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Empirical correlations for the estimation of global solar radiation using meteorological data in WA, Ghana

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ABSTRACT

Monthly average daily global solar radiation data are essential in the design and study of solar energy convention devices. In this study, multiple linear regression models were developed to estimate the monthly average daily global solar radiation using seven parameters during a period of two years from 2010 to 2011 for Wa Polytechnic weather station. The parameters used were the extraterrestrial radiation, mean ambient temperature, mean soil temperature, relative humidity, declination,ratio of the difference between the maximum and minimum monthly mean ambient temperature to the minimum monthly mean ambient temperautre and ratio of sunshine duration. Selected models were compared on the basis of the statistical error tests; mean bias error (MBE), mean percent error (MPE), root mean square error (RMSE) and the t-test. Based on the statistical results, the correlation equation that could be employed for the purposes of estimating global solar radiation of locations that have the same climate, latitude and altitude as Wa Polytechnic weather station is given as

$$\overline{H} = -1.350 + 0.007RH + 44.800\,\overline{n}/\overline{N} + 2.000\sin\delta$$

The present work will help to advance the state of knowledge of global solar radiation to the point where it has applications in the estimation of monthly average daily global solar radiation.

Keywords: Daily global solar radiation, empirical models, multiple linear regression, t-statistics.

INTRODUCTION

Information of solar radiation at a given location is essential for many applications, such as in the design of projects, meteorological forecasting, solar heating, drying and architectural design. Hence, solar radiation data are required by solar engineers, architects and agriculturists. Furthermore, monthly mean data are needed for the estimation of long-term solar systems performances. In the applications of solar energy listed above, the most important parameters that are often needed are the average solar irradiation and its components. Unfortunately, few meteorological stations, especially in many developing countries, measure accurately and continuously these data. One way of solving this is using appropriate correlations which are empirically established, that can be used to estimate global solar radiation from more readily available meteorological parameters such as sunshine hours, daily temperature and relative humidity.

Empirical modelling is an essential and economical tool for the estimation of global solar radiation. The accuracy of such models depends on the quality of the measured data used. Though less accurate, modelling is a better tool for the estimation of global solar radiation at places where measurements are not available [20]. Several empirical models have been developed to calculate solar radiation using various parameters. [7] developed the earliest model used for estimating global radiation, in which the sunshine hours data and clear sky radiation data, were used. Many

researchers have used Angstrom's model to develop empirical correlations [1,17, 20, 21, 22, 24, 25]. In addition, other empirical models have been developed to calculate solar radiation from other parameters such as relative humidity, ambient temperature, soil temperature, number of rainy days and evaporation [2, 11, 13, 14, 15, 20, 25].
In this study, the first aim was to determine monthly variation of mean global solar radiation, extraterrestrial radiation, mean ambient temperature, relative humidity, mean sunshine hours and mean soil temperature in Wa Polytechnic.The second aim was to to develop equations that correlate monthly average daily global radiation and the other variables to select the most appropriate model for Wa Polytechnic in northern Ghana. We then reviewed all the equations and retained some of them. This was followed by statistical comparison methods such as MBE, RMSE and t-statistics, of the retained equations to select the best.

ESTIMATION METHODS

Monthly mean daily extraterrestrial radiation $\overline{H}_O$, daylength $\overline{N}$,angle of declination δ and sunset hour angle ω_s, using the average day of the month, were calculated from equations (1) – (4), respectively [12].

