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Evaluation of the Temperature based Models for the Estimation of Global Solar Radiation in Pretoria, Gauteng province of South Africa

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Abstract *–The measurement of solar radiation is difficult to carry out due to the cost and techniques involved especially in developing countries like South Africa. A variety of solar models with different weather parameters as inputs have been used to estimate the global solar radiation around the world. Since air temperature records are readily available around the world, models based on air temperature for estimating solar radiation have been widely accepted. Estimation of global solar radiation (H) from the daily range of air temperature (ΔT) offers an important alternative in the absence of the measured H or sunshine duration. In our present work, the estimation of the monthly average daily global solar radiation for Pretoria has been determined, based on two models: Hargreaves - Samani and Clemence. The performance of the two models is validated by comparing the measured and the estimated global solar radiation for the three different stations under study. The statistical comparison between the estimated and measured value leads to the conclusion that the two temperature models have potential to estimate the global solar radiation in the area under study.*

Keywords – air temperature, energy, empirical models, global solar radiation, temperature data.

1. INTRODUCTION

The increase in the use of renewable energy technologies will reduce the dependency of energy supply on the conventional energy resources and reduces the threat to our future life. The advantage of renewable energy resources: resources which are abundantly and free on the earth surface make it a solution to the world energy crisis [1] – [4]. Development of solar power plants in rural areas where there are no electricity grid lines must start with the assessment of solar radiation at those areas. The feasibility study of solar radiation potential in this area depends on the correct information of solar radiation and its components [1], [5] – [6].

Energy access is a fundamental factor for rural development, especially when working effectively on investing on renewable energy investment as a potential to create green energy jobs in rural communities [5], [7] – [11]. Solar radiation measurements could be used to estimate the potential power levels that can be generated from photovoltaic cells and necessary for determining cooling loads for buildings. These applications require complete knowledge and analysis of the solar radiation potential at a ground level in a selected area. In area where measured global solar radiation is not available, the challenge is the development of models which can achieve a satisfactory performance in predicting the global solar radiation [6], [7]. Measurements of the global solar radiation reaching the surface of the earth are also essential in most research fields of solar energy [7].

In South Africa (SA) some institutions are measuring different weather parameters, like global solar radiation, diffuse solar radiation, direct solar radiation, rainfall, sunshine hours, temperature data, humidity, *etc*. Some of those institutions are South Africa Weather Services (SAWS), Agricultural Research Council (ARC), Southern African Universities Radiometric Network (SAURAN), and Electricity Supply Commission (ESKOM). Although SAWS had been measuring these parameters for quite some number of years, some of the data is not freely available while some stations are no longer functional.

Considering that SA is still in the developing stage, these measurements of global weather parameters are not available for most rural areas, which are suitable to use renewable energy due to lack of grid lines. Establishing a weather station and its maintenance is one of the problems due to cost implication. The alternative way of solving this particular problem is the use of empirical models to estimate the global solar radiation at that particular area. An accurate modelling and prediction depends on the quality and quantity of the measured data used and is a good tool for generating global solar radiation at locations where measured data are not available.

Several methods which use different weather parameters have been developed around the world to estimate the global solar radiation [9], [5] – [6], [12] – [21]. Sharifi *et.al.*[3], uses the wavelet regression, ANN, GEP and empirical models which use temperature based approaches to estimate the global solar radiation.As the air temperature data is a measured meteorological parameter, it is easily measured in the developing countries and can be used as an input on solar radiation estimation techniques. Meenal, *et al.*, [22], Pandey and Katiyar [23], Bristow and Campbell [24], and Allen [25] have used the temperature data to estimate global solar radiation from different location in the world. Their studies show that the maximum and minimum

