Energy xxx (2015) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Changes in the relationship between solar radiation and sunshine duration in large cities of China

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ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form
20 January 2015
Accepted 21 January 2015
Available online xxx

Keywords:
Solar radiation
Sunshine duration
Angstrom model
Linear relationship
Calibration

ABSTRACT

Based on the linear relationship between solar radiation and sunshine duration, the Angstrom model is widely used to estimate solar radiation from routinely observed meteorological variables for energy exploitation. However, the relationship may have changed in quickly developing regions in the recent decades under global “dimming” and “brightening” context, with increasing aerosols due to industrial pollutions. Solar radiation stations under different climate conditions in six large cities in China are selected to test this hypothesis. Analysis of the related meteorological items shows that Guiyang has the lowest solar radiation with the average annual value of 10.5 $MJm^{-2}d^{-1}$, while Lhasa on the Tibetan Plateau has the highest of 20.1 $MJm^{-2}d^{-1}$. Both radiation and sunshine hours decreased from 1961 to 2010, but at different rates. A moving linear regression method is used to investigate the changes in the relationship between radiation and sunshine duration, the results indicate an abrupt change in the correlation coefficients in 1980–1990s, which can be attributed to the aerosol load resulting from air pollution caused by the industrial development in 1980s under China's Open Door Policy. The sky condition has been changing from clean to dirty, thus the relationship between solar radiation and duration changes in the 1980's and has recovered in the recent decades. This finding implies that it might not necessarily be right to use long data sets for model calibration. Further investigation confirms that the Angstrom model performs the best with higher *NSE* (nash-sutcliffe efficiency) of 0.914 and lower *MAPE* (mean absolute percentage error) and *RMSE* (root mean square error) values of 13.7 w/m^2 and 23.9 w/m^2 respectively, when calibrated with a 10-year data set. In contrast, the model performs worst when it is calibrated with a 40-year data set, with *NSE*, *MAPE* and *RMSE* values of 0.891, 15.1 w/m^2 and 25.3 w/m^2, respectively. Based on the findings of this research, a 10-year data set is recommended as the national standard for model calibration in rapidly developing regions of China. Further analogous investigations are needed in other industrial regions to make an international standard for Angstrom model calibration.

1. Introduction

Compared to the energy from fossil fuels, solar energy is believed to be even more important as clean energy not contributing to global warming [1]. Accurate identification of the temporal and spatial distribution of solar radiation is the essential premise to solar energy exploitation. However, solar radiation is not a routinely observed meteorological item as temperature or rainfall due to the high cost of instruments and maintenance. Up to now, solar radiation is only observed at very few particular stations in the developing nations, which means that the estimation of solar radiation is of vital importance for scientists in the domain of energy, meteorology, and agronomy, among others e.g. Refs. [2–5].

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http://dx.doi.org/10.1016/j.energy.2015.01.068
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Robust numerical models have already been established by meteorologists, but the requirement of too many input parameters makes this kind of model suitable only for theoretical analysis rather than practical applications [6,7]. In contrast, simple empirical models are still the main tool for solar radiation estimation [8]. Based on the relationship between solar radiation and readily available meteorological parameters, such as sunshine duration, temperature, rainfall etc., different kind of simple empirical models have been developed [9–12]. Comparison of different kinds of empirical models identified that the sunshine-based model performed better than the temperature- and rainfall-based ones [4,13–15], even under the unique alpine conditions [16], and the sunshine-based Angstrom model is likely the most popular empirical model for solar radiation estimations [13,17–21]. Since the coefficients of the Angstrom model are site-specific, the first step for the model application is to calibrate the model with the collected radiation and sunshine data set. However, the length of the data set used for the calibration seems casual. Different lengths of the data set have been used for model calibration, varying from 1 year [4], 5 years [13], 10 years [20] to 40 year or so [22]. There seems an intuitive tendency that the calibration should be made with data set as long as possible, if only the related data set can be obtained [23]. Of course, in the view of statistics, longer data sets for model calibration always means more reliable parameters [24], under assumption that the relationship between solar radiation and sunshine duration is stationary.