$$\overline{H}_O = \frac{24\times 3600}{\pi}\times G_{sc}\left(1+0.033\cos\frac{360\overline{n}}{365}\right)\times\left(\cos\phi\cos\delta\sin\omega_s+\frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \quad (1)$$

$$\overline{N} = \frac{2}{15}\cos^{-1}\left(-\tan\phi\tan\delta\right) \quad (2)$$

$$\delta = 23.45\sin\left(360\times\frac{284+\overline{n}}{365}\right) \quad (3)$$

$$\omega_s = \cos^{-1}\left(-\tan\phi\tan\delta\right) \quad (4)$$

METHODOLOGY

Extraterrestrial radiation on a horizontal surface in monthly periods were calculated numerically using declination angle, latitude and sunset hour angle using the estimation methods. Available monthly mean daily global solar radiation, sunshine duration hours, relative humidity, soil temperature and ambient temperature were taken from the site of the weather station of Wa Polytechnic, for the periods 2010 and 2011. The graphical location of Wa Polytechnic weather station is latitude 10.01º N, with an altitude of 322 m above sea level.Monthly averages over the two 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 Wa Polytechnic

Month	$\overline{H}$(MJ/m^2)	$\overline{H}_o$ (MJ/m^2)	$\overline{T}_a$(ºC)	RH(%)	$\overline{n}/\overline{N}$	$\overline{T}_s$ (ºC)	$\sin\delta$ (ºC)	θ
Jan	19.65	31.99	26.56	27.75	0.48	31.47	-0.36	1.72
Feb	20.01	34.60	29.83	47.56	0.48	31.80	-0.22	1.18
Mar	21.95	36.91	30.82	58.03	0.51	31.75	-0.04	0.86
Apr	22.35	37.94	29.86	72.47	0.51	33.76	0.16	0.99
May	21.83	37.57	28.26	81.27	0.49	32.04	0.32	0.78
Jun	19.76	37.01	26.67	90.26	0.44	29.60	0.39	0.70
Jul	18.42	37.11	25.35	92.50	0.41	28.12	0.36	0.66
Aug	16.37	37.55	24.75	94.32	0.37	27.52	0.23	0.62
Sep	17.43	37.08	25.03	97.29	0.40	28.86	0.04	0.61
Oct	21.36	35.11	25.86	94.15	0.50	30.40	-0.17	0.87
Nov	17.95	32.50	26.06	90.17	0.43	30.88	-0.32	1.06
Dec	18.77	31.09	25.40	44.10	0.46	29.10	-0.39	2.01

The changes of the global solar radiation and extraterrestrial radiation in monthly periods throughout the two year period were investigated and shown in Fig.1.

