Turkish Journal of Physics

http://journals.tubitak.gov.tr/physics/

Research Article

Turk J Phys
(2015) 39: 264 – 271
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doi:10.3906/fiz-1505-9

# Evaluation of the global solar irradiance in the Vhembe district of Limpopo Province, South Africa, using different theoretical models

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**Received:** 14.05.2015 • **Accepted/Published Online:** 10.09.2015 • **Printed:** 30.11.2015

**Abstract:** An attempt has been made to employ three different theoretical models for the determination of global solar radiation for the climate conditions of the Vhembe district of Limpopo Province in South Africa. The models are: 1) the Angstrom linear-based model, 2) the Hargreaves and Samani (temperature-based) model, and 3) the Garcia model. These models require the following meteorological data inputs: temperature, sunshine hours, and global solar irradiance on the horizontal surface. The regression coefficients from our previous study were also employed in the calculations. A 4-year (2007–2010) global solar irradiance and temperature data set from the Agricultural Research Council and the actual sunshine data set from the South African Weather Services were used. The monthly average global solar irradiance for the four selected areas of study were computed and compared with the in situ data. The results obtained show that the Angstrom linear and temperature-based models are suitable methods for predicting the global solar irradiance in this study area. The difference between the observed and the predicted data is less than 6.5 MJ/($m^2$ day). Their root mean square error varies between 0.0112 and 0.0368. Graphical representations of the irradiances versus the days of the year showed high values during summer for all the models used.

**Key words:** Global solar irradiance, root mean square error, sunshine hours, regression coefficients

## 1. Introduction

Solar radiation falling at a given location plays a major role in controlling the energy input to the soil system and influences the moisture level. In South Africa many agricultural fields and rural farmers do not have suitable instrumentation to measure the solar radiation and they rely on the weather stations established by the Agriculture Research Council (ARC). Due to lack of financial resources, the ARC is unable to establish weather stations and maintain them in many places and hence some of the meteorological data is not readily available to the rural farmers. To alleviate this problem it will be beneficial to utilize theoretical models to evaluate solar radiation data. This can thus meaningfully replace the need for weather station measurements. In addition to this, the South African government through the Department of Energy has strategized to expand its energy resources by including nuclear and renewable energy supplies. By the year 2020 it is expected that 15% of the electricity supply will be generated from renewable energy [1]. In order to reach this target, a thorough knowledge of solar radiation (theoretical and experimental) is needed for the design and production of solar energy systems as well as for agriculture and the building of renewable power plants (technical knowledge). The feasibility studies of solar energy systems require parameters such as the average monthly or daily data for climatological studies [2]. Data for shorter periods, like hourly global solar radiation, are also needed to simulate

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the performance of solar energy devices. The development of these devices needs reliable information about the solar energy falling at a specific area. Due to inadequate meteorological stations that measure the global solar irradiance, the predicted data are very useful [3,4]. This situation of inadequate data measurements has prompted the prediction of global solar radiation data for the places where the observed data are not available so as to compare them and test the validity of the theoretical models that are used. There are several models that can be used for the estimation of global solar radiation [3–9]. In this study, several factors have been taken into consideration when selecting the models to be employed. Consideration and choice of model used is based on the requisite data required as the model input as well as the availability of the requisite meteorological data. Hence, the temperature-based, Angstrom–Prescott linear, and Samani models were chosen [7–10]. The model that gives a good comparison of the predicted and the observed data for the study areas will be selected and used to predict solar irradiance for an area with a similar climatic condition. Presently there is no literature about the suitable model that can be used to predict the global solar irradiance for the Vhembe district, particularly in the areas where there are no data available.

## 2. Study area

South Africa is divided into nine provinces and Limpopo is one of them. Limpopo consists of five districts, namely Mopani, Waterberg, Capricorn, Sekhukhune, and Vhembe. This study is based on the Vhembe district, which is situated in the far northeast of South Africa. This district has four local municipalities, namely Makhado, Musina, Thulamela, and Mutale, and its GPS coordinates are 22.9333°S, 30.4667°E.