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temperature data can be used to estimate the global solar radiation. Comparison study between the three temperature models was performed by Pandey and Katiyar, and the results show that the computed global solar radiation data from Bristow and Campbell's model for Ahmedabad, Calcutta, and Pune are higher due to higher values of temperature difference while Allen model gives satisfactory results [23], [24]. However, Pandey and Katiyar model with their third-order correlation provides more accurate estimates than the model of Bristow and Campbell and also that of Allen [24]. Okundamiya *et al.* [26], used the ambient temperature to deduce a two parameter temperature based linear model for estimating global solar radiation. Trabea and Shaltout [27] studied the correlation between the measurements of global solar radiation and the meteorological parameters for different parts of Egypt. Thus estimation of solar radiation has been the subject of study by many researchers [13] – [26]. Most of these models concluded that the results depend on the climatic pattern of the location under study. It is therefore better to estimate a reliable set of solar radiation data in a particular location in a given region and compare with the observed data. Several investigations which use the Angstrom and modified Angstrom based (Prescott-Angstrom) model have shown its global solar radiation predictive ability as well as the correlation of the clearness indices and the relative sunshine duration. In general, solar energy conversion systems are essentially sensitive to sunlight and ambient temperature, which lead to the estimation of global solar radiation using temperature data. However, one of the advantages of using temperature based models is that ambient temperature can easily be measured in most places [11], [22], [24], [29], [30].

As described above, a reliable set of solar radiation estimated from temperature data is becoming increasingly important in the field of renewable energy with regards to Photovoltaic (PV) solar cells and thermal energy. In the current study two temperature based models, Hargreaves-Samani, and Clemence were selected. These models were selected based on the fact that they only use the temperature data as input, which is universally available. Clemence model was developed for Southern Africa climatic conditions, while Hargreaves-Samani can be used in both coastal and inland climatic conditions. To study the validity of these two theoretical equations, three stations were selected in Pretoria location, Gauteng Province of South Africa.

2. STUDY AREA

Gauteng province is situated in the interior plateau of South Africa. It is said to offer one of the world's best climates with warm and free sunny days and crisp and clear winter days are crisp and clear. Johannesburg and Pretoria differ in temperature by about 2%, Pretoria being the warmer of the two [31], [32]. Pretoria climate is similar to Johannesburg, but it lies at lower altitude than its neighbour and its air temperatures are on average about. two degrees higher. Pretoria gets its rainfall during summer seasons. Between November and February summer thunderstorms produce flashes of lightning and brief torrential downpours. Summer days are hot, though rarely to the point of discomfort. For six years, the temperature data (maximum and minimum) from three of the ARC stations were evaluated to estimate the global solar radiation using, the two mentioned models above. The study uses the temperature data collected at Arcadia, Botanical and Wonderboom ARC stations in Pretoria. The geographical coordinates of all the stations are tabulated in Table 1.

Table 1. The geographical coordinates of the three selected stations.

Station	Latitude	Longitude	Altitude
Arcadia	-25.73857	28.20733	1400
Botanical	-25.73361	28.30967	1411
Wonderboom	-24.46554	29.61416	772

3. THEORETICAL CONSIDERATIONS AND METHODOLOGY

The daily mean maximum and minimum temperatures, together with the global solar radiation were obtained from ARC in South Africa for the period of six years for each station. The extraterrestrial solar radiation on a horizontal surface (H_0), was calculated using the well-established equation [1], [2], [4], [6] – [11], [16] – [23]:

$$H_0 = \frac{(24*3600)*I_{sc}}{\pi}\left[1 + 0.033\cos\left(360 * dn3652\pi*\omega s360\sin\phi\, sin\delta - \cos\delta\, sin\ \omega s\right.\right. \qquad (1)$$

where I_{sc} is the solar constant (1367 Wm^{-2}), ϕ is the latitude of the site, δ is the declination, ω_s is the mean hour angle for a given month and d_n is the day of the year from 01 January to 31 December.

The hour angle ω_s for horizontal surface is given by the equation [1] – [5], [10] – [18]:

$$\omega_s = cos^{-1}(-tan\phi * tan\delta) \qquad (2)$$

The declination (δ) angle can be obtained using the relation [1] – [5], [10] – [18]:

$$\delta = 23.45 * \sin\left(\frac{360 * (284 + d_n)}{365}\right) \qquad (3)$$

Most of the empirical relations use the temperature data, sunshine hours and other related parameters as inputs to modify the regression coefficients at a particular location. The following temperature based models were employed in the present study and brief descriptions of these models are given as follows:

3.1. Hargreaves and Samani

Hargreaves and Samani developed a temperature based model using maximum and minimum temperature data to estimate the global solar radiation. The following relation represents the model [12], [13], [33]:

$$H = H_0 * \left(k_r\sqrt{\Delta T}\right) \quad (4)$$

where k_r is the empirical coefficient for inland regions given by 0.16 and ΔT is the difference between the minimum and maximum average daily temperature. The model uses only the temperature data of the area to estimate the global solar radiation, which makes it to be a suitable model to be used in developing countries.