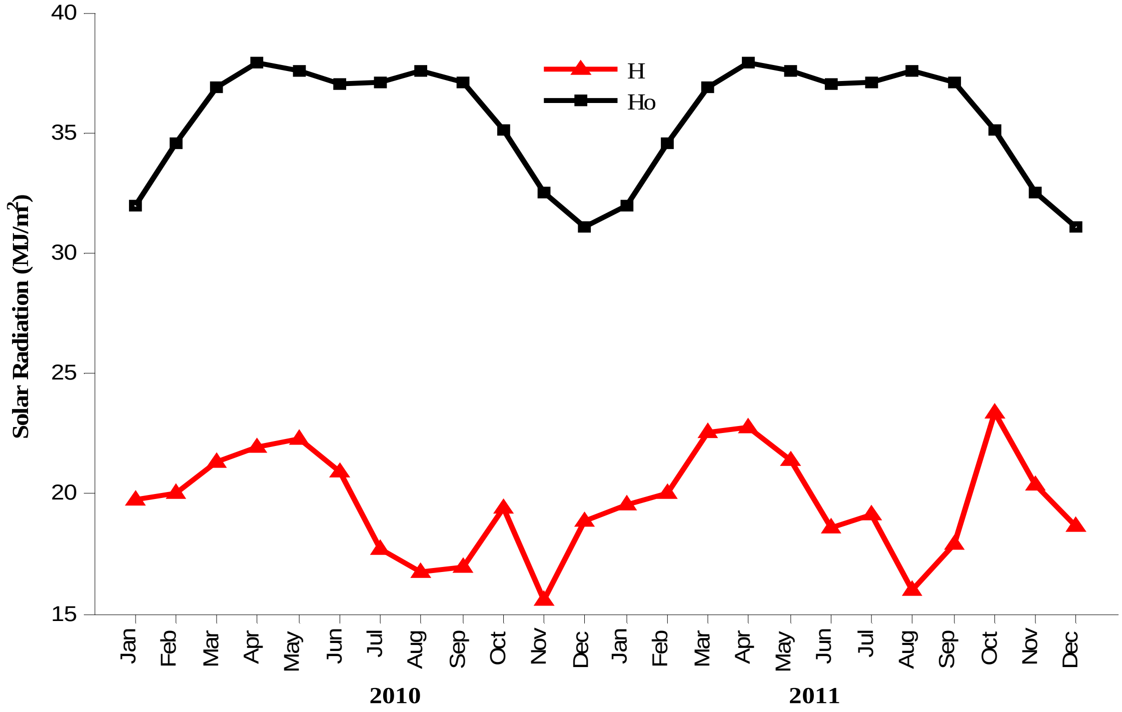

Figure 1: The changes of the mean global solar radiation and extraterrestrial radiation for the two years

The monthly change of the other meteorological parameters such as soil temperature, ambient temperature, relative humidity and sunshine hours were seen in Fig. 2.

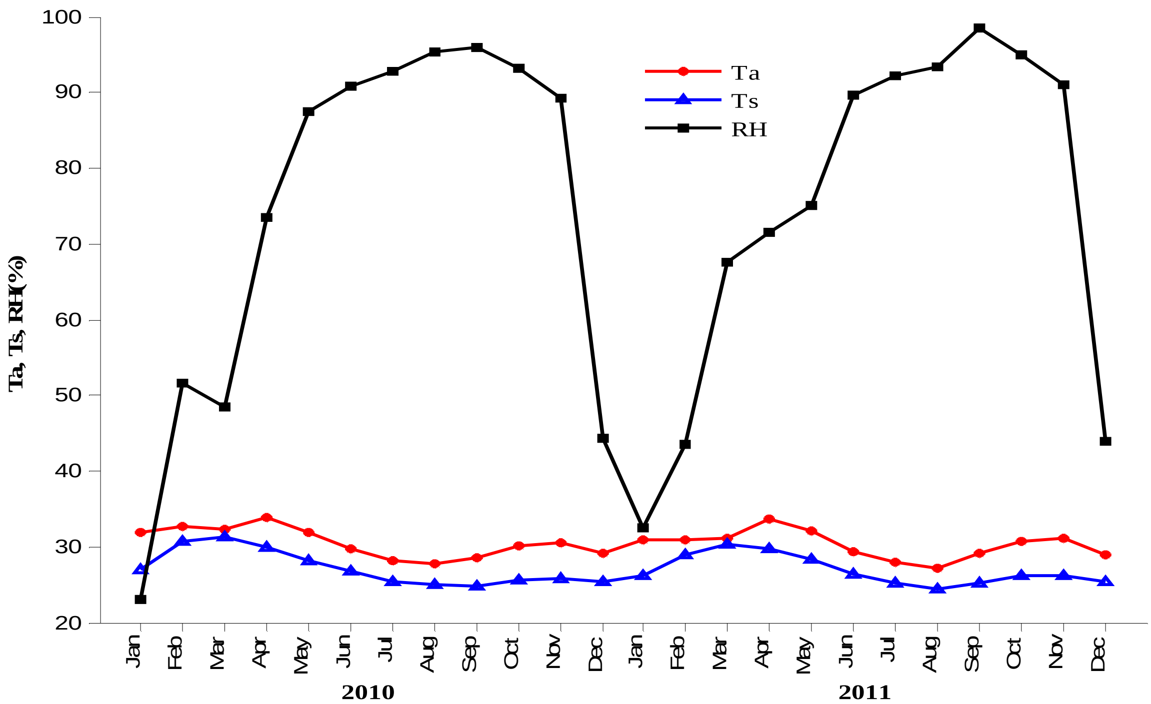

Figure 2: The mean monthly change of ambient temperature, soil temperature and relative humidity