Most of the people in this province are unemployed and hence they cannot afford to buy sufficient electricity from the service provider. According to Maluleke, the people of the Vhembe district are still using alternate energy resources such as biomass, paraffin, and gas [11]. The economy depends on agricultural crops such as avocados and bananas [12]. The rate of economic development in this district has a significant impact on poverty. Some of the areas are located in the wilderness near the Limpopo river valley with steep mountains [13].

## 3. Methodology

### 3.1. Models under evaluation

A number of models for predicting global solar radiation data using different parameters were previously developed in different countries [3–9,14–17]. In South Africa, only limited research studies predicting solar radiation were undertaken, particularly in the Vhembe district. This study evaluates the three models mentioned in Section 1. These models use different parameters such as observed temperature, sunshine hours, and regression coefficients. Thus, the study aims to evaluate and test the suitability of these three different models for the climatic conditions of the Vhembe district. The global solar radiation regression model developed by Angstrom has been used by many researchers globally to predict global solar radiation [2–3,5–9]. This relation gives a good correlation between the monthly clearness indices and the relative sunshine duration. In this work, the Angstrom model is used to evaluate the global solar radiation in the Vhembe district. The input parameters used in the Angstrom–Prescott linear model are the extraterrestrial solar irradiance ($H_0$), actual and possible sunshine hours, that varies from one site to another, since it is latitude-dependent. The Hargreaves and Samani model, referred to as the temperature-based model, was employed as the second method for the comparisons. This model uses the observed temperature data and the empirical coefficients, which depend on the regions (coastal and inland). The Garcia model was also considered as this model incorporates both the regression coefficients and the observed temperature data for the given particular location.

#### 3.1.1. Model 1: Angstrom–Prescott relation

The Angstrom regression equation relates monthly average daily radiation to a clear day's radiation in a given location and an average fraction of possible sunshine hours [3–10], and it is given by:

$$\frac{H}{H_0} = a + b * \frac{S}{S_0}. \tag{1}$$

The clearness index $K_T$ $(= H \,/\, H_0)$ represents the percentage deflection by the sky of the incoming global solar radiation and therefore indicates both the level of availability of solar radiation and changes in atmospheric conditions in a given area, while relative sunshine hours (RSSH), given by $RSSH\,(= \frac{S}{S_0})$, is a measure of the cloud cover. $H$ represents the daily average global radiation (MJm$^{-2}$ day$^{-1}$) on a horizontal surface, $H_0$ the daily extraterrestrial radiation (MJm$^{-2}$ day$^{-1}$), $S$ the daily sunshine duration (hours), and $S_o$ the maximum sunshine duration or day length (hours). Eq. (1) can now be expressed as follows [18,19]:

$$K_T = \, a + b\,(RSSH)\,, \tag{2}$$

$$H_o = \frac{24}{\pi}\left(1367\,W/m^2\right)\left(1 + 0.33cos\left(\frac{360n}{365}\right)\right)\left(\frac{\pi}{180}\omega_s \sin\varphi \sin\delta + \cos\varphi\cos\delta\sin\omega_s\right), \tag{3}$$

where $a$ and $b$ are the regression coefficients. Their physical significances are as follows: $a$ is the measure of the overall atmospheric transmission; if $n \neq 0$, the condition is not totally cloudy; and $b$ is the rate of increase of $K_T$ with $RSSH$. The transmission under clear days is given by the sum of $a$ and $b$.

During summer seasons, the sun rises at 0500 hours and sets at about 1900 hours. The approximate sunshine hours are 13.5, which correlates with the computed day length hours, while during winter season, the sunshine hours are about 10.5.

#### 3.1.2. Model 2: Hargreaves and Samani (temperature-based) model

Hargreaves and Samani used the principle of the difference between the maximum $(T_{max})$ and minimum $(T_{min})$ air temperatures, which are influenced by the degree of cloud cover, humidity, and solar radiation, and formulated a temperature-based model that is empirical in nature [9,14–17] and takes the following form:

$$H = H_0 * K_r * \left(T_{\max} - T_{\min}\right)^{0.5}, \tag{4}$$

where $H_0$ is the daily extraterrestrial solar radiation, $T_{max}$ is the mean daily maximum air temperature, $T_{min}$ is the mean daily minimum air temperature, and $K_r$ is an empirical coefficient. For the coastal region $K_r$ takes a value of 0.19, while for interior region the value is 0.16 [7,13].

#### 3.1.3. Model 3: Garcia model

The Garcia model was first used in Peru to estimate the global solar radiation. This is an adaption of the Angstrom and temperature-based models as its input data are the optimum temperature data, the regression coefficients $a$ and $b$, and $S_0$ (the maximum daily sunshine duration). The relation is described in references [11,19,20] and is expressed as follows:

$$\frac{H}{H_0} = a + b * \frac{\Delta T}{S_0}. \tag{5}$$

The site specifications for calculating the extraterrestrial solar radiation are latitude and sunset hour angle.

In order to evaluate the global solar irradiance observed in the Vhembe district, four weather stations were selected, namely Mutale in Thohoyandou, Mhinga in Malamulele, Alldays in Louis Trichardt, and Rabali in Makhado. A 4-year meteorological data set (including the global solar irradiance) was supplied by the ARC. The stations under study from the ARC do not have the in situ measurements of the actual sunshine hours, $s$, so these data were obtained from the South African Weather Services (SAWS). The selected four stations under study are at close proximity to Thohoyandou and their weather conditions are equivalent, so this enabled us to use the SAWS data measured at Thohoyandou for all stations under study.

The regression coefficients used in this study were sourced from Mulaudzi et al. [3], where $a = 0.212$ and $b = 0.415$. These values were used in model 1 as well as model 3. The extraterrestrial solar radiation $(H_o)$ of each of the above-mentioned models were calculated using Eq. (3).

### 3.2. Statistical tests and comparisons of models

There are many models available for the estimation of global solar radiation [5,6,21]. In the current investigation three different models have been evaluated and the degree of accuracy of each method to fit the measured global solar radiation data is evaluated by the following statistical tests: root mean square error (RMSE), mean bias error (MBE), and mean percentage error (MPE). The RMSE is defined in references [2,5,6,8,22,23] and expressed as:

$$RMSE = \frac{1}{n}\sum_{1}^{n}\sqrt{(H_{Oi} - H_{Ei})}^{2}, \tag{6}$$

where $H_{Oi}$ and $H_{Ei}$ are observed and estimated values of global solar radiation for day $i$, respectively, and n is the total number observations. RMSE is a good measure of how accurately the model predicts the response. This test provides information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the calculated value and the measured value; the smaller the value, the better the model's performance. RMSE indicates the absolute fit of the model to the data and how close the observed data points are to the model's predicted values.

$$\text{Mean bias error} \quad MBE = \frac{1}{n}\sum_{1}^{n}(H_{Oi}-H_{Ei}) \tag{7}$$

Mean bias error indicates the average of the over- or underprediction. A positive value gives the average amount of overestimation in the calculated value and vice versa [2,5,6,8,22,24].

$$\text{Mean percentage error} \quad MBE = \frac{1}{n}\sum_{1}^{n}\frac{(H_{Oi} - H_{Ei})}{H_{Oi}} \times 100\% \tag{8}$$

Mean percentage error defines the percentage deviation of the monthly average daily radiation values estimated by the model used from the measured values.

## 4. Results and discussion

In order to compare the estimated global solar radiation data computed from the three selected models with the observed global solar radiation data, scatter plots were drawn using MATLAB. As an example, the scatter plots for the year 2010 are presented in the Figures 1–4. These graphical representations are used for the comparison of the estimated and observed global solar radiation. The day of the year, season, and time of the day are some of the factors of the amount of global solar radiation falling on the earth. The observed (measured) data are represented by red dots, the Hargreaves and Samani (H & S) method by green diamonds, Garcia (GR) by yellow dots, and Angstrom–Prescott (ANG) by blue dots.