However, there is increasing evidence that the amount of solar radiation incident at the earth's surface is not stable over the years but undergoes significant decadal variations [25], which is referred to as "global dimming" and "brightening" [26]. As for the quickly developing regions like China, Qian et al. [27] suggested that the increasing aerosol loading from emissions of pollutants is responsible for the observed reduced global radiation. It was identified that both radiation and sunshine duration have decreased in the recent decades, partly or entirely due to changes in aerosol concentrations under global "dimming" and "brightening" context [25–28]. If the changing trend of radiation and sunshine duration were not synchronized, we can cautiously envisage that the relationship between solar radiation and sunshine duration may have changed. But up to now, no research to our knowledge has been conducted to test this hypothesis.

With the Open Door Policy in the 1980s, China developed quickly with significant environmental issues, especially air pollution due to increasing aerosols [27]. In this research, solar radiation and sunshine duration data were collected at radiation stations in six large cities of China under different climate conditions. The objectives of the study are: (1) to test the hypothesis that the relationship between radiation and sunshine duration has changed in the large cities of China, under "global dimming and brightening" context; (2) to address a corresponding strategy for solar radiation estimation, if the hypothesis can be validated; and (3) to give the scientific basis for a national standard of solar radiation estimation.

2. Data collection and methodology

2.1. Database

For this research, access to the database of the NMIC (national meteorological information center) was given by the CMA (China meteorological administration). Study of the influence of different time scales on the Angstrom calibration indicated that calibration made on daily basis has important advantages on monthly scale with stabilized coefficients and more accurate prediction [22], therefore daily solar radiation and the related meteorological parameters, including sunshine duration, cloud coverage and rainy days, were collected from the NMIC/CMA database. The data for radiation and sunshine duration were screened according to the rules described by Persand et al. [29]: (1) daily observations were excluded from the database if either sunshine duration or solar radiation was missing; (2) daily observations were excluded if the measured radiation/extra-terrestrial radiation or the actual sunshine duration/potential sunshine duration was greater than 1; and (3) the data for an entire month were excluded if more than 10 days of radiation or sunshine duration were missing for that month. Additionally, stations were selected for this research based on two more strict criteria: (1) the selected stations should measure 4 parameters, i.e. radiation, sunshine duration, cloud cover and rainy days simultaneously; and (2) stations were excluded if the corresponding visibility was not measured. In the end, six radiation stations were selected with data from 1961 to 2010. The distribution of the selected stations is shown in Fig. 1, and more detailed information can be seen in Table 1 [30].

2.2. Methodology

Based on the linear relationship between solar radiation and sunshine duration, the Angstrom model was first suggested in 1924 [17] and modified by Prescott in 1940 [18] as follows:

$$\frac{R_a}{R_e} = a + b\frac{S}{S_0} \tag{1}$$

in which R_a is the actual solar radiation, R_e the daily extra terrestrial solar radiation, S the actual sunshine duration, and S_0 the theoretical sunshine duration. R_e can be calculated according to equations described by Allen et al. [19], and the relationship between R_a/R_e and S/S_0 can be fitted by linear regression [24], through which coefficients of the model and correlation coefficient r between solar radiation and sunshine duration can be obtained.

The *NSE* (nash-sutcliffe efficiency), the *MAPE* (mean absolute percentage error), and the *RMSE* (root mean squared error) [13,14,16,20,22,23], were used as criteria in evaluating the model performance in this study; these statistics can be expressed as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \tag{2}$$

$$MAPE = \frac{\sum_{i=1}^{n}\frac{|O_i - S_i|}{O_i} \times 100}{n} \tag{3}$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2\right]^{\frac{1}{2}} \tag{4}$$

in which O_i is the observed value, S_i the simulated value, $\overline{O}$ the average value of the observed radiation, and n the number of data pairs. *%MAPE* and *%RMSE*, which are the ratios of *MAPE* and *RMSE* to the average value of the observed radiation $\overline{O}$ respectively, are also used for model evaluation. The model is believed to be performed better with a higher value of *NSE* and lower values of *MAPE*, *RMSE*, *% MAPE* and *%RMSE*.

The *t*-test is used to identify the significant differences between parameters before and after the 1980s. The value of t is calculated as [16,23]: