Journal of Atmospheric and Solar-Terrestrial Physics 146 (2016) 110–122

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Estimation of global solar radiation using an artificial neural network based on an interpolation technique in southeast China

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ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form
5 May 2016
Accepted 30 May 2016
Available online 31 May 2016

Keywords:
Artificial neural network
Spatial interpolation
Empirical models
Global solar radiation

ABSTRACT

Solar radiation plays important roles in energy application, vegetation growth and climate change. Empirical relations and machine-learning methods have been widely used to estimate global solar radiation (GSR) in recent years. An artificial neural network (ANN) based on spatial interpolation is developed to estimate GSR in southeast China. The improved Bristow–Campbell (IBC) model and the improved Ångström–Prescott (IA–P) model are compared with the ANN model to explore the best model in solar radiation modeling. Daily meteorological parameters, such as sunshine duration hours, mean temperature, maximum temperature, minimum temperature, relative humidity, precipitation, air pressure, water vapor pressure, and wind speed, along with station-measured GSR and a daily surface GSR dataset over China obtained from the Data Assimilation and Modeling Center for Tibetan Multi-spheres (DAM), are used to predict GSR and to validate the models in this work. The ANN model with the network of 9-17-1 provides better accuracy than the two improved empirical models in GSR estimation. The root-mean-square error (RMSE), mean bias error (MBE), and determination coefficient (R^2) are 2.65 MJ m^{-2}, $-$0.94 MJ m^{-2}, and 0.68 in the IA$-$P model; 2.19 MJ m^{-2}, 1.11 MJ m^{-2}, and 0.83 in the IBC model; 1.34 MJ m^{-2}, $-$0.11 MJ m^{-2}, and 0.91 in the ANN model, respectively. The regional monthly mean GSR in the measured dataset, DAM dataset, and ANN model is analyzed. The RMSE (RMSE %) is 1.07 MJ m^{-2} (8.91%) and the MBE (MBE %) is $-$0.62 MJ m^{-2} ($-$5.21%) between the measured and ANN-estimated GSR. The statistical errors of RMSE (RMSE %) are 0.91 MJ m^{-2} (7.28%) and those of MBE (MBE %) are $-$0.15 MJ m^{-2} ($-$1.20%) between DAM and ANN-modeled GSR. The correlation coefficients and R^2 are larger than 0.95. The regional mean GSR is 12.58 MJ m^{-2}. The lowest GSR is observed in the northwest area, and it increases from northwest to southeast. The annual mean GSR decreases by 0.02 MJ m^{-2} decade^{-1} over the entire southeast China. The GSR in 52 stations experiences a decreasing trend, and 21% of the stations are significant at the 95% level.

1. Introduction

Solar radiation is the primary energy source on earth and is indispensable for numerous applications. For example, this radiant energy provides energy for crop growth and affects the potential yield and water use of crops (Hook and Mcclendon, 1992, Supit and Van Kappel, 1998), it leads to different climate zones on earth and determines the regional climate (Budyko, 1969, Tymvios et al., 2005), and it significantly affects the hydrological characteristic and the balance of the ecological system of earth (Ramanathan et al., 2001, Rivington et al., 2005, Zhang et al., 2015a, b). Continuous and accurate solar radiation measurement is imperative to scientific research and energy application over the long term. However, lack of direct measurement of solar radiation is a common issue in many remote and undeveloped areas (Antonanzas-Torres et al., 2014, Davies et al., 1975). Therefore, predicting methods for achieving accurate and continuous solar radiation have been developed in recent decades (Bakirci, 2009, Mohandes and Rehman, 2010).

Many researchers have exploited techniques for solar radiation estimating, and satellite remote-sensing data have been used to derive radiation since the 1960s (Pinker et al., 1995). Chen et al. (2014) estimate the direct, diffuse, and global solar radiation (GSR) during 2003–2011 based on moderate-resolution imaging spectroradiometer (MODIS) products, and a good agreement is observed between the estimated radiation and observations. Polo et al. (2011) estimate the daily global and direct solar radiation in India by using Meteosat-images from 2000 to 2007. Journee and Bertrand (2010) improve the spatial and temporal resolution of

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http://dx.doi.org/10.1016/j.jastp.2016.05.013
1364-6826/

GSR with the site-based data and satellite images over Belgium. Vignola et al. (2007) estimate hourly global, beam, and diffuse irradiance by using GOES8 satellite images. These researchers also test and validate the model with the data from the University of Oregon Solar Radiation Monitoring Network and from Kimberly Idaho. According to Zhang et al. (2015a, b), satellite radiation models show higher accuracy in generating daily irradiation than measured data from ground stations. Qin et al. (2011) demonstrate that remote-sensing data can estimate the radiation in remote regions because they provide continuous signals in space and time. However, the spatial resolution of satellite data is coarse, and the time series of the data is short; thus, reconstructing sophisticated and historical solar radiation is difficult (Bindi and Miglietta, 1991).

Empirical relation models based on climatic variables are useful in estimating solar radiation. Angstrom (1924) and Prescott (1940) propose the Ångström–Prescott (A–P) model to explore the linear relationship between sunshine duration (SSD) and GSR. Almorox and Hontoria (2004) employ the A–P model and several improved A–P models to estimate the GSR in Spain using SSD as inputs. Rehman (1999) propose a new model by improving the site-specific coefficients in the A–P model and compare it with many existing SSD-based models to predict GSR at Saudi Arabia. Yang et al. (2001, 2006) propose the Yang hybrid model on the basis of the A–P model, which is proven to be one of the best sunshine-based broadband models for GSR estimating. Yaniktepe and Genc (2015) compare and analyze eight different linear, second, and third order polynomial models in Turkey and propose the best third-order polynomial model to estimate the GSR in the study area. Temperature-based models that explore the relationship between solar radiation and maximum/minimum temperatures, such as the Bristow–Campbell (BC) and Richardson–Wright models, are important models for estimating GSR according to Bristow and Campbell (1984) and Richardson and Wright (1984). Meza and Varas (2000) estimate monthly mean GSR by using two temperature-based models in Chile. Rehman and Mohandes (2008) estimate the GSR in Saudi Arabia by using the measured temperature and precipitation data during 1998–2002. Panday and Katiyar (2010) use several temperature-based models to estimate the GSR in India, and they prove that temperature-based models can replace SSD-based models for estimating solar radiation. Other meteorological data, such as precipitation, humidity, and cloud cover, are used to model solar radiation worldwide (Ehnberg and Bollen, 2005, Muneer and Gul, 2000, Thornton et al., 2000, Thornton and Running, 1999, Wilks, 1999).

Spatial interpolation (Bindi and Miglietta, 1991, Hay and Suckling, 1979, Rivington et al., 2006) estimates solar radiation at one site by employing interpolated values from nearby stations, but it is rarely applied in areas where sparse stations are detected (Supit and Van Kappel, 1998). Suckling (1985) used extrapolation to estimate daily GSR form nearby stations; Rehman and Ghori (2000) employed the geo-statistical technique to estimate GSR, the kriging was used to predict GSR at stations without radiation values. ANN is an efficient solar radiation estimation technique using meteorological and geographical variables (Kashyap et al., 2015, Mohandes et al., 1998, Teke et al., 2015). The ANN model has been widely used in recent years to predict and forecast global, direct, and diffuse solar radiations worldwide. For example, Mohandes et al. (2000) use the radial basis functions in NN to estimate the GSR in 41 sites in Saudi Arabia. Amrouche and Le Pivert (2014) combine ANN and spatial modeling to predict the horizontal GSR in France. Rehman and Mohandes (2009) use ANN with the inputs of day, temperature, and relative humidity to estimate the diffuse solar radiation in Saudi Arabia. Wang et al. (2016) use three types of ANN and the improved BC model to estimate the solar radiation in China.

In China, solar radiation measurement began since 1957. According to Tang et al. (2013) and Wang et al. (2015), approximately 700 routine meteorological stations and only 122 radiation stations have been established from 1961 over the entire country. The radiation stations are sparsely distributed and mainly deployed in relatively low-altitude and developed areas. Many researchers have estimated and calibrated the solar radiation over China by using satellite data, empirical model, and ANN model. For example, Chen and Li (2013) develop 20 empirical models based on SSD and temperature to estimate the monthly mean daily GSR in the Yangtze River Basin. Liu et al. (2015) explore the relationship between SSD and GSR in large cities in China. Zhang et al. (2015a, b) use MODIS atmospheric data and the digital elevation model to estimate downward surface shortwave radiation. Jiang (2009) proposes a feed-forward back-propagation (BP) network to estimate the daily GSR in eight typical cities in China and proves that the ANN model is an excellent empirical model. However, these studies have mainly focused on radiation estimation at a single site or reconstructed long-time serial solar radiation at one site (Lam et al., 2008, Tang et al., 2013).

The present study attempts to estimate solar radiation at multiple sites in southeast China for a long-term period by developing an ANN model based on spatial interpolation. Different meteorological variables, including sunshine duration (SSD), average temperature (ΔT), maximum/minimum temperature (T_M/T_m), relative humidity (R_h), precipitation (P_{re}), air pressure (P_a), water vapor pressure (P_{wv}), and wind speed (W_s), are combined to explore the optimal network. Two improved empirical models, namely, IBC and IA–P models, are compared with the ANN model to evaluate their performances of solar radiation estimation in this study. All model results are evaluated with the root-mean-square errors (RMSEs), mean bias errors (MBEs), and determination coefficient (R^2) in this work. Interpolation is also used to analyze the spatial characteristics of site-measured GSR, ANN–predicted, and DAM-modeled GSR in southeast China. Finally, the long-term trends of GSR in 60 stations are investigated in detail.

2. Material and method

2.1. Study area and data

Southeast China is located between 20°–32°N and 108°–123°E (Fig. 1). Low hills and mountains are the main landforms in this region, which mainly comprises a subtropical monsoon climate zone that is hot and rainy in summer and warm and moist in winter. The 10 radiation stations and 60 meteorological stations from 1961 to 2010 are shown in Fig. 1, and the details of the geographical location of the 10 radiation stations with measured GSR are shown in Table 1. The annual mean GSR ranges from 10.89 MJ m^{-2} day^{-1} at station 57461 to 13.85 MJ m^{-2} day^{-1} at station 59316. The annual mean temperature varies from 16.65 °C at station 58457 to 21.62 °C at station 59316. The annual mean SSD increases from 4.15 h at station 57957 to 5.58 h at station 59316. The annual total P_{re} is between 1138.02 and 1627.08 mm in the 10 stations, and the annual mean R_h ranges from 74.91% at station 57993 to 80.23% at station 59316. The highest ΔT, SSD, R_h, and GSR are observed at station 59316, which may be due to its low latitude (23°23′) and altitude (2.9 m). The geographical and meteorological information of 50 meteorological stations without GSR data is presented in Table 2. The annual mean SSD ranges from 3.42 h to 5.59 h, and the annual mean temperature ranges from 15.79 °C to 22.20 °C. The monthly variations in SSD, P_{re}, R_h, ΔT and T_M/T_m at the 10 radiation stations are shown in Fig. 2. High daily ΔT are observed in July (28.82 °C) and August (28.38 °C). The cold months are January (7.34 °C) and February (9.26 °C), and the annual mean