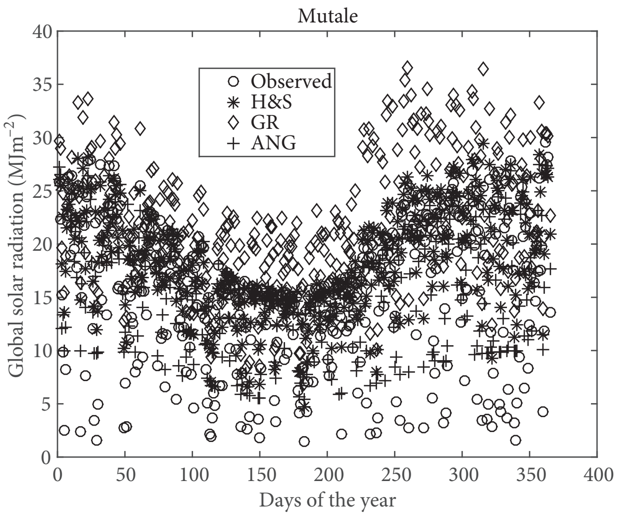


**Figure 1.** Comparisons between the calculated global solar radiations from different models and the measured global solar radiation for the Mutale station for 2010.

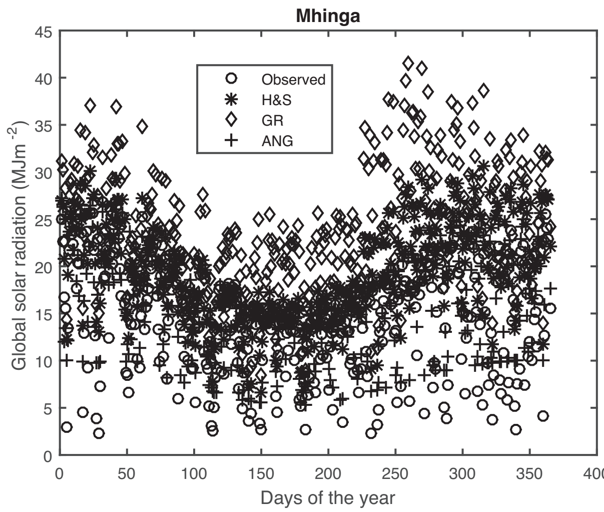


**Figure 2.** Comparisons between the calculated global solar radiation from different models and the measured global solar radiation for the Mhinga station for 2010.

It is evident from Figure 1 that the Angstrom–Prescott and Hargreaves and Samani models are more suitable for estimating global solar radiation. The estimated global solar radiation fits very well with the measured data throughout the year 2010. The Garcia model overestimated the global solar radiation, especially during the summer season. There are more outliers for the month of August 2010. It is normally windy during the month of August; therefore, the wind might have contributed to this deviation. It can be observed that the global solar radiation predicted using Angstrom and temperature-based models give a good relationship.

In this Figure 2, the Hargreaves and Samani model is comparable with the observed global solar radiation during the trimester quarter of the year (i.e. January to April 2010). This model overestimated the irradiance from May to December 2010, so this is not a good model to be used at this station. The Garcia model does not fit to predict the global solar radiation at this station because it has overestimated the data for about 7 months. The only model that gives a good prediction in this station is Angstrom–Prescott.

Figures 3 and 4 show that the data estimated by the Angstrom–Prescott and Hargreaves and Samani models are comparable to the observed global solar radiation. It can be seen from Figures 3 and 4 that very few data are overestimated from the month of September.

The above four scatter plots give the comparison between the estimated values of the global solar radiation from different models and observed global solar radiation for the year 2010. We observe that the scatter plots illustrate the nonlinear relationship of the variables, days of the year, and global solar radiation. It is shown from the scatter plots that as the variable on the horizontal axis (days of the year) increases in value, the other variable tends to fluctuate. It is also seen that the general trend of the incident solar radiation is high during summer and low during winter.

