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Estimation of Solar Radiation Using Polynomial Models in Yola, Nigeria

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Abstract: **- This study presents polynomial models for estimating diffuse solar radiation in Yola, Nigeria. The models were compared with the widely applicable models. The accuracy of estimation of these models is tested by calculating the Nash-Sutcliffe equation (NSE), The t-statistic, mean percentage error (MPE), mean bias error (MBE), and root mean square errors (RMSE). Statistical indices show that all models produce reasonably good estimates of diffuse solar radiation. The lowest values of -0.002 kWhm^{2}day^{-1}, 0.320 kWhm^{2}day^{-1}, 0.160 kWhm^{2}day^{-1} and 0.015 kWhm^{2}day^{-1} for MPE, RMSE, MBE and t-statistic respectively are obtained for Tasdemiroglu and Sever model provided reasonably high degree of precision in the forecast of monthly average of diffuse solar radiation on the horizontal surfaces.**

Keywords: **Polynomial models, diffuse solar radiation, Statistical Analysis, Yola.**

I. INTRODUCTION

Solar radiation data provide information on how much of the sun's energy strikes a surface at a location on earth during a particular time period. The data gives values of energy per unit of area. Readily available solar radiation data is a key to design and simulation of all solar energy applications. At present, values for the magnitude of input solar radiation at the surface of the earth are acquired in two basic ways. Radiation values are either measured with instrumentation or modeled from empirically derived relationships between solar radiation and more readily available atmospheric variables. Often, one of these methods is used to test the validity of the other (Malinovic*et al.*, 2006). Solar radiation affects the earth's weather processes which determine the natural environment. Its presence at the earth's surface is necessary for the provision of food for mankind. Thus it is important to be able to understand the physics of solar radiation, and in particular to determine the amount of energy intercepted by the earth's surface at different locations (Muneer *et al*., 2007). The global solar radiation can be divided into two components: diffuse solar radiation, which results from scattering caused by gases in the Earth's atmosphere, dispersed water droplets and particulates; and direct solar radiation, which have not been scattered. Global solar radiation is the algebraic sum of the two components. The quantity of solar radiation reaching the Earth's surface varies dramatically as a function of changing atmospheric conditions as well as the changing position of the Sun through the day. Accurate data of global solar radiation are necessary at various steps of the design, simulation, and performance evaluation of any project involving solar energy (Donatelli*et al*., 2003). The solar radiation modeling has shown significant progress in recent decades, reaching at present integration in geographic information systems that allow quantification at its spatial distribution, also provide detailed estimates or forecast climate changes which have improved significantly in recent years. Several models have been proposed for generation of global radiation (Tovar and Baldasano, 2001).

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The direct measurement of solar radiation is done in two basic ways as well. The values are measured either by using ground-based instrumentation known collectively as pyranometers, or remotely with satellites. These methods are often used in combination to validate one another (Kimothi*et al.*, 2004). In general, pyranometeric data from adequately maintained instruments provide an accurate description of the solar radiation values in the immediate area. It is generally accepted that models for solar radiation prediction are necessary, because in most cases the density and number of solar radiation measuring stations cannot describe the necessary variability (Muneer *et al*., 2007). It is understandable then that new models and improvements to existing modeling techniques are continually proposed which intend to improve estimates of solar radiation values with the use of more readily available meteorological variables (Donatelli*et al.*, 2003; Younes and Muneer, 2006).

Meteorological data obtained from direct measurement provide the necessary information of radiation and weather parameters. However, in the developing countries such as Nigeria, insufficient and unreliable measuring instruments and poor maintenance culture, has led to poor data records and more often, unreliable solar radiation data. In the absence of these measurements, theoretical models have become the desired tools to predict and estimate the global solar radiation of a place using some meteorological parameters such as linear, quadratic and quadratic equations. The results of this research would generate knowledge of distinct quadratic models used to predict global solar radiation from metrological parameters, as well as help in the design and construction of solar energy systems and equipment in Adamawa State. In this study, quadratic models were used to estimate the global solar radiation. The purpose of using different models is to identify the most appropriate models for the estimation of global solar radiation for Yola, Adamawa State.

