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Estimation of global solar radiation on horizontal surfaces in Jeddah, Saudi Arabia

A.A. El-Sebaii *, A.A. Al-Ghamdi, F.S. Al-Hazmi, Adel S. Faidah

Physics Department, Faculty of Science, King Abdul Aziz University, P. O. Box 80203, Jeddah 21589, Saudi Arabia

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ABSTRACT

The measured data of global solar radiation on a horizontal surface, as well as the number of sunshine hours, mean daily ambient temperature, maximum and minimum ambient temperatures, relative humidity and amount of cloud cover, for Jeddah (latitude 21° 42′37″N, longitude 39° 11′12″E), Saudi Arabia for the period 1996–2006 are analyzed. The data are divided into two sets. The sub-data set 1 (1996–2004) are employed to develop empirical correlations between the monthly average of daily global solar radiation fraction (H/H_0) and various meteorological parameters. The nonlinear Angström type model developed by Sen and the trigonometric function model proposed by Bulut and Büyükalaca are also evaluated. New empirical constants for these two models have been obtained for Jeddah. The sub-data set 2 (2005, 2006) are then used to evaluate the derived correlations. Comparisons between measured and calculated values of H have been performed. It is indicated that, the Sen and Bulut and Büyükalaca models satisfactorily describe the horizontal global solar radiation for Jeddah. All the proposed correlations are found to be able to predict the annual average of daily global solar radiation with excellent accuracy. Therefore, the long term performance of solar energy devices can be estimated.

1. Introduction

Solar radiation data are a fundamental input for solar energy applications such as photovoltaics, solar-thermal systems and passive solar design. The data should be reliable and readily available for design, optimization and performance evaluation of solar technologies for any particular location. Unfortunately, for many developing countries, solar radiation measurements are not readily available because of not being able to afford the measuring equipments and techniques involved. Therefore, it is necessary to develop methods to estimate the solar radiation on the basis of the more readily available meteorological data.

It is very common to design solar energy systems based on the monthly average of global solar radiation and other climatic data. Also, it is rather important to determine the beam and diffuse components of total radiation incident on a horizontal surface. Once these components are determined, they can be transposed over tilted surfaces, and hence, the short as well as the long-term performances of tilted flat plate collectors, photovoltaic modules and other solar devices can be estimated. Many models have been developed to estimate the amount of global solar radiation on horizontal surfaces using various climatic parameters, such as sunshine duration, cloud cover, humidity, maximum and minimum ambient temperatures, wind speed, etc. (Chegaar and Chibani, 2001; El-Sebaii and Trabea, 2005; Gopinathan, 1988; Halouani et al., 1993; Jacovides et al., 2006; Sabziparavar and Shetaee, 2007; Supit and Van Kappel, 1998). Recently, Wu et al. (2007) used the metrological data from 1994 to 2005 of Nanchang station (China) to predict daily global solar radiation from sunshine hours, air temperature, total precipitation and dew point. They indicated that the best results were derived from the models that use sunshine duration, and the temperature-based models can be improved by adding other variables such as total precipitation and mean dew point. Sen (2007) proposed a nonlinear model for the estimation of global solar radiation from available sunshine duration data. This model is an Angström type model with a third parameter appears as the power of the sunshine duration ratio that gives the nonlinear effects in solar radiation and sunshine duration relationship. He concluded that the nonlinear model is applicable locally for Turkish cities and may be applied in different parts of the world. A simple model for estimation of monthly average of daily global solar radiation data on horizontal surfaces was recently proposed by Bulut and Büyükalaca (2007). The model was based on a trigonometric function, which has only one independent parameter, namely the

* Corresponding author. Permanent address: Physics Department, Faculty of Science, Tanta University, Tanta, Egypt. Fax: +96 26951106.
E-mail address: aasebaii@yahoo.com (A.A. El-Sebaii).

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day of the year. The model was tested for 68 provinces of Turkey. It was found that the model can be used for estimating monthly average of daily global radiation with a high accuracy.

Few papers have appeared concerning estimation of solar radiation over Saudi Arabia. Sabbagh et al. (1977) estimated the daily global solar radiation for various places in Egypt, Kuwait, Lebanon, Sudan and Saudi Arabia. Al-Ayed et al. (1998) proposed empirical correlations for calculating the monthly average of daily global, direct and diffuse solar radiation in Riyadh (capital of Saudi Arabia) using the data of one year (1986). Multiple correlations between different solar parameters have been proposed by Benghanem and Joraid (2007) for estimation of the monthly average of global and diffuse solar radiation in Medina. A linear correlation between ambient temperature and global radiation was found to be applicable in Medina site from sunrise until sunset. However, a polynomial correlation between temperature and global radiation was given from midday until sunset. It is worth mentioning that all the proposed models contain empirical constants, which depend on the season and the geographical location of the place (El-Sebaii and Trabea, 2003; Khogali and Al-Bar, 1992). Therefore, suggesting models for calculation of different components of solar radiation incident on horizontal and tilted surfaces in different places of Saudi Arabia is still of considerable interest.

Jeddah is a Saudi city located 21° 42′37″N (latitude), 39° 11′12″E (longitude) and it is one of the most solar energy abundant cities all days of the year. Therefore, solar energy devices can be operated with high performance. The main purpose of this paper is to develop empirical correlations to estimate the monthly average of daily global solar radiation on horizontal surfaces in Jeddah using the available meteorological data, such as sunshine duration, relative humidity and cloud cover as well as maximum, minimum and daily mean of ambient temperature covering the years 1996–2006. Another aim is to evaluate the two models that recently proposed by Sen (2007) and Bulut and Büyükalaca (2007) for estimation of global solar radiation using the measured climatic parameters for Jeddah during the period 1996–2006.

2. Calculation procedure

In the present work, data of the monthly average of daily global solar radiation H on a horizontal surface, number of bright sunshine hours s, ambient temperature T, cloud cover c_w, relative humidity R_h and maximum $T_{\max}$ and minimum $T_{\min}$ ambient temperatures for Jeddah for the period 1996–2006 were taken from Saudi Ministry of Defense and Aviation, Meteorology and Environmental Protection Administration, Jeddah. The data were averaged to obtain the monthly mean daily values by taking the data for the average day of each month as recommended by Duffie and Beckman (1991). The mean daily values for each month were then averaged over the past 11 years. The obtained average values were then divided into two sub-data sets, one of which from 1996–2004 was used for calibrating and developing models, and another for the years 2005 and 2006 for evaluating models. The correlations to which the measured data were fitted are as follows:

$$\frac{H}{H_0} = a + b\left(\frac{s}{s_0}\right) \tag{1}$$

$$\frac{H}{H_0} = a + b\left(\frac{s}{s_0}\right) + c\left(\frac{s}{s_0}\right)^2 \tag{1a}$$

$$\frac{H}{H_0} = a + b\left(\frac{s}{s_0}\right) + cT \tag{2}$$

$$\frac{H}{H_0} = a + b\left(\frac{s}{s_0}\right) + cR_h \tag{3}$$

$$\frac{H}{H_0} = a + bT + cR_h \tag{4}$$

$$\frac{H}{H_0} = a + b(T_{\max} - T_{\min}) + cc_w \tag{5}$$

$$\frac{H}{H_0} = a + b(T_{\max} - T_{\min})^{0.5} + cc_w \tag{6}$$

$$\frac{H}{H_0} = a + b\left(\frac{s}{s_0}\right) + cc_w \tag{7}$$

$$\frac{H}{H_0} = a + b\left(\frac{s}{s_0}\right)^c \tag{8}$$

where a, b and c are empirical constants and s_0 is the maximum possible monthly average daily sunshine duration or the day length. The measured data were used in linear and multiple linear regression analysis to obtain the values of empirical constants in Eqs. (1)–(8). Proper computer programs were written in Pascal language for the regression analysis by writing subroutines for calculating the extraterrestrial radiation values H_0 and the day length s_0 using the standard procedure (Duffie and Beckman, 1991). As a next step, the computer programs were used to calculate the empirical constants of Eqs. (1)–(8) with the aid of the measured values of H and other meteorological parameters. The obtained correlations were then employed to estimate the global radiation H for the considered location (Jeddah) for the period 1996–2006. The calculated values of H were then compared with the measured data. The accuracy of estimation of H was tested by calculating the mean bias error (MBE), root mean square error (RMSE) and the mean percentage error (MPE). Low values of RMSE and MPE are desirable. Positive MBE shows overestimation while negative MBE indicates underestimation. The MBE, RMSE and MPE are defined as in the following equations:

$$\text{MBE} = \frac{[\sum(H_{i,c} - H_{i,m})]}{n} \tag{9}$$

$$\text{RMSE} = \left\{\left[\frac{\sum(H_{i,c} - H_{i,m})^2}{n}\right]\right\}^{1/2} \tag{10}$$

$$\text{MPE} = \frac{\sum(H_{i,c} - H_{i,m})/H_{i,m}}{n} \times 100 \tag{11}$$

where $H_{i,c}$ and $H_{i,m}$ are the ith calculated and measured values of H and n is the number of observations.

One of the objectives of this paper is to check if the nonlinear model proposed by Sen (2007) and the Bulut and Büyükalaca (2007) model, which were used to estimate H for different places of Turkey are valid for estimation of H in Jeddah or not. Sen (2007) model is presented above by Eq. (8). Bulut and Büyükalaca (2007) model that was based on a trigonometric function with only one independent variable, namely the day of the year d is given by

$$H = I_2 + (I_1 - I_2)\left|\sin\left[\frac{\pi}{365}(d+5)\right]\right|^{1.5} \tag{12}$$

For 1st January $d = 1$, and for 31st December $d = 365$. I_1 and I_2 are empirical constants and they should be determined for each location separately by the method of regression analysis. The data available for Jeddah were used to find the coefficients I_1 and I_2.