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Research paper

Estimation of available global solar radiation using sunshine duration over South Korea

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ABSTRACT

Besides designing a solar energy system, accurate insolation data is also a key component for many biological and atmospheric studies. But solar radiation stations are not widely available due to financial and technical limitations; this insufficient number affects the spatial resolution whenever an attempt is made to construct a solar radiation map. There are several models in literature for estimating incoming solar radiation using sunshine fraction. Seventeen of such models among which 6 are linear and 11 non-linear, have been chosen for studying and estimating solar radiation on a horizontal surface over South Korea. The better performance of a non-linear model signifies the fact that the relationship between sunshine duration and clearness index does not follow a straight line. With such a model solar radiation over 79 stations measuring sunshine duration is computed and used as input for spatial interpolation. Finally monthly solar radiation maps are constructed using the Ordinary Kriging method. The cross validation results show good agreement between observed and predicted data.

1. Introduction

Precise knowledge of the amount of incoming radiation is not only essential in designing solar power system, but also a vital requirement for many climatological and agricultural forecasting systems. One of the components of nature that has a profound impact on agricultural yield especially in case of grain crops, is solar radiation availability. Therefore, in every simulation model of productivity forecasting, global solar radiation (GSR) is an essential criterion (Na, 2013). Besides, in many global climatic models temporal changes and spectral responsivity of solar radiation are important parameters (Gu et al., 2012; Schmidt et al., 2012; Ermolli et al., 2013; Rind et al., 2014; Vindel et al., 2015). The influence of GSR on atmospheric optical properties has also been well studied in the last few decades (Kaskaoutis et al., 2006; 2008; Guleria et al., 2014). Hence, it can be said that GSR does not only gain its attention as a renewable energy source but also as an important input aspect in many climatological and biological simulation or forecasting models. Thus, at present, there is a growing demand for accurate solar radiation data to evaluate the agricultural production and health as well as to guide decision making system for site selection and assessing the availability of solar energy. However, due to the high installation and maintenance cost, the number of solar radiation stations is still inadequate. This leads to the development of different empirical models using readily available meteorological parameters *e.g.* temperature (Meza and Varas, 2000; Weiss and Hays, 2004; El-Metwally, 2005; Scafetta, 2009; Li et al., 2011), sunshine duration (Iziomon and Mayer, 2002; Wang and Zhang, 2010; Badescu, 2013; Park et al., 2013), cloudiness (Ehnberg and Bollen, 2005; Badescu and Dumitrescu, 2014) and relative humidity, or a combination of them (Kambezidis et al., 1999; Kambezidis and Badescu, 2000). Among them sunshine-based models are widely accepted and they generally provide more accurate results. In 1924, Angstrom proposed a linear equation correlating solar radiation and sunshine hours which was modified by Prescott in 1940. The combined equation generally known as Angstrom–Prescott equation is as follows:

$$K = a + bS \tag{1}$$

Here K ($=H/H_0$), known as clearness index, is the ratio of global radiation at the earth's surface (H) and the extraterrestrial radiation (H_0). Whereas S is the fraction of bright sunshine hours. a and b are equation constants. Sunshine fraction (S) can be rewritten as follows:

$$S = n/N \tag{2}$$

Here n and N are the observed and theoretical sunshine hours in clear-sky conditions respectively.

Subsequently, many modifications and improvement of the

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model for more precise results have been extensively studied by scientists all over the world. The objective of the present work is to compare and validate some models based on sunshine ratio (S) and develop a most suitable one for estimating solar radiation over South Korea.

2. Data and methodology

2.1. Data

The Korean peninsula has a wet temperate climate with distinctive seasonal trend. Cool and dry wind from north-west decreases the ambient temperature throughout winter, whereas south-east wind brings ample amount of moisture with it causing high rainfall during July–August. There are approximately 460 Automatic Weather Stations (AWS) and 96 weather stations for measuring temperature and precipitation, but solar radiation is measured only at 37 of them. Among these, 22 stations have been selected only because of the presence of continuous solar radiation dataset from 2001 to 2013. Daily solar radiation data from 2001 to 2012 is used to develop the models and data from 2013 is used to validate the models. The monthly mean radiation over the rest 15 stations is used for cross validation after interpolation. The details of the data used in this study is summarized in Table 1.

