JOURNAL OF METEOROLOGY & CLIMATE SCIENCE
J. Met & Clim. Sci. 10(1):22-28 (2012)

N.Met.S
Nigerian Meteorological Society

A PARABOLIC MODEL PRESENTATION OF SOLAR RADIATION DATA AT A TROPICAL SITE, ILE-IFE, NIGERIA

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Abstract: Monthly average hourly global and diffuse solar radiation at a tropical station, Ile-Ife, Nigeria has been analysed and simple parabolic models established for predicting them. The models appear in the form of parabolic equations with three parameters. The necessary physical interpretations of the model parameters, their temporal variations and implications for the characteristic variation of hourly solar radiation at the station are also presented. Significant relationships between these parameters are also shown. The parabolic model parameters are handy tools for calculating the monthly average hourly global and diffuse solar radiation amounts, the extreme radiation values, i.e. the maximum and minimum and the time of day that extreme values are received on the surface and the diurnal trend of the solar fluxes which are required for solar energy applications. The models can be applicable in any part of the tropics to evaluate the temporal distribution of solar radiation amounts by reassessing the model parameters for the particular site.

Key words: Solar radiation, models, solar energy, conversion

INTRODUCTION

The design, development and application of solar energy collection and conversion systems required for the exploitation of the vast energy of the Sun, and the performance evaluation of such energy conversion systems within a particular region require information on the variation characteristics and distribution of the amount of solar radiation received on the surface at the location (Duffie and Beckman, 1991, Coppolino, 1994). The separation of solar irradiance into the various components is also necessary for a wide range of these solar engineering tasks (Iqbal, 1983). For most practical purposes, solar energy can be divided into two components, namely, direct radiation and scattered or diffuse radiation. The radiation received directly from the sun is called direct radiation. Direct radiation is the radiation which gives rise to sharp shadows. On the other hand, diffuse radiation is the radiation scattered by clouds, dust, etc. Since diffuse radiation arrives from all directions, it does not give shadows. The relative proportion of direct to diffuse radiation is site specific and depends on month of the year and time of day (Dunn, 1986). In designing a solar power device, it is necessary to know how the power density varies during the day, from month to month, and also the effect of tilting a collector surface at some angle to the horizontal. Statistical analysis of hourly and daily clearness index (Okogbue, 2007) showed that the local sky conditions at Ile-Ife, a tropical site were almost devoid of clear skies and overcast skies. The sky conditions were rather predominantly cloudy. A number of authors have also observed the predominance of cloudy sky conditions in tropical locations (Saunier et al, 1987 and Udoh, 2000)

A full understanding of the radiation climatology is necessary before an efficient and economic apparatus can be designed for the conversion and utilization of solar energy. For example, in the construction of a solar water heater, details of the radiation regime must be known before the capacity of the auxiliary water heater and the size of the storage tank can be determined (Black, 1964). The importance of the analysis of solar radiation data in a way which make them useful in the design of solar house heating systems, in the applications of solar energy to house cooling, and in other applications where energy storage for several days is needed had been discussed by several authors (Liu and Jordan, 1960, Hawas andMuneer, 1984 and Wang and Hua, 2005).

The main purpose of this paper therefore, is to present simple statistical models for estimating the monthly average hourly global and diffuse radiation amounts for solar energy application based on the nine year record of solar radiation measured at Ile-Ife, Nigeria which is a tropical site.

DATA AND METHODOLOGY

Data

Measurement was carried out at the solar radiation measurement station located on the rooftop of the 20m high, three-storey Department of Physics building within the campus of Obafemi Awolowo University, Ile-Ife, Nigeria on hourly bases. The instrument comprised of two Kipp and Zonen pyranometers models CM11 for the global radiation and CM11/121 (incorporating a shadow ring) for diffuse radiation. More details on the station, instrumentation and data reduction can be found in ([5] and [12])

