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Empirical Correlations of Global Solar Radiation with Meteorological data for Onne, Nigeria

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Abstract

Multiple linear regression models were developed to estimate the monthly average daily global solar radiation using ten parameters during a period of sixteen years (1984 to 1999) for Onne, Nigeria; the extraterrestrial radiation, average daily temperature, ratio of minimum and maximum daily temperature, relative humidity, ratio of sunshine duration, solar declination, average soil temperature, average pan evaporimeter, average rain fall and average daily dew. Even though up to ten variable correlations has been developed; the results showed that eight variable correlations with the highest value of correlation coefficient R gives the best result when considering the error terms (mean percentage error (MPE), mean bias error (MBE), root mean square error (RMSE)) and it has a percentage error within the range of –3.85% to 3.91%. This correlation equation is given as

$$\begin{array}{l} H = -7.489 + 0.316\,H_\circ + 0.236\,T - 7.000\,\theta + 6.758\times 10^{-2} RH \\ +17035\,n/N + 4.444\times 10^{-2}\delta - 0.177\,ST + 674.342\,EV \end{array},$$

where H, H_o, T, θ, RH, n/N, δ, St and EV are the global solar radiation, extraterrestrial radiation, temperature, ratio of minimum and maximum temperature, ratio of shine duration, declination, soil temperature and pan evaporimeter. The developed correlation can use for estimating global solar radiation of locations within the rainforest climatic zone of southern Nigeria.

1. Introduction

Global solar radiation data is essential for the study and design of the economic viability of systems that use solar energy. There are, of course, other uses of such information, including forecasts of evaporation from dams, agricultural potential and meteorological forecasting. In spite of the importance of global solar radiation data, few meteorological stations, especially in developing countries, measure accurately and continuously these data. This situation can be solved using correlation, which estimate global solar radiation from available meteorological parameters, such as sunshine duration hours, daily temperature, relative humidity etc. The correlation models developed can be used in estimating global solar radiation in locations of similar latitude, altitude and climatology.

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Empirical modeling is an essential and economical tool for the estimation of global solar radiation .The accuracy of such models depends on the quality and quantity of the measured data used. Though less accurate, modeling is a better tool for the estimation of global solar radiation at places where measurements are not available [1]. There are several correlations available for estimating global solar radiation. The most common is the Angstrom-type one-parameter equation correlating the global solar radiation to the percentage of bright sunshine hours in a simple linear regression form [2–9, 11–19]; and its second order regression [10]. The correlation equation for estimating global solar radiation from meteorological data was later developed by Sabbagh et al [20]; this model has been employed by Telahun [21] to estimate the daily solar radiation from sunshine hours, meteorological and geographical parameters for the Addis Ababa region. Of recent, Ertekin and Yildiz [22] have developed a multiple linear regression model with nine variables to estimate the monthly average daily global solar radiation for Antalya, Turkey. Sambo [23] also developed some empirical models for estimating global solar radiation with meteorological data for Northern Nigeria.

In this article, we develop equations that correlate monthly average daily global solar radiation for Onne in southern Nigeria. The applicability of the models developed is also examined. Similar analysis had been carried out on global solar radiation at this station [24].

2. Methodology

Monthly average daily global solar radiation, sunshine duration hours, temperature and other meteorological parameters data were obtained from IITA (International Institute of Tropical Agriculture) station of Onne, located within the rainforest climatic zone of southern Nigeria, during the period 1984 to 1999. Onne is located at latitude 4° 46 N, longitude 7° 10 E with an altitude of 10 m. Monthly averages (over the sixteen year period) of the data, processed in preparation for the correlation, are presented in Table 1.

Table 1. Global solar radiation and relevant meteorological data for Onne.

Month	H (MJ/m^2)	H_O (MJ/m^2)	T (oC)	θ	RH (%)	n/N	δ (Deg)	ST (oC)	RFx10^{-3} (m)	EVx10^{-3} (m)	Dx10^{-5} (m)
J	11.23	34.52	21.93	0.55	56.31	0.34	-20.92	24.18	0.61	2.96	5.50
F	14.10	36.37	26.57	0.66	66.88	0.40	-12.96	30.13	1.71	4.22	6.80
M	13.67	37.61	26.28	0.68	71.19	0.31	-2.42	27.45	3.84	3.79	7.50
A	14.99	37.42	27.79	0.74	77.44	0.33	9.42	27.23	4.80	3.69	8.60
M	13.82	36.09	26.99	0.75	78.94	0.34	18.79	29.17	7.25	3.59	9.50
J	13.24	35.11	26.29	0.77	81.94	0.27	23.09	27.80	10.22	2.93	8.80
J	10.66	35.40	25.34	0.80	84.25	0.18	21.18	26.48	12.92	2.45	8.10
A	10.36	36.61	25.45	0.81	84.13	0.14	13.46	24.18	12.47	2.18	5.20
S	11.36	37.30	26.36	0.78	83.44	0.22	2.22	26.70	10.90	2.54	7.40
O	11.89	36.53	24.46	0.72	76.75	0.30	-9.60	27.40	8.36	2.67	8.80
N	12.27	34.83	25.19	0.70	74.19	0.38	-18.91	28.36	4.78	2.82	10.10
D	12.08	33.81	24.03	0.61	64.88	0.38	-23.05	24.00	0.85	2.80	6.40

In computing the extraterrestrial solar radiation on a horizontal surface, H_o, we employed the equations used in [24]. Multiple linear regression equation for estimating H with ten parameters is as follows [25]:

$$y = a + bx_1 + cx_2 + dx_3 + ex_4 + fx_5 + gx_6 + hx_7 + jx_8 + kx_9 + nx_{10} \tag{1}$$

Where $a \ldots n$ are the regression coefficients and x_i is the correlated parameter. The estimated values were compared to the measured values in each regression equation through correlation coefficients R and standard errors of estimate σ.

2.1. Correlations

The various meteorological parameters shown in Table 1 are all related to global solar radiation in varying degrees. In order not to overlook any particular parameters or group of parameters, multiple linear regression analysis of ten parameters (H_o, T, θ, RH, n/N, δ, ST, EV, RF and D) was employed to estimate global solar radiation. Here, H is the monthly average daily global solar radiation on a horizontal surface (in units of $\mathrm{MJm^{-2}day^{-1}}$); H_o is the monthly average daily extraterrestrial radiation on a horizontal surface (in units of $\mathrm{MJm^{-2}day^{-1}}$); T is the monthly average daily temperatures; θ is monthly average ratio of minimum-to-maximum daily temperatures; RH is the monthly average daily relative humidity; n/N is the monthly percent possible sunshine; δ is solar declination; ST is the monthly average daily soil temperature (in °C); EV is the monthly average daily pan evaporimeter (in cm); RF is the monthly average daily rainfall; and D is the monthly average daily dew. The various linear regression analyses are as follows.

(i) **One variable correlation:** This correlation gives the highest R as 0.663 for ST, and the lowest value of R as 0.125 for θ with their corresponding σ:

$$H = -0.897 + 0.497\,ST (\text{with } R = 0.663 \text{ and } \sigma = 1.1569) \tag{2}$$

$$H = -14.149 + 2.347\,\theta (\text{with } R = 0.125 \text{ and } \sigma = 1.5334) \tag{3}$$

(ii) **Two variable correlations:** The incorporation of one extra parameter to the sets of correlation equations for one variable yield a high value of R (0.935) for T and θ and low value of R (0.330) for θ and δ, with their corresponding σ:

$$H = -4.652 + 1.128\,T - 16.391\,\theta (\text{with } R = 0.935 \text{ and } \sigma = 0.5795) \tag{4}$$

$$H = 20.282 + 10.937\,\theta + 4.758 \times 10^{-2}\,\delta (\text{with } R = 0.330 \text{ and } \sigma = 1.5380) \tag{5}$$

(iii) **Three variable correlations:** The highest R (= 0.958) in the three variable equations was found for RF, EV and RH, and the lowest R (0.337) was determined for the variables θ, RH and δ with their respective σ as:

$$H = -3.779 - 331.719\,RF + 1661.134\,EV + 0.178\,RH (\text{with } R = 0.958 \text{ and } \sigma = 0.497) \tag{6}$$

$$H = 19.582 - 0.201\,\theta - 9.290 \times 10^{-2}\,RH + 4.500 \times 10^{-2}\,\delta (\text{with } R = 0.337 \text{ and } \sigma = 1.6272) \tag{7}$$