3.2. Clemence Model

Clemence has developed the temperature based equation for estimating global solar radiation given by [15],

$$H = H_0(1.233 * H_0 * \Delta T + 10.593 * T_{max} - 0.713 * T_{max}\Delta T + 16.548 * 0.0418 \quad (5)$$

The model was developed for the Southern Africa climatic conditions. This makes it to be a suitable model on this study. A program in MATLAB software was developed to compute the global solar radiation from the above models. Statistical data analysis was used to test the accuracy of the estimated global solar radiation values. The equations for root mean square error (RMSE), mean bias error (MBE) and mean percentage error (MPE) are given as [1] – [2], [7] – [9], [16] – [40],

$$RMSE = \sqrt{\sum_{i=1}^{n}\left(\frac{H_{e_i} - H_{m_i}}{n}\right)^2} \quad (6)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(H_{m_i} - H_{e_i}) \quad (7)$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_{e_i} - H_{m_i}}{H_{e_i}}\right) * 100\ \% \quad (8)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(H_{m_i} - H_{e_i}\right)^2}{\sum_{i=1}^{n}\left(H_{m_i} - H_{e_i}\right)^2} \quad (9)$$

$$t = \left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}\right]^{\frac{1}{2}} \quad (10)$$

where n is total number of observed data in a year, H_{m_i} and H_{e_i} are yearly mean measured and estimated values of global solar radiation, respectively.

The above mentioned statistical equations are used to test the performance of the two temperature models used for estimating global solar radiations. Low values of root mean square error (RMSE), mean bias error (MBE) and mean percentage error (MPE) are desirable. RMSE tests provide information on the short-term performance whereas MBE and MPE tests provide information on long-term performance. Since the model is expected to 'explain' most of the observed trends, then it is important to know how much RMSE is systematic and what portion of data is unsystematic. For a good model, the systematic difference should approach zero. MBE is actually the difference between the model predicted values and the observed. The values of the R^2 are suggested to range between 1 and 0. The R^2 value around 1 indicates a perfect linear relationship between the estimated and measured values. The R^2 values around zero indicate that there is no linear relationship between the two values. The t statistics depends on both RMSE and MBE criteria. It is used to determine if two independent groups of data are significantly different or not. The smaller the value of t the better the model performance.

The computer codes for the temperature based empirical models were developed using latest computing MATLAB software. The first step was to compute the extraterrestrial radiation for the three selected station and then use the daily minimum and maximum temperature to compute the global solar radiation for the different stations. The statistical test on the computed and measured global solar radiation were calculated using the development of the calculation in MATLAB software.

4. RESULTS

Six years' temperature data obtained from three different stations were used to compute the global solar radiation using two different temperature models. The average yearly global solar radiation computed using the two temperature based models are presented in Tables 2, 3, 4, for Arcadia, Botanical garden and Wonderboom stations, respectively. To test the performance and accuracy of the temperature based models, the computed global solar radiation data was compared to the observed data. The estimated and observed global solar radiations for the year 2012 for the three stations are graphically represented in Figures 1 to 3. As illustrated on the figures, it may be observed that the highest and lowest values of the global solar radiation occur during the summer and winter seasons respectively. The highest values of global solar radiation are obtained in summer where we also observe the highest temperature values. For both stations, the peak global solar radiation occurs from January to March and from October to December. This is the summer season in South Africa, in which we experience hot days as well as rainfall.