Yola, the capital of Adamawa State, comprising of Yola North and Yola South Local Government Areas, is located between Longitudes 12° 12'E, 12° 33'E of the Prime Meridian and between Latitudes 09° 12'N, 09° 19'N of the Equator. It is situated in the Benue Valley area of the state with a mean elevation 186 m.a.s.l. The area falls within the Tropical Wet and Dry/ West African Savanna Climate zone of Nigeria, with pronounced dry season in the low-sun months and wet season in the high-sun months. It is characterized by an average range of sunshine hours of 5.5 hours per day in August to 9.7 hours per day from the months of January through March. On balance, there are 2,954 sunshine hours annually and approximately 8.1 sunlight hours per day (Yola Climate and Temperature, 2012). Its Temperature characteristic is high all year round due to high solar radiation effect. However, seasonal changes usually occur such that there is a gradual increase in temperature from January to April when the seasonal maxima is recorded. Then a distinct gradual decline is recorded from the onset of rains in April/May due to cloud effects. This temperature characteristic continuous until October when a slight increase is experienced at the cessation of rains before the arrival of cold dry continental winds (harmattan) conditions (Adebayo, 1999). Thus, the study area is characterized by a mean temperature of 27.9 °C with a mean monthly range of 6.5 °C. The warmest mean maximum/ high temperature of the area is 39 °C in March & April, while the coolest mean minimum/ low temperature is 16 °C in December (Yola Climate and Temperature, 2012).

II. METHODOLOGY

The simple model used to estimate monthly average daily global solar radiation on horizontal surface is the modified form of the Angstrom-type equation. The original type regression equation related monthly average daily radiation to clear day radiation at the location in the equation and average fraction of possible sunshine hours.

$$\frac{\bar{H}}{\bar{H}_o} = a + b\frac{\bar{S}}{\bar{S}_0} \tag{1}$$

Where $\bar{H}$ is the monthly average global solar radiation (MJm^{-2}day^{-1}), $\bar{S}$ is the monthly average daily bright sunshine hour, $\bar{S}_0$is the maximum possible monthly average daily sunshine hour or the day length, and b are coefficients of Angstrom's formula.

$\bar{H}_o$, is the monthly average daily extraterrestrial radiation which can be expressed as:

$$H_{o} = \frac{24\times360}{\pi} I_{sc}\left(1+0.033\cos\left(360\frac{\bar{D}}{365)}\right)\right)\cos\emptyset\cos\delta\ \sin\omega + \omega\sin\emptyset\sin\delta \tag{2}$$

Where $\bar{D}$ is the Julian day number, I_{sc} = 1367Wm^{-2} is the solar constant, $\emptyset$ is the latitude of the location, δ is the declination angle given as:

$$\delta = 23.45\sin\left(360\frac{284+\bar{D}}{365}\right) \tag{3}$$

And ω is the sunset hour angle as

$$\omega = \cos^{-1}(-\tan\emptyset\tan\delta) \tag{4}$$

The maximum possible sunshine duration $\bar{S}_0$is given by

$$\bar{S}_0 = \left(\frac{2}{15}\right)\omega \tag{5}$$

a and b were computed for each month using Equations (3.1) and (3.2), respectively. Also the values of $\bar{H}_o$ and $\bar{S}_0$were computed for each month by using Equation (3.2) and (3.5), respectively, $\bar{H}$was also obtained using equation (3.1).

It is understandable that new models and improvements to existing modeling techniques are continually proposed which intend to improve estimates of solar radiation values with the use more readily available. The quadratic models that will be used in work are given below:

Mode1 1: Tasdemiroglu and Sever (1991) developed a correlation between $(\frac{H}{H_o})$ and $(\frac{S}{S_o})$ in a second order quadratic equation for six locations (Ankara, Antalya, Diyarbakir, Gebze, Izmir and Samsun) of Turkey as follow:

$$\frac{H}{H_o} = 0.225 + 0.014\frac{S}{S_o} + 0.001\left(\frac{S}{S_o}\right)^2 \tag{6}$$

Model 2:Lewis (1992) derived three-order quadratic relationships between the monthly average values of $(\frac{H}{H_o})$ and $(\frac{S}{S_o})$ for locations in Tennessee as:

$$\frac{H}{H_o} = 0.81 - 3.34\frac{S}{S_o} + 7.38\left(\frac{S}{S_o}\right)^2 - 4.51\left(\frac{S}{S_o}\right)^3 \tag{7}$$

Model 3: Tiris*et al.*, (1996) also suggested the following correlations:

$$\frac{H}{H_o} = 0.4177 - 0.0070\frac{S}{S_o} - 1.9096\left(\frac{S}{S_o}\right)^2 - 1.19\left(\frac{S}{S_o}\right)^3 \tag{8}$$

Model 4: Ertekin and Yaldiz (2000) have suggested following quadratic correlation equations for Antalya:

$$\frac{H}{H_o} = -2.4275 + 11.946\frac{S}{S_o} - 16.745\left(\frac{S}{S_o}\right)^2 + 7.9575\left(\frac{S}{S_o}\right)^3 \quad (9)$$

Model 5: Ulgen and Hepbasli (2004) developed the following empirical correlations for the city of Izmir, Turkey, for estimating H.