(iv) **Four variable correlations:** The four variable equations involving n/N, δ, ST and H_o resulted in the highest R as 0.976 and those using δ, ST, D and H_o resulted in the lowest R as 0.679 with their corresponding value of σ:

$$H = -13.272 + 24.822\,n/N + 7.063 \times 10^{-2}\,\delta - 0.148\,ST + 0.620\,H_0 (\text{with } R = 0.976 \text{ and } \sigma = 0.4046) \tag{8}$$

$$H = -6.706 - 9.760 \times 10^{-2}\,\delta + 0.453\,ST + 3548.117 D + 0.187 H_0 (\text{with } R = 0.679 \text{ and } \sigma = 1.3565) \tag{9}$$

(v) Five variable correlations: Maximum $R = 0.978$ was obtained for RH, n/N, δ, ST, and EV in the five variable linear regression equations, while minimum $R = 0.892$ was obtained for θ, RH, n/N, $\delta$and ST as :

$$H = 0.529 + 0.125RH + 14.283n/N + 1.447 \times 10^{-2}\delta - 0.314ST + 2210.946EV(R = 0.978; \sigma = 0.4158) \tag{10}$$

$$H = 2.029 + 25.416\theta - 0.192RH + 21.859n/N + 5.623 \times 10^{-2}\delta + 4.890 \times 10^{-3}ST(R = 0.892; \sigma = 0.9019) \tag{11}$$

(vi) Six variable correlations: The highest $R = 0.982$ and the lowest $R = 0.947$ for six variable equations were obtained from the variables H_o, T, θ, RH, n/N and δ, and H_o, T, θ, RH, n/N and ST, respectively, as follows:

$$H = -7.875 + 0.303H_o + 0.479T - 14.629\theta + 4.906 \times 10 - 2RH + 13.358n/N + 4.938 \times 10^{-2}\delta \\ (R = 0.982; \sigma = 0.4177) \tag{12}$$

$$H = -6.921 + 2.726 \times 10^{-2}H_o + 0.909T - 12.099\theta + 1.908 \times 10^{-2}RH + 5.272n/N + 3.006 \times 10^{-2}ST \\ (R = 0.947; \sigma = 0.7003) \tag{13}$$

(vii) Seven variable correlations: The estimation of global solar radiation on a horizontal surface using the seven variable equations gave the highest $R = 0.984$ for H_0, T, θ, RH, n/N, δ and RF, and the lowest $R = 0.977$ for θ, RH, n/N, δ, ST, D and RF:

$$H = -9.477 + 0.357H_o + 0.202T - 7.897\theta + 9.562 \times 10^{-2}RH + 12.644n/N + 5.806 \times 10^{-2}\delta - \\ 210.422RF(R = 0.984; \sigma = 0.4342) \tag{14}$$

$$H = -2.777 - 20.868\theta + 0.361RH - 4.817n/N + 5.804 \times 10^{-2}\delta + 0.363ST - 7.830D - 711.400RF \\ (R = 0.977; \sigma = 0.5835) \tag{15}$$

(viii) Eight variable correlations: The variables H_o, T, θ, RH, n/N, δ, ST and EV were used to obtain the highest value of $R = 0.984$ for the eight variable equations, while the variables T, θ, RH, n/N, δ, ST, D and RF gave the lowest value of R=0.975:

$$H = -7.489 + 0.316H_o + 0.236T - 7.000\theta + 6.758 \times 10^{-2}RH + 17.358n/N + 4.444 \times 10^{-2}\delta - \\ 0.177ST + 674.342EV(R = 0.984; \sigma = 0.4990) \tag{16}$$

$$H = 0.379 + 1.105T - 5.035\theta - 0.181RH - 60526n/N + 2.405 \times 10^{-2}\delta - 0.155ST + 28284.937D + \\ 165.039RF(R = 0.975; \sigma = 0.6309) \tag{17}$$