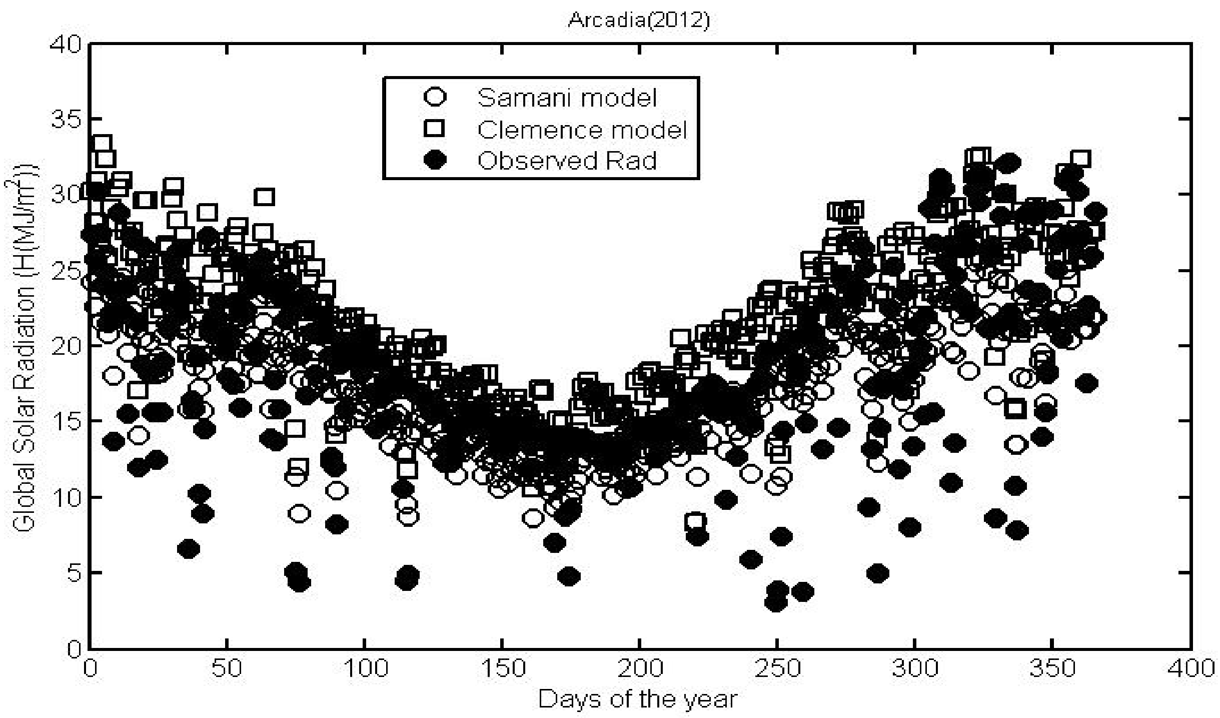

Fig. 1. Comparison between the annual estimated global solar radiation and observed for the year 2012 for Arcadia ARC station.