Parabolic Models

Diurnal Plots of monthly average hourly global and diffuse solar radiation at Ile-Ife, Nigeria [13] showed a general trend which approximates a near symmetric distribution about the midday. Similar trend was observed by Zekai and Tan (2007) for monthly average hourly global or diffuse radiation in the northern part of Turkey and they adopted a second order parabolic equation to model monthly average hourly global radiation and the diffuse component for each month at Gebze Turkey (40°47'N, 29°25'E) a mid-latitude site. This method has been adopted in this study for Ile-Ife, Nigeria, a tropical site (7.5æ%N, 4.57æ%E). Monthly mean global and diffuse solar radiation at Ile-Ife, Nigeria has therefore been modelled by parabolic equations as:

$$I = at^2 + bt + c \quad (1),$$

where I represent both monthly average hourly global or diffuse radiation amounts, t indicates time in hours within one day and a, b and c are the model parameters that are to be estimated from the available data.

The time and amount of maximum radiation in the day can also be derived from equation (1) respectively after Zekai and Tan (2007):

$$t_{\max} = -\frac{b}{2a} \quad (2)$$

$$I_{\max} = -\frac{b^2}{4a} + c \quad (3)$$

The method of regression analysis has been used to obtain the model parameters in equation (1) together with the coefficient of determination R^2 using the available data at Ile-Ife, Nigeria. Equations (2) and (3) have also be used to determine the time of maximum global and diffuse solar radiation and the respective maximum average monthly hourly radiation values using the 11-years hourly global and diffuse solar radiation at Ile-Ife, Nigeria

RESULTS AND DISCUSSIONS

Tables 1 and 2 show the respective values of the model parameters (a, b and c) resulting from equation (1) and the coefficient of determination R^2 obtained for the monthly average hourly global and diffuse solar radiation at Ile-Ife, Nigeria.

Table 1: Monthly average daily global radiation parabolic model parameters

Month	a	b	c	R^2
Jan	-21.16	531.49	-2737.2	0.96
Feb	-25.02	628.88	-3232.5	0.96
Mar	-22.90	570.46	-2878.7	0.96
Apr	-23.30	580.33	-2914.3	0.97
May	-21.65	537.94	-2669.8	0.98
Jun	-19.12	476.91	-2377.5	0.97
Jul	-14.37	365.06	-1866.4	0.96
Aug	-13.81	352.85	-1825.9	0.95
Sep	-17.63	442.80	-2249.5	0.96
Oct	-21.10	522.56	-2608.8	0.96
Nov	-23.12	569.08	-2822.3	0.97
Dec	-22.37	554.91	-2805.9	0.96
Average	-20.46	511.11	-2582.4	0.96

Table 2: Monthly average daily diffuse radiation parabolic model parameters and the coefficient of determination (R^2)

Month	a	b	c	R^2
Jan	-10.53	261.64	-1300.6	0.99
Feb	-12.49	311.24	-1540.5	0.99
Mar	-14.29	352.95	-1733.4	0.98
Apr	-13.45	330.63	-1591.8	0.98
May	-12.45	303.54	-1432.4	0.98
Jun	-11.13	272.98	-1301.8	0.98
Jul	-10.63	265.98	-1326.2	0.98
Aug	-10.18	258.55	-1309.5	0.98
Sept	-13.73	343.28	-1723.5	0.98
Oct	-12.39	303.38	-1472.3	0.98
Nov	-10.92	265.17	-1253.1	0.99
Dec	-11.89	289.18	-1382.2	0.97
Average	-12.01	296.54	-1447.3	0.98

Table 3: The times of maximum radiation (t_m) and the maximum radiation (I_{max}) for the various months of the year.