(ix) Nine variable correlation: To obtain the highest $R = 0.984$ in the nine variable equations, we used the variables θ, RH, n/N, δ, ST, D, RF, EV and H_o. The variables T, θ, RH, n/N, δ, ST, D, RF and EV lead to the lowest R= 0.983. For this we have

$$H = -8.372 - 8.466\theta + 0.165RH + 13.938n/N + 5.273 \times 10^{-2}\delta - 6.060 \times 10^{-2}ST - 3877.646D - 124.133RF + 594.135EV + 0.330H_o (R = 0.984; \sigma = 0.6140) \quad (18)$$

$$H = 4.758 + 0.831T + 3.364\theta - 0.226RH + 20.337n/N - 1.630 \times 10^{-2}\delta - 0.750ST + 36506.225D + 694.122RF + 2553.330EV (R = 0.983; \sigma = 0.6396) \quad (19)$$

(x) Ten variable correlations: An equation with ten variables (H_o, T, θ, RH, n/N, δ, ST, D, RF and EV) had $R = 0.984$:

$$H = -5.366 + 0.271H_o + 0.424T - 2.735\theta - 3.560 \times 10^{-2}RH + 17.462n/N + 3.317 \times 10^{-3}\delta - 0.294ST + 11894.632D + 146.910RF + 878.016EV (R = 0.984; \sigma = 0.8573) \quad (20)$$

3. Results and Discussion

For a better analysis of the developed correlations we look at those relations that have higher values of correlation coefficients R: Equations (2), (4), (6), (8), (10), (12), (14), (16), (18) and (20). Equations (14), (16), (18) and (20) have the highest value of the correlation coefficient, while the remainders have lower value of R. The applicability of the proposed correlations in predicting H is tested by estimating H values for Onne location used in the analysis. Estimated values of H for Onne, along with the measured data, are shown in Table 2. Inspection of the Table shows that Equations (6), (10), (12) and (16) estimate H fairly accurately. However, the errors in the estimated data are low, between 3.33% to 3.91%. Accurate estimations are possible for most months from Equation (20). However, the error in the estimated values reaches 5.79%. The accuracy of Equation (4) exhibits error up to 8.28%. The accuracy of the estimated data from Equations (8) and (18) are found to be high, 35.53% and 22.36%, respectively, compared to other equations.

Table 2. Comparison between measured and estimated values of the correlation equations.

	H	Models									
Month	(MJ/m^2)	Eqn.2	Eqn.4	Eqn.6	Eqn.8	Eqn.10	Eqn.12	Eqn.14	Eqn.16	Eqn.18	Eqn.20
J	11.23	11.12	11.07	10.96	12.84	11.07	11.31	11.27	11.11	11.24	11.88
F	14.10	14.08	14.50	14.57	19.11	13.81	14.20	14.00	14.05	14.02	14.42
M	13.67	12.75	13.85	13.92	13.51	13.62	13.68	13.67	13.55	13.70	13.69
A	14.99	12.64	14.57	14.54	14.76	14.67	14.62	13.68	14.76	14.77	14.53
M	13.82	13.60	13.50	13.83	14.55	14.30	14.36	14.35	14.36	14.39	13.77
J	13.24	12.92	12.38	12.28	12.72	12.71	12.86	12.73	12.73	14.91	12.01
J	10.66	12.26	10.82	11.00	10.72	11.04	10.87	10.81	10.80	10.83	10.23
A	10.36	11.12	10.78	10.68	10.27	10.47	10.22	10.31	10.32	10.35	9.96
S	11.36	12.37	12.30	11.68	11.52	11.37	11.79	11.60	11.60	13.90	11.60
O	11.89	12.72	11.14	11.55	12.09	12.00	11.68	11.64	11.71	13.28	11.98
N	12.27	13.20	12.29	12.53	12.22	12.29	12.29	12.31	12.21	12.28	12.88
D	12.08	11.03	12.46	12.14	11.94	12.39	12.08	12.12	12.19	12.19	12.36

The following observations can be made from a study of Table 3. Based on the RMSE, Equation (16) produces the best correlation, while Equation (8) gives the worst with larger value of RMSE. For MBE, the result shows that Equation (6) is the best while Equation (14) is the worst. Even though Equations (8) and (14) appears to have the largest values of RMSE and MPE respectively, it should be noted that both equations have terms involving parameters that have not been normalized (ST (in °C), T (in °C) and RF (in m)), as shown in Table 1. With respect to MPE, Equation (16) offers the best correlation while Equation (18) gives the worst.