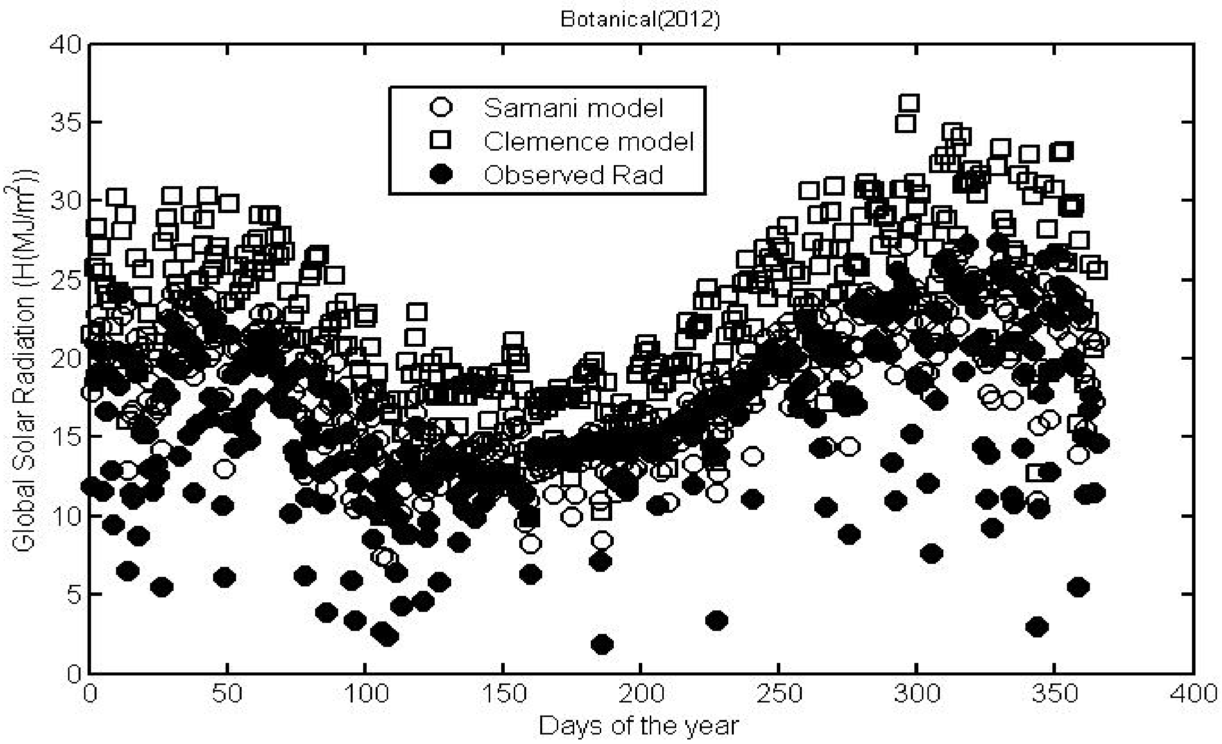

Fig. 2. Comparison between the annual estimated global solar radiation and observed for the year 2012 for Botanical Garden ARC station.

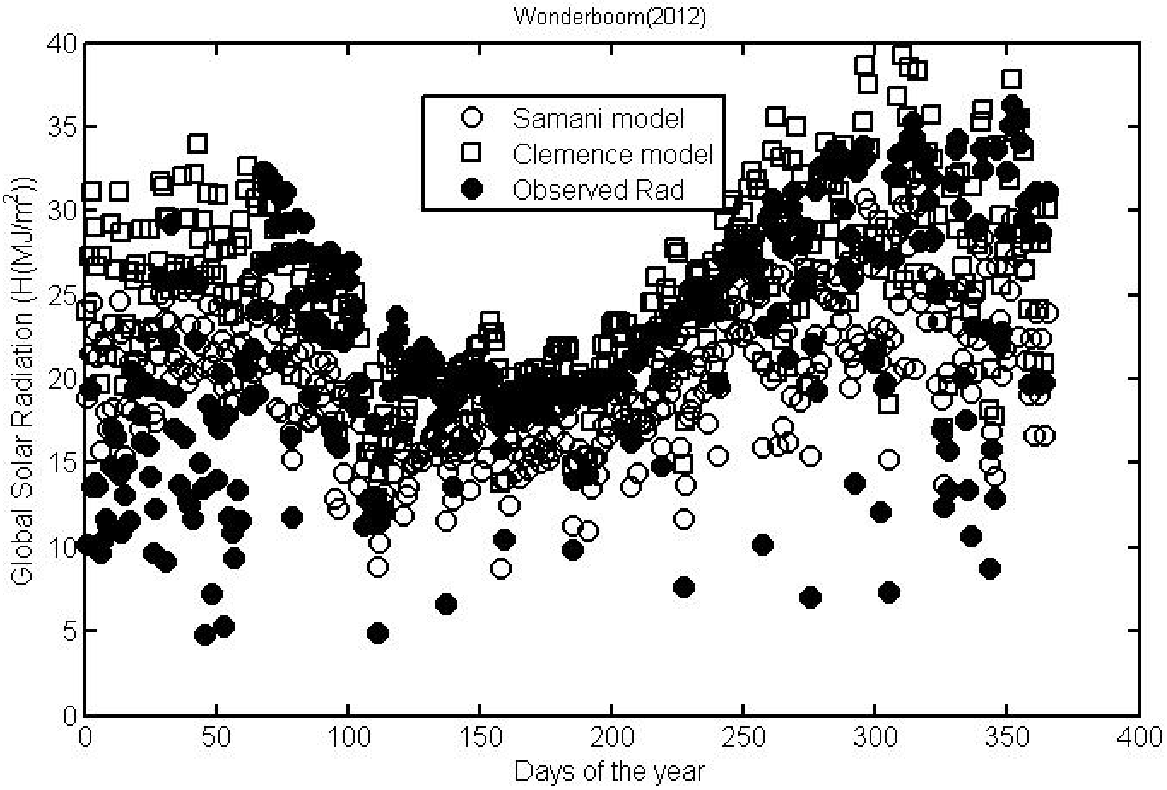

Fig. 3. Comparison between the annual estimated global solar radiation and observed for the year 2012 Wonderboom ARC Station.