2.2. Filtration of aberrant data

For a pre-defined S value the clearness index (K) differs due to variation in solar declination angle and atmospheric transparency. Depending on the season, for the same sunshine duration the corresponding K value can be varied and it may appear to be somewhat scattered without any flawed in the measurements. But then again sunshine duration measurement is error prone (WMO, 2008). The most common sources of errors are the difference between reference and actual threshold value of global radiation due to weather condition, inaccurate time counting procedure and poor quality of maintenance (Iqbal, 1983; WMO, 2008). Therefore, this inaccurate measurement of S adds unnecessary weight to the performance of models. It may also increase the error parameters as well as lead to a false judgment in selecting the best model. Hence prior to analysis, the measurements errors should be identified and excluded from the dataset. However, as the dataset is affected by natural variation and instrumental error at the same time, it is very difficult to distinguish between the two. For this reason we decided to exclude only questionable data to avoid further introduction of bias. As shown in Fig. 1a there are some cases where according to the data almost 60% of the solar extra-terrestrial radiation was transmitted when bright sunshine duration is only 10% and only 20% of solar radiation was recorded even when there is bright sunshine for 80% of daylight period (as given in red circle). To exclude these questionable data, a statistical bound is employed using boxplot model (Hoaglin et al., 1983).

A standardized method of establishing reasonable or acceptable bounds in the range of any dataset is to use four times of the difference between 3rd and 1st quartile. In the present study, at first, the whole dataset is divided into 100 smaller bands according to their S value. Each band has a width of 0.01. The general statistics of K values for all S bands (*e.g.* 0.11–0.12) is then estimated and the upper and lower limits of K for each band are centered on the median of the corresponding band. The upper and lower limits of K outside 0.1–0.9 S band range considerably diverge from linear trend against S due to concentration of aberrant readings in these regions (Fig. 1b). More stable bounds for the extreme S values were established by extrapolating the bound from the 0.1–0.9 band (red line in Fig. 1b). Data below and above the accepted bounds was excluded. Only 2.3% of the data points have found to be out of the range.

Table 1
Data summary.

Variables	No. of stations	Data type	Time period
Solar radiation			
Model development	22	Daily	2001–2012
Model validation	22	Daily	2013
Validation after interpolation	15	Monthly mean	2013
Sunshine duration			
Model development	22	Daily	2001–2013
Interpolation	79	Daily	2013

2.3. Calculation of extraterrestrial radiation and possible sunshine hours

Assuming that in a day the Sun–Earth distance is constant, the density of solar flux incident on a horizontal surface is computed from the following equations (Duffie and Beckman, 1991)

$$H_0 = \frac{24 \times 3600 G_{SC}}{\pi}\left(1 + 0.033\cos\frac{360 \times \mathrm{DOY}}{356}\right) \times \left(\cos\theta\cos\delta\sin\omega + \omega\sin L\sin\delta\right) \quad (3)$$

$$\delta = 23.45\sin\left(360\frac{284 + \mathrm{DOY}}{365}\right) \quad (4)$$

$$\omega = \cos^{-1}(-\tan\theta\tan\delta) \quad (5)$$

where G_{SC} is the solar constant *i.e.* 1366.1 W m^{-2} (Greymard, 2004), DOY is the day of year, θ is the latitude of the station (deg), δ is the declination angle (deg) and ω is the sunrise hour angle (deg).

Furthermore, the hours of possible sunshine, N is expressed by

$$N = \left(\frac{2}{15}\right)\omega \quad (6)$$

2.4. Model selection

Numerous models have been developed after Angstrom–Prescott equation to estimate solar radiation from sunshine duration (Angstrom, 1924; Prescott, 1940). Various non-linear and more complicated models which include the function of latitude, altitude and average sunshine duration have been proposed in literature (Rietveld, 1978; Kilic and Ozturk, 1983; Bahel et al., 1987; Gopinathan, 1988; Elagib and Mansell, 2000; Jin et al., 2005; Sen, 2007; Badescu, 2013). The empirical models used in the present study are given in Table 2.

The parameters ($P1$, $P3$ and $P4$) of linear and quadratic models are attributed to the function of latitude (θ), annual mean sunshine ratio (S_A) and altitude (Z) of the stations. The values of the intercept ($P2$ and $P5$) are found to be randomly distributed; also the range of their variability is very low (5.01% and 5.98% respectively). Hence the mean value is used in the models.

The parameters of the rest of the models, however, are not found to be significantly correlated with any of the above mentioned three variables and thus have been left as a constant for all stations. Therefore the first 12 models are location based and following 5 models are same for whole country. In view of the nature of our dataset, sometimes the equations have been slightly