Month	Global	Diffuse		
	t_m	I_{max}(Whm^{-2})	t_m	I_{max}(Whm^{-2})
Jan	12.56	600.2	12.42	324.2
Feb	12.57	719.5	12.46	398.0
Mar	12.46	673.9	12.35	445.9
Apr	12.45	699.7	12.29	440.1
May	12.42	671.7	12.19	417.5
Jun	12.47	597.0	12.26	371.8
Jul	12.70	451.7	12.51	337.5
Aug	12.78	428.5	12.70	332.8
Sep	12.56	531.2	12.51	423.0
Oct	12.38	626.1	12.25	385.4
Nov	12.30	679.0	12.14	356.8
Dec	12.40	635.7	12.16	375.5
Average	12.51	609.5	12.35	384.0

Table 3 shows the times of maximum radiation and the maximum radiation for the various months of the year. Fig. 1 and 2 shows the fitted model curves and the measured monthly average solar radiation for January to June and July to December respectively. Fig. 3 and 4 show similar plots for the diffuse solar radiation. The R^2 values (Tables 1 and 2) confirm that the second order parabolic equation is suitable as a model of the diurnal variation of monthly average hourly global solar radiation at Ile-Ife, Nigeria. One interesting observation is the change of model parameters with months (Tables 1 and 2). Clearly, Fig. 5 indicates a systematic variation of parameter a and b within the year with the variation of parameter a being the inverse of that of b. The variation of parameter b is particularly interesting, starting from a peak value in February in the dry months, decreasing to a minimum in August during the wet season and rising to second peak in November.

This bimodal distribution with a prominent depression in August of parameter b is characteristic of the annual trend of monthly average solar radiation at the station (Okogbue et al, 2008, 2009) and indeed most tropical stations and this has been associated with the large variability of the degree of cloudiness over the area in the wet months coupled with the fluctuating levels of aerosol loading of the atmosphere during the dry months and the latitudinal movement of the over-head sun which accounts for the large day-to-day variations of the radiation fluxes (Okogbue, 2007, (Okogbue and Adedokun, 2002 and Babatunde and Aro, 2000).

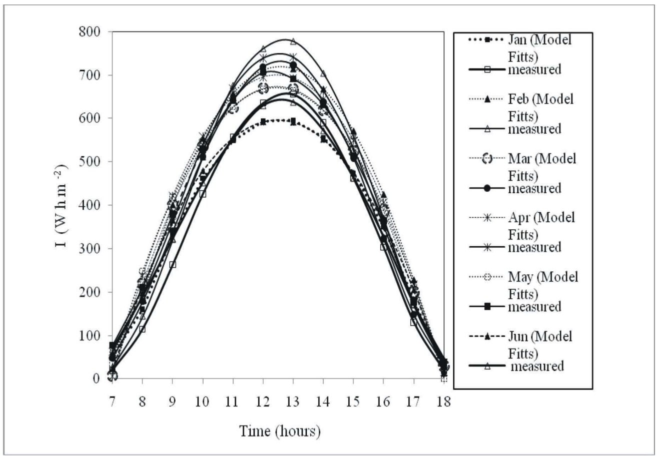

Fig. 1: Monthly Average global solar radiation (I in W h m^{-2}) and the parabolic fits (January – June)

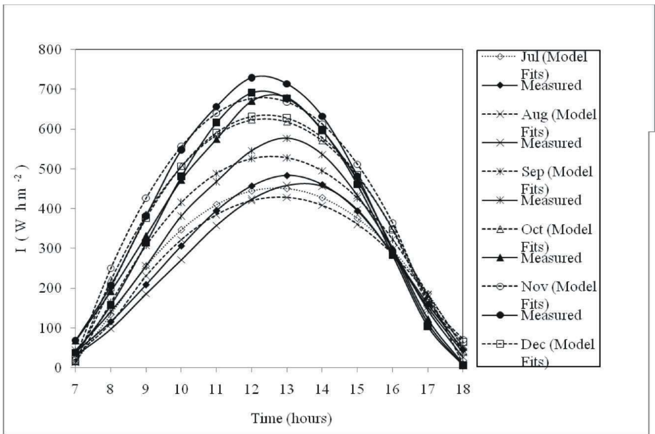

Fig. 2: Monthly Average global solar radiation (I in W h m^{-2}) and the parabolic fits (July - December)