From Figures 1 to 3, it can be observed that Hargreaves-Samani model performs better than Clemence model, even though the latter model was developed for Southern African weather conditions while, the former model was developed using the USA data for coastal and inland conditions. From the scatter plots we can actually consider Samani model to be a relatively good model for the sites under study.

Table 2. Average observed global solar radiation and estimated from the two models for the period of six years for Arcadia station.

Model/Year	2007	2008	2009	2010	2011	2012
Samani	17.408	16.973	16.724	16.919	16.759	17.215
Clemence	22.019	21.494	21.143	21.299	21.200	21.783
Observed	17.832	17.104	17.221	16.882	17.261	18.334

Table 3. Average observed global solar radiation and estimated from the two models for the period of six years for Botanical station.

Model/Year	2007	2008	2009	2010	2011	2012
Samani	18.490	18.628	17.914	18.213	18.058	18.058
Clemence	23.385	23.631	22.580	23.084	22.807	22.807
Observed	18.843	18.798	19.401	17.858	16.090	16.090

Table 4. Average observed global solar radiation and estimated from the two models for the period of six years for Wonderboom station.

Model/Year	2007	2008	2009	2010	2011	2012
Samani	20.329	19.897	19.669	19.464	19.791	19.791
Clemence	25.719	25.158	24.913	24.782	25.137	25.137
Observed	16.243	16.084	17.409	14.330	21.848	21.848

Tables 2 to 4 show the average global solar radiation for each station and suggest that the two models can be used to estimate the global solar radiation for the current climatic conditions of Pretoria under study. From the tables it can also be observed that the average values obtained from Clemence model are higher than Samani model. Both models show higher predicted values at Wonderboom station compared to Arcadia and Botanical Garden.

This can be due to the accuracy of the temperature model at the area under study or the inaccuracy of the measured temperature data. As these stations are in the city areas, the increase in the temperature may be due to the processes, of different activities like manufacturing, etc., around the city and can contribute to the inaccuracy of the temperature data, which is measured at ground level.

Tables 5, 6, and 7 give the statistical comparison between the predicted and measured values at the three different stations.The values of RMSE from the three station range from 0.009 to 0.016 for Arcadia, 0.09-0.022 for Botanical Garden and 0.011 to 0.044 for Wonderboom. The other statistical parameters (MBE, MPE) also produce satisfactory results. The coefficient of determination R^2 varies from 0.603 to 0.971 for both model, which shows a good agreement between the estimated and measured data. Clemence model gives lower value, ranging from 0.603 to 0.948, while Samani gives the values ranging from 0.853 to 0.971. Thus, the R^2 suggest that the Samani model performs better compared to Clemence model for the station under study. The value of the t statistics ranges from 0.013 to 0.938 which illustrate that there is no significant different between the estimated and measured values.

The difference in the estimated and measured results may be caused by the error occurring during the time of the measurements of the data at that particular station or from the fact that the pyranometers may need regular calibration. The data measured in each of the station under study mainly differ due to the sensor used and the methodology used to collect such data. From the correlation and statistical agreement of the results, the two models have shown to be reasonably accurate methods for estimating global solar radiation in Pretoria region. The quality of these estimates varies with sites environment and latitude.

Table 5. Statistical comparison between measured and average yearly global solar radiation (MJ/m^2) estimated using different models for Arcadia ARC station.

Year	RMSE		MBE		MPE		R^2		t	
	SAM	CLE	SAM	CLE	SAM	CLE	SAM	CLE	SAM	CLE
2007	0.008	0.014	-0.001	0.011	-0.116	1.147	0.971	0.921	0.140	0.833
2008	0.010	0.015	-0.00012	0.012	-0.036	1.203	0.956	0.896	0.036	0.796
2009	0.009	0.013	-0.001	0.011	-0.136	1.075	0.967	0.921	0.158	0.810
2010	0.008	0.016	-0.00012	0.012	0.010	1.210	0.970	0.877	0.013	0.745
2011	0.008	0.013	-0.001	0.011	-0.138	1.079	0.902	0.851	0.165	0.809
2012	0.010	0.013	-0.003	0.009	-0.306	0.945	0.963	0.935	0.317	0.739

Table 6. Statistical comparison between measured and average yearly global solar radiation (MJ/m^2) estimated using different models for Botanical Garden ARC station.