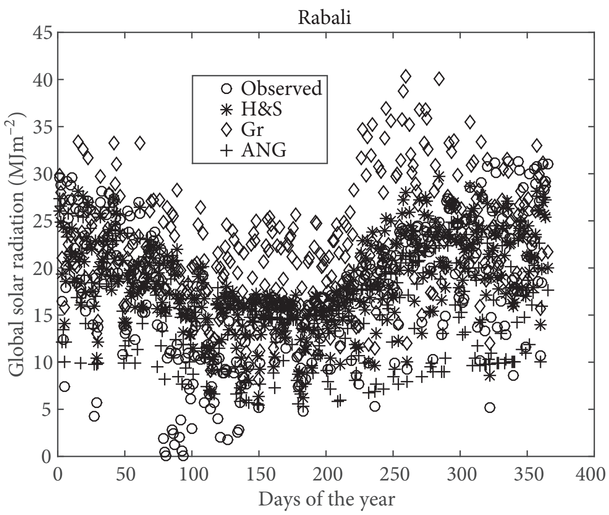


**Figure 3.** Comparisons between the calculated global solar radiation from different models and the measured global solar radiation for the Rabali station for 2010.

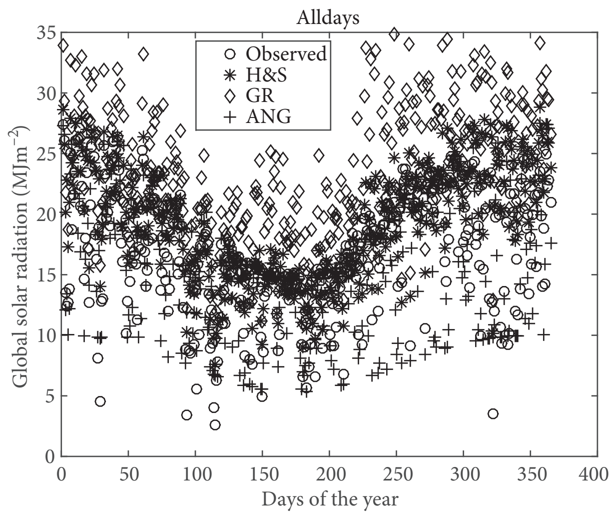


**Figure 4.** Comparisons between the calculated global solar radiation from different models and the measured global solar radiation for the Alldays station for 2010.

The comparisons of the predicted and observed global solar irradiance are again recorded in Tables 1–3. The statistical errors obtained from the three models are very low. The highest mean percentage error observed from Table 4 is 4.19% from the Rabali area. The comparison tables and the statistical errors table depict that there is a good agreement between the predicted global solar radiation data by the Hargreaves and Samani temperature-based model and the observed data.

**Table 1.** Comparison of the observed and predicted global solar radiation from the temperature-based model for different years and stations.

| Year | Mhinga (Temp) MJ m$^{-2}$ | Mhinga (Obs) MJ m$^{-2}$ | Mutale (Temp) MJ m$^{-2}$ | Mutale (Obs) MJ m$^{-2}$ | Alldays (Temp) MJ m$^{-2}$ | Alldays (Obs) MJ m$^{-2}$ | Rabali (Temp) MJ m$^{-2}$ | Rabali (Obs) MJ m$^{-2}$ |
|---|---|---|---|---|---|---|---|---|
| 2007 | 20.02 | 17.11 | 18.80 | 16.28 | 19.23 | 18.55 | 19.27 | 18.41 |
| 2008 | 20.16 | 16.85 | 19.04 | 15.57 | 19.53 | 17.70 | 19.35 | 16.32 |
| 2009 | 19.73 | 15.16 | 18.39 | 14.84 | 18.97 | 18.86 | 18.59 | 17.91 |
| 2010 | 19.36 | 14.62 | 18.08 | 15.16 | 19.13 | 16.92 | 18.38 | 17.40 |

**Table 2.** Comparison of the observed and predicted global solar radiation from the Garcia model for different years and stations.