Table 3. Error values (in units of MJ/m^2) for the developed correlation models.

Error	Models									
Terms	Eqn.2	Eqn.4	Eqn.6	Eqn.8	Eqn.10	Eqn.12	Eqn.14	Eqn.16	Eqn.18	Eqn.20
MPE	0.7975	0.1617	0.3958	3.3108	0.2725	0.6092	0.5075	-0.1533	3.9858	-0.1867
MBE	0.0935	-0.0401	0.0067	4.3961	0.0448	0.1937	-0.7869	-0.1886	4.1435	-0.2310
RMSE	8.9171	1.9984	1.3286	19.1565	0.6343	0.5894	1.6118	0.5137	7.7612	1.9976
% Error	-15.680 to 15.010	-6.500 to 8.280	-7.250 to 3.330	-1.530 to 35.530	-4.000 to 3.570	-2.870 to 3.910	-8.740 to 15.000	-3.850 to 3.910	-1.470 to 22.360	-9.290 to 5.790

Since the MPE gives information on the long-term performance of the examined regression equations, a positive MPE value provides the average amount of overestimation in the calculated values while a negative MPE value gives underestimation. On the whole, a low MPE is desirable. However, an overestimation of MPE may be cancelled by an underestimation. The test on RMSE conveys information on the short-term performance of different equations, since it enables a term-by-term comparison of the actual variations between the estimated and measured values. For more accurate estimation, lower values of RMSE should be obtained.

Figure shows plots of Equations (16) and (18) with extreme values of RMSE together with the monthly average daily global solar radiation measured for sixteen years. Equation (16) gives an almost exact fit to the global solar radiation data, while Equation (8) does not fit the measured data very well, with a very big overestimation in the month of February. In general, the monthly radiation pattern as shown by Figure can be explained in terms of two maxima and minima as observed recently by Akpabio and Etuk [24].

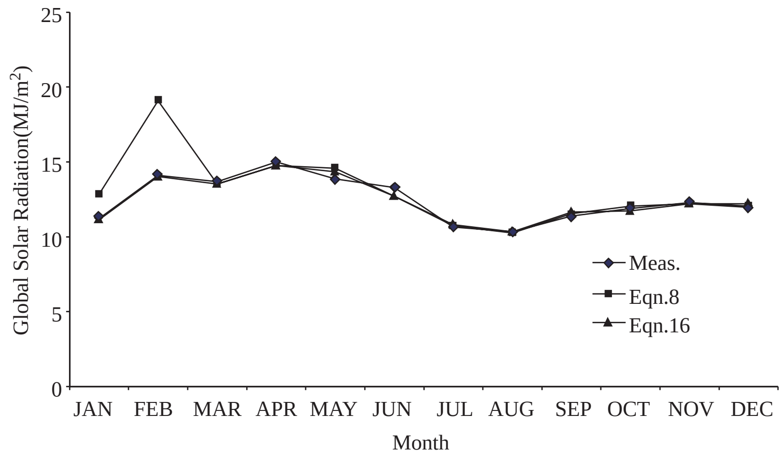

Figure. Comparison of measured and estimated (from two models) of monthly average daily global solar radiation.

4. Conclusions

Multiple regressions have been employed in this study to develop several correlation equations used to describe the dependence of global solar radiation on other meteorological data for Onne location. Even though up to ten variable correlations has been developed, it is observed that the eight variable correlations which is one of the equations with the highest value of R gives the best result when considering the error terms, i.e. MPE, MBE and RMSE. Again, fractional error of -3.85% to 3.91% is within the range of acceptable values and it is far better than what has been reported for the same location by Akpabio and Etuk [24] for the Angstrom-type correlation.

Hence, the multiple regression equation that could be employed for the purposed of estimating global solar radiation of locations that have the same climate, latitude and altitude as Onne within the rain forest climatic zone of southern Nigeria is the correlation equation with the least value of the RMSE as

$$H = -7.489 + 0.316\,H_{\circ} + 0.236\,T - 7.000\,\theta + 6.758\times10^{-2}RH$$
$$+17035\,n/N + 4.444\times10^{-2}\delta - 0.177\,ST + 674.342\,EV$$

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