Year	RMSE		MBE		MPE		R^2		t	
	SAM	CLE	SAM	CLE	SAM	CLE	SAM	CLE	SAM	CLE
2007	0.013	0.019	-0.001	0.012	-0.097	1.245	0.936	0.868	0.074	0.662
2008	0.011	0.018	-0.000	0.013	-0.047	1.324	0.954	0.878	0.042	0.736
2009	0.010	0.012	-0.004	0.009	-0.408	0.871	0.963	0.948	0.397	0.721
2010	0.015	0.022	0.001	0.014	0.097	1.432	0.902	0.800	0.063	0.654
2011	0.009	0.020	0.005	0.018	0.539	1.840	0.853	0.770	0.582	0.922
2012	0.009	0.020	0.005	0.018	0.539	1.840	0.956	0.795	0.582	0.922

Table 7. Statistical comparison between measured and average yearly global solar radiation (MJ/m2) estimated using different models for Wonderboom ARC station.

Year	RMSE		MBE		MPE		R^2		t	
	SAM	CLE	SAM	CLE	SAM	CLE	SAM	CLE	SAM	CLE
2007	0.014	0.028	0.011	0.026	1.119	2.596	0.898	0.603	0.789	0.926
2008	0.014	0.027	0.010	0.025	1.044	2.486	0.905	0.638	0.768	0.938
2009	0.011	0.022	0.006	0.021	0.619	2.056	0.942	0.780	0.541	0.918
2010	0.035	0.044	0.014	0.029	1.407	2.864	0.200	-0.232	0.400	0.657
2011	0.016	0.017	-0.006	0.009	-0.564	0.901	0.920	0.769	0.357	0.518
2012	0.016	0.017	-0.006	0.009	-0.564	0.901	0.931	0.916	0.357	0.518

Generally, through the data generated from these two temperature models as compared to the measured global solar radiation data, one can conclude that the model are acceptable to be used in this study area. However, there is a need to extend the study for a long period to evaluate the very same models and also to be tested for different climatic conditions. Hargreaves model uses K_r values for the inland region in this study. From our results it is clear that the value obtained using Hargreaves and Samani model are better compared to Clemance model. Thus we hope to extend this study to other stations around Pretoria to validate the performance of these models in these climatic conditions.

Minor over-estimated data from Clemence model is observed in Wonderboom as well as Arcadia from June to December 2012, but this is acceptable. For accuracy, the two stations, Wonderboom and Arcadia may use Hargreaves and Samani model to estimate the amount of global solar radiation at any given day of the year. There is therefore a need to measure temperature data for a long time so as to enable us to modify the Clemence model or just compute a new constant in the model that is suitable for the South Africa weather conditions.

The estimated and measured global solar radiation using the two models for the three different stations are plotted in Figure 4. It can be observed from the figure that the estimated and the measured global solar radiation are closer to each other. The R^2 statistical values of these two sets of data show a good agreement as illustrated by the values on the figures. The R^2 values suggested that the two-model's performance is accepted on the area under study and hence these models can be used to estimate the global solar radiation at this climatic condition under study.

4. CONCLUSION

A six years temperature data to estimate the global solar radiation were obtained from Arcadia, Bortanical garden and Wonderboom ARC stations in Pretoria. Two empirical temperature models were employed to estimate the global solar radiation and compare it to the measured data. The values of RMSE obtained from the three stations range from 0.009 to 0.016 for Arcadia, 0.09-0.022 for Botanical Garden and 0.011 to 0.044 for Wonderboom, which illustrate that the difference in the results are negligible. From the values of R^2 and t, which ranges from 0.603 to 0.971 and 0.013 to 0.938 respectively suggest that, both Clemence and Hargreaves and Samani, temperature based methods can be used to compute the global solar radiation in this area and can assist the energy planners and installers of solar conversion devices to design suitable devices for this region. It was observed that the Clemence model estimated higher values and this suggest that the method needs to be tested using the temperature data from other station in this area.