| Year | Mhinga (Gra) MJ m$^{-2}$ | Mhinga (Obs) MJ m$^{-2}$ | Mutale (Gra) MJ m$^{-2}$ | Mutale (Obs) MJ m$^{-2}$ | Alldays (Gra) MJ m$^{-2}$ | Alldays (Obs) MJ m$^{-2}$ | Rabali (Gra) MJ m$^{-2}$ | Rabali (Obs) MJ m$^{-2}$ |
|---|---|---|---|---|---|---|---|---|
| 2007 | 25.35 | 17.11 | 23.09 | 16.28 | 23.46 | 18.55 | 24.10 | 18.41 |
| 2008 | 25.25 | 16.85 | 23.34 | 15.57 | 23.93 | 17.70 | 24.07 | 16.32 |
| 2009 | 24.55 | 15.16 | 22.37 | 14.84 | 23.02 | 18.86 | 22.77 | 17.91 |
| 2010 | 23.86 | 14.62 | 21.85 | 15.16 | 23.17 | 16.92 | 22.40 | 17.40 |

**Table 3.** Comparison of the observed and predicted global solar radiation from the Angstrom model for different years and stations.

| Year | Mhinga (Ang) MJ $m^{-2}$ | Mhinga (Obs) MJ $m^{-2}$ | Mutale (Ang) MJ $m^{-2}$ | Mutale (Obs) MJ $m^{-2}$ | Alldays (Ang) MJ $m^{-2}$ | Alldays (Obs) MJ $m^{-2}$ | Rabali (Ang) MJ $m^{-2}$ | Rabali (Obs) MJ $m^{-2}$ |
|---|---|---|---|---|---|---|---|---|
| 2007 | 17.64 | 17.11 | 17.69 | 16.28 | 17.65 | 18.55 | 17.63 | 18.41 |
| 2008 | 17.30 | 16.85 | 17.34 | 15.57 | 17.32 | 17.70 | 17.29 | 16.32 |
| 2009 | 16.79 | 15.16 | 16.83 | 14.84 | 16.80 | 18.86 | 16.78 | 17.91 |
| 2010 | 15.75 | 14.62 | 15.79 | 15.16 | 15.76 | 16.92 | 15.74 | 17.40 |

**Table 4.** Statistical validations of the different models.

| Station | RMSE | | | MBE | | | MPE | | |
|---|---|---|---|---|---|---|---|---|---|
| | Temp | Ang | Gar | Temp | Ang | Gar | Temp | Ang | Gar |
| Mutale | 0.0130 | 0.0084 | 0.0206 | 0.0080 | 0.0017 | 0.0183 | 0.7995 | 0.1705 | 1.8318 |
| Mhinga | 0.0158 | 0.0076 | 0.0273 | 0.0124 | 0.0031 | 0.0253 | 1.2358 | 0.3103 | 2.5330 |
| Rabali | 0.0303 | 0.0445 | 0.0290 | 0.0303 | 0.0420 | 0.0237 | 3.0269 | 4.1968 | 2.3723 |
| Alldays | 0.0105 | 0.0102 | 0.0192 | 0.0061 | 0.0032 | 0.0171 | 0.6058 | 0.3162 | 1.7128 |

## 5. Conclusion

From our investigations we notice that it is more preferable to use the linear Angstrom–Prescott model to estimate global solar radiation, rather than the models based on temperature. However, most of our weather stations have greater availability of temperature data, and it is also noted that the Hargreaves and Samani temperature-based model tested here can also make reliable estimation of the global solar radiation for the climatic conditions of the stations in the Vhembe district. The results depicted graphically demonstrate that each model is capable of making a reasonable estimation at some locations and less reliable ones at others stations. The Hargreaves and Samani model has overestimation error in the late winter and early summer period for the Mhinga in Malamulele station only. The Garcia model tends to overestimate values in the winter to early spring and summer periods at all the stations. Thus, the Angstrom and Hargreaves and Samani models can be used in this climatic region to estimate the global solar radiation. The estimated global solar radiation from the Angstrom and Hargreaves and Samani models for the stations studied was comparable with the observed data from the ARC.

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