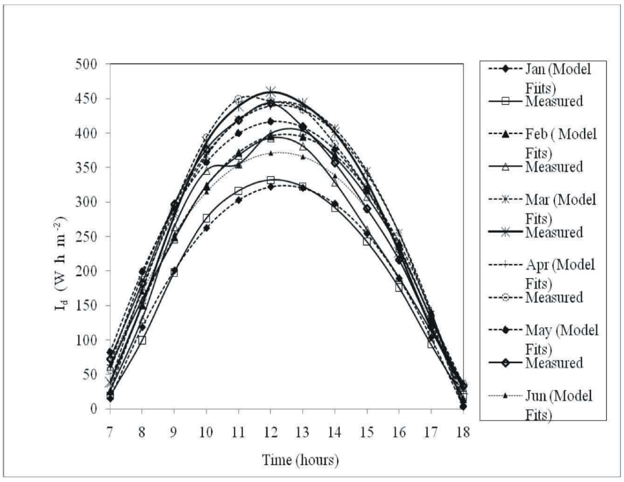

Fig. 3: Monthly Average diffuse solar radiation (I in W h m^{-2}) and the parabolic fits (January – June)

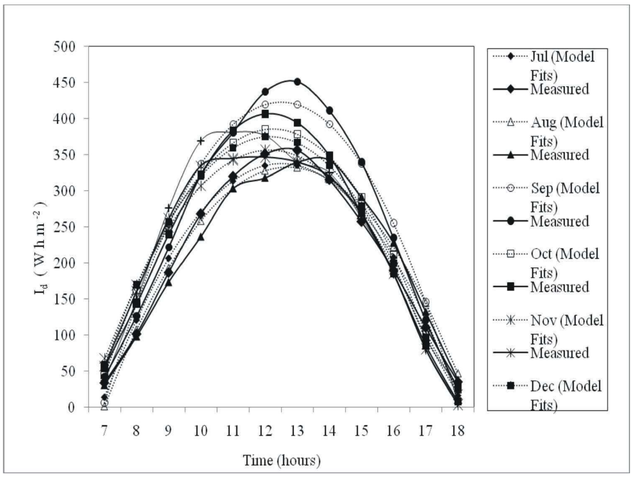

Fig. 4: Monthly Average diffuse solar radiation (I in W h m^{-2}) and the parabolic fits (July - December)

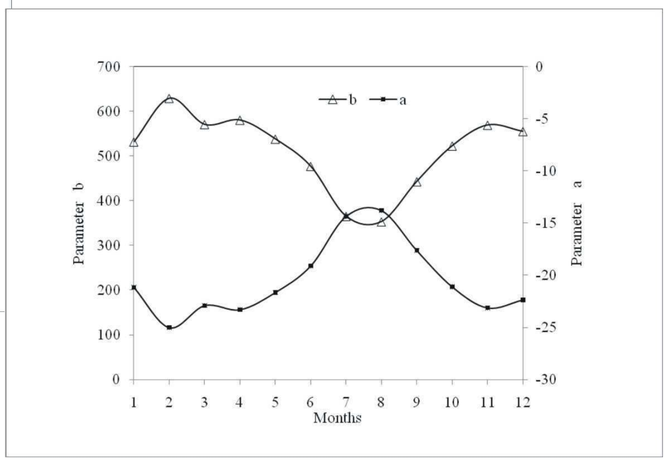

Fig. 5: Monthly variation of Parameters a and b in equation (1) with months for global solar radiation

The behaviour of the c parameter follows that of a (the plot is not shown here). An increase in parameter a value indicates a decrease in b but an increase in the c value (Tab. 1). Figs. 6 and 7 which show the scatter diagram between parameters a and b as well as a and c confirm this trend.

