radiation heat transfer from the air layer to the upper atmosphere. For the surface layer, the instantaneous energy balance equation is as follows.

$$\frac{\partial E_{soil}}{\partial t} = \alpha_2 H_2 + h_1(T_a - T_s) + \lambda(T_a - T_s)/\delta + R_1 + q_1 \quad (2)$$

In Eq. (2), $\frac{\partial E_{soil}}{\partial t}$ is the variation of the unit surface layer per unit time; q_1 is the heat transfer from the surface layer to the deep underground layer.

Eq. (3) is arrived at by combining Eqs. (1) and (2).

$$\frac{\partial E_{air}}{\partial t} + \frac{\partial E_{soil}}{\partial t} = \alpha_1 H_1 + \alpha_2 H_2 + k_1(T_u - T_a) + R_2 + q_1 \quad (3)$$

For solar radiation, heat transfer between the air layer and the

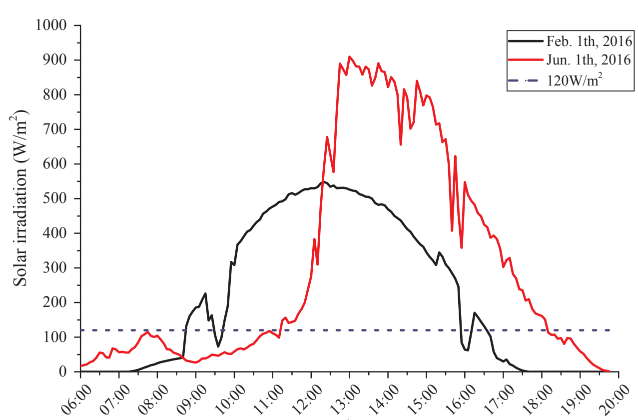

Fig. 1. Variation of solar radiation with time.