$$\frac{H}{H_o} = 0.3092 + 0.3625\frac{S}{S_o} - 0.4597\left(\frac{S}{S_o}\right)^2 + 0.3708\left(\frac{S}{S_o}\right)^3 \quad (10)$$

Statistical Analysis

The performance of the models was evaluated on the basis of the following statistical error tests: The Nash-Sutcliffe equation (NSE) was used to evaluate the models. The model is more efficient when NSE is closer to 1. the Mean Percentage Error (MPE), Root Mean Square Error (RMSE) and Mean Bias Error (MBE). These tests are the ones that are applied most commonly in comparing the models of solar radiation estimations. MPE, MBE and RMSE are defined as below: Mean Percentage Error: The Mean percentage error is defined as

$$MPE = \frac{[\sum(H_{i,m} - H_{i,c})/H_{i,m}]100}{N} \quad (11)$$

Where $H_{i,m}$ is the measured value, $H_{i,c}$is the calculated value of solar radiation and N is the total number of observations.

Root Mean Square Error: The root mean square error is defined as:

$$RMSE = \left(\left[\frac{\sum\{H_{i,c} - H_{i,m}\}^2}{N}\right]\right)^{1/2} \quad (12)$$

The RMSE is always positive, a zero value is ideal. This test will provide information on the short-term performance of the models by allowing a term by term comparison of the actual deviation between the calculated value and the measured value.

Mean Bias Error: The mean bias error is defined as:

$$MBE = \frac{[\sum\{H_{i,c} - H_{i,m}\}]}{N} \quad (13)$$

$$NSE = 1 - \frac{\sum_i^N{=}1(H_{i,m} - H_{i,c})^2}{(H_{i,m} - \overline{H_{i,m}})^2} \quad (14)$$

Where $\overline{H_{i,m}}$is the mean measured global solar Radiation.

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}\right]^{\frac{1}{2}} \quad (15)$$

III. RESULTS AND DISCUSSION

Results

Table 1 presents the measured and estimated global solar radiation from different models. Table 2 presents different models with statistical parameters to test predictive ability. Figure 1 presents monthly average daily global solar radiation of measured value and quadratic models used.

Table 1: Measured and estimated global solar radiation from different models in $MJm^{-2}day^{-1}$ for the period of eight years (2009 – 2016)

	Hm	Model 1	Model 2	Model 3	Model 4	Model 5
January	33.68	33.12	32.96	32.47	34.16	33.24
February	34.67	33.81	34.30	33.17	34.64	33.87
March	33.95	33.59	34.23	32.76	34.31	33.61
April	34.24	33.34	34.63	32.81	34.42	34.42
May	33.34	33.45	33.08	31.46	33.42	33.60
June	31.33	30.93	30.97	29.38	31.28	30.76
July	29.94	29.54	29.47	28.03	29.95	29.34
August	29.64	30.75	30.52	28.92	30.93	28.55
September	30.93	30.32	30.32	28.72	30.67	30.92
October	32.57	32.27	32.14	30.37	32.23	32.18
November	33.62	34.05	33.93	32.16	33.75	33.61
December	34.54	34.61	34.32	33.16	34.76	34.31

Table 2: Different models with statistical parameters to test predictive ability

Models No.	MBE	RMSE	MPE	t	NSE
$\frac{H}{H_o} = 0.225 + 0.014\frac{S}{S_o} + 0.001\left(\frac{S}{S_o}\right)^2$	-0.002	0.320	0.160	0.015	0.806
$\frac{\mathbf{H}}{\mathbf{H_o}} = \mathbf{0.81 - 3.34\frac{S}{S_o} + 7.38\left(\frac{S}{S_o}\right)^2 - 4.51\left(\frac{S}{S_o}\right)^3}$	0.018	0.331	0.211	0.122	0.824
$\frac{\mathbf{H}}{\mathbf{H_o}} = \mathbf{0.4177 - 0.0070\frac{S}{S_o} - 1.9096\left(\frac{S}{S_o}\right)^2 - 1.19\left(\frac{S}{S_o}\right)^3}$	-0.311	1.371	10.400	9.421	0.151
$\frac{\mathbf{H}}{\mathbf{H_o}} = \mathbf{-2.4275 + 11.946\frac{S}{S_o} - 16.745\left(\frac{S}{S_o}\right)^2 + 7.9575\left(\frac{S}{S_o}\right)^3}$	0.207	0.415	1.567	1.306	0.719
$\frac{\mathbf{H}}{\mathbf{H_o}} = \mathbf{0.3092 + 0.3625\frac{S}{S_o} - 0.4597\left(\frac{S}{S_o}\right)^2 + 0.3708\left(\frac{S}{S_o}\right)^3}$	-0.056	0.417	1.467	0.432	0.835