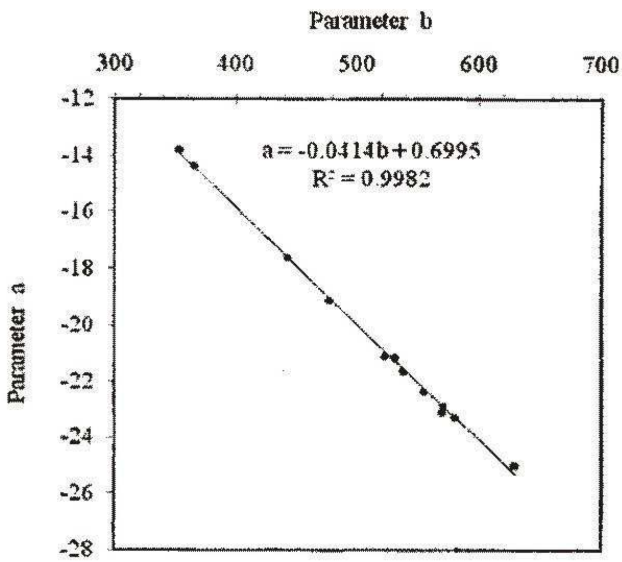

Fig. 6: Scatter diagram between parameter a and b for monthly average global radiation

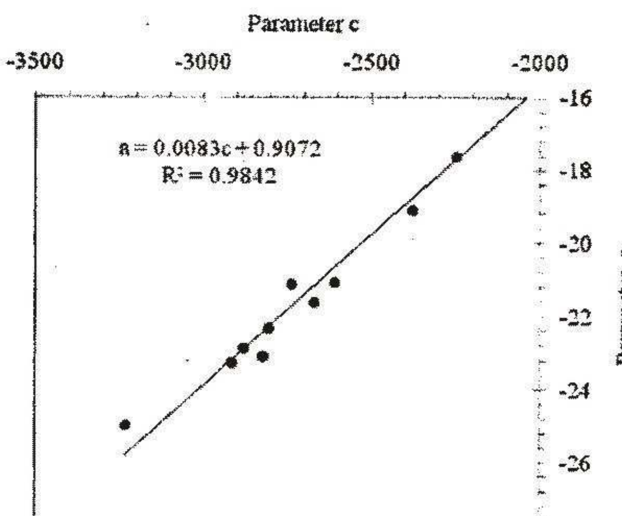

Fig. 7: Scatter diagram between parameter a and c for monthly average global radiation

It is obvious that they are related, according to the least squares technique, as:

$$a = -0.0414b + 0.6995 \quad \text{............} (4)$$

and

$$a = 0.0083c + 0.9072 \quad \text{..................} (5)$$

The coefficients of determination (R^2) are 0.9982 and 0.9842 respectively. Similarly, Fig. 8 shows the variations of parameters a and b from month to month for the monthly average hourly diffuse radiation and again parameter b replicates an inverse pattern of parameter a though in this case the variation is not systematic. The scatter diagrams are shown in Figs. 9 and 10 and the resulting equations are:

$$a = -0.0407b + 0.0691 \quad \text{........................} (6)$$

$$a = 0.0077c - 0.8471 \quad \text{........................} (7)$$

Again parameter b can be calculated provided parameter a is known and vice versa and these parameters can then be used in equation (1). The coefficients of determination (R^2) are 0.9869 and 0.9025 respectively. Once parameters a, b and c of equation (1) are known for any site then the values can be substituted into equation (1) to calculate either the monthly average global or diffuse solar radiation at the site.