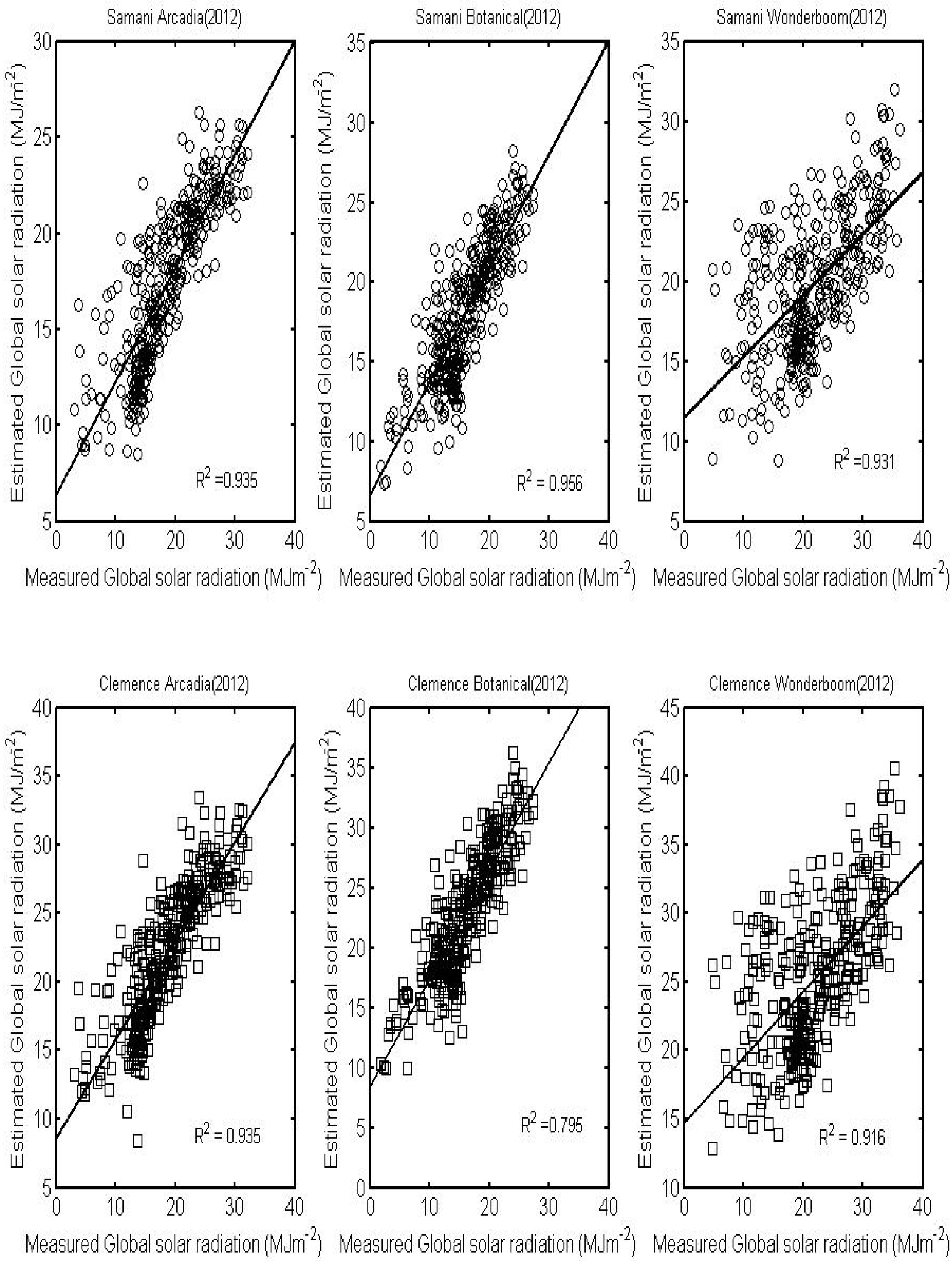

Fig. 4. Observed and estimated annual daily global solar radiation for the year 2012 for Arcadia, Botanical Garden and Wonderboom ARC Stations obtained from the two models as indicated.

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