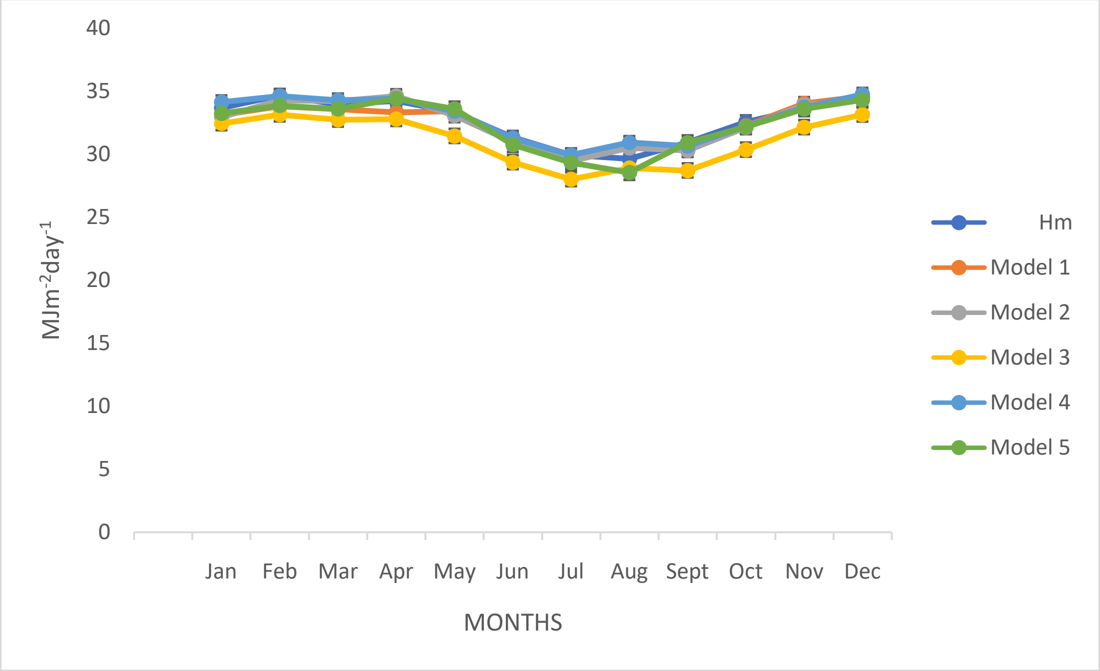

Figure 1: Monthly average daily global solar radiation of measured and quadratic models.

IV. DISCUSSION

The measured data for Yola were used to obtain regression equations of H/Ho with respect to meteorological variables. From the equations, the values of the regression constants (a, b, c, d, e), MBE, MPE, RMSE, NSE, t, and regression coefficients r, were obtained and listed in table 1. The values of measured and estimated global solar radiation on horizontal surface as predicted from (3.1) to (3.6) are presented in table 1 and Fig. 1 shows the corresponding graphical representation of the relationship between the measured and predicted values.It is observed that the coefficient of determination R^2 ranges from 0.918 to 0.994. This shows that the models can give a future reliable prediction of the global solar radiation. Looking at the MBE value of the models, models (1), (3), (5) and (6) give underestimated values of the solar radiation with negative values of MBE, while models (2) and (4) give overestimated values with positive values of MBE. However, the least underestimation is given by model (1) having MBE of -0.003, while the least overestimated is provided by model (2) with MBE value of 0.029. The RMSE values range from 0.401 to 1.490, while NSE values range from 0.2690 to 0.9464. These are all acceptable values of indices of good prediction except for model (5). The model is said to be a good predictor when RMSE is small and NSE is closer to 1. The t- statistics shows that at the critical value of 1.796 and at 0.96 level of confidence, model (1), (2) and (5) with the values of 0.016, 0.222, and 1.521 respectively are statistically significance, while models (3), (4) and (6) are not statistical significant since their calculated t-values are higher than the critical value of t-statistics. Generally, it is observed that models (1), (2) and (4) have satisfied all the statistical tests of reliability, approximation and significance for good estimation of global solar radiation.

V. CONCLUSION

The study evaluated the diffuse solar radiation models by Tasdemiroglu and Sever, Lewis, Tiris, Ertekin and Yaldiz, Ulgen and Hepbasli The performances for the models have been done in terms of widely used statistical indicators, Nash-Sutcliffe equation (NSE), The t-statistic, Mean Percentage Error (MPE), Mean Bias Error (MBE), and Root Mean Square Error (RMSE). It was observed from statistical indicators that Tasdemiroglu and Sever model provided reasonably high degree of precision in the forecast of monthly average of diffuse solar radiation on the horizontal surfaces. The results were in agreement with the results of Okundamiya and Nzeako, (2011). This work will set a very strong platform for the energy planners to utilize the solar energy potential for Yola, Adamawa State.

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