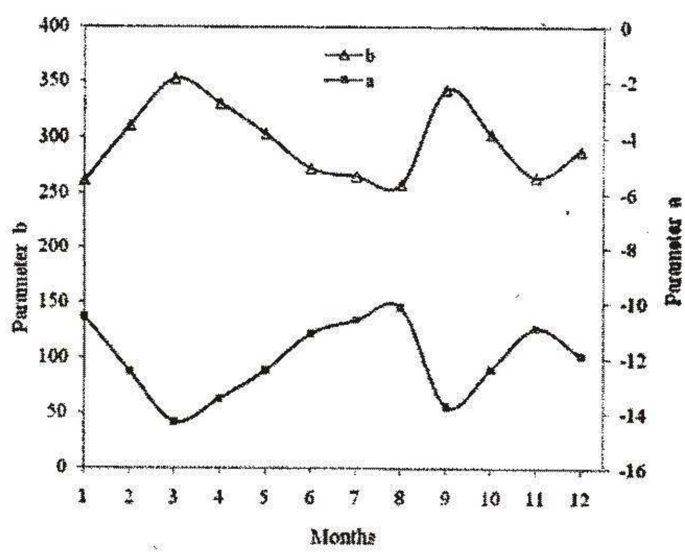

Fig. 8: Monthly variation of Parameters a and b in equation (1) with months for global solar radiation

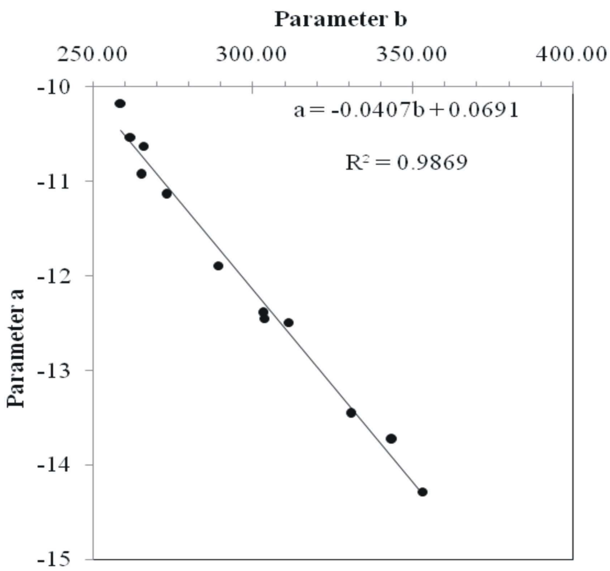

Fig. 9: Scatter diagram between parameters a and b for monthly average hourly diffuse radiation

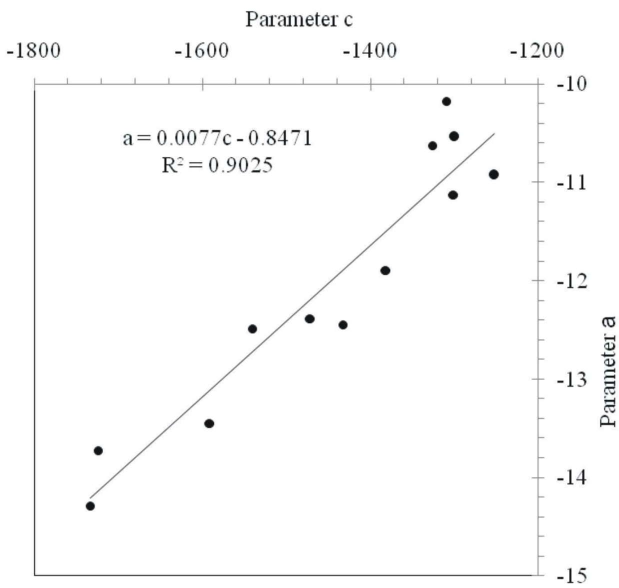

Fig. 10: Scatter diagram between parameters a and b for monthly average hourly diffuse radiation

CONCLUSION

Simple parabolic models of solar radiation data are developed for monthly average hourly global and diffuse solar radiation amounts in a tropical site, Ile-Ife, Nigeria. The dataset used for the study which consisted of 10-year hourly global and diffuse solar radiation on a horizontal surface was measured at the Obafemi Awolowo university campus, Ile-Ife, Nigeria. The general trends in the radiation change with daytime hours for each month are depicted by a second order parabolic model, and their parameters are estimated by using the classical least squares technique. The developed models provide very simple and direct ways of calculating the monthly average daily global and diffuse radiation values for any month and the variation characteristics which are crucial for solar energy applications. The extreme values of the global and diffuse solar radiation at the site and their time of occurrence can also be calculated from the models.

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