We then developed equations to estimate the monthly mean global solar radiation $\bar{H}$ by applying multiple linear regression to various parameters such as $\overline{H}_0$, $\overline{n}/\overline{N}, \sin\delta$, θ, $\overline{T}_a$, $\overline{T}_s$ and $RH(\%)$. The values of $\overline{H}$ were estimated using these equations. Starting with one parameter, the equation in linear regression took the form;

$$Y = \beta_0 + \beta_1 x \qquad (5)$$

where a and b are regression coefficients and x is the correlated parameter. Multiple linear regression equation for estimating $\bar{H}$ with seven parameters is as follows;

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 \qquad (6)$$

CORRELATIONS

The setup of the weather station at Wa Polytechnic measures the wind speed, solar radiation, soil temperature, relative humidity, sunshine hours and ambient temperature. In order not to overlook any parameter or group of parameters, multiple linear regression analysis of the seven driving variables were employed to develop equations to estimate the mean monthly global solar radiation.

The various linear regression analyses are as follows in Table 1.

Table 2: Multiple Linear Regression Model Equations

Number of Variables	Number of Model Equations
One variable correlation	7
Two variable correlations	21
Three variable correlations	35
Four variable correlations	35
Five variable correlations	21
Six variable correlations	7
Seven variable correlations	1

A total of 127 model equations were formed and analysed for the best model equation that can predict the monthly average solar radiation (in MJ/m^2) with the least error.Seventeen model equations were then chosen for comparison using % error analysis. The values from $\bar{H}$ equations were compared with the corresponding meteorological values. The seventeen linear regression model equations are as follows:

$$\overline{H} = -1.350 + 0.007RH + 44.800\,\overline{n}/\overline{N} + 2.000\sin\delta \;(R = 0.999,\; \sigma = 0.054) \qquad (7)$$

$$\overline{H} = -1.540 + 44.300\,\overline{n}/\overline{N} + 1.960\sin\delta + 0.014\overline{T}_a\,(R = 0.100, \sigma = 0.054) \qquad (8)$$

$$\overline{H} = -1.460 + 0.007RH + 44.500\,\overline{n}/\overline{N} + 2.000\sin\delta + 0.008\overline{T}_s\,(R = 0.999, \sigma = 0.057) \qquad (9)$$

$$\overline{H} = -1.460 + 0.007RH + 44.500\,\overline{n}/\overline{N} + 2.000\sin\delta + 0.008\overline{T}_s\,(R = 0.999, \sigma = 0.057) \qquad (10)$$

$$\overline{H} = -2.030 + 0.007RH + 44.400\,\overline{n}/\overline{N} + 1.840\sin\delta + 0.003\overline{T}_a + 0.022\overline{H}_o\,(R = 1.000, \sigma = 0.053) \qquad (11)$$

$$\overline{H} = -1.510 + 0.008RH + 44.400\,\overline{n}/\overline{N} + 1.950\sin\delta + 0.016\overline{T}_a - 0.004\overline{T}_s\,(R = 0.100, \sigma = 0.058) \qquad (12)$$

$$\overline{H} = -1.110 + 0.006RH + 44.600\,\overline{n}/\overline{N} + 1.920\sin\delta + 0.002\overline{T}_a - 0.114\theta(R = 1.000, \sigma = 0.054) \qquad (13)$$

$$\overline{H} = -1.09 + 0.006RH + 44.600\,\overline{n}/\overline{N} + 1.920\sin\delta + 0.001\overline{T}_s - 0.121\theta(R = 1.000, \sigma = 0.054) \qquad (14)$$

$$\overline{H} = -2.05 + 0.007RH + 44.500\,\overline{n}/\overline{N} + 1.830\sin\delta + 0.001\overline{T}_s + 0.024\overline{H}_o\,(R = 1.000, \sigma = 0.053) \qquad (15)$$

$$\overline{H} = 0.191 + 45.000\,\overline{n}/\overline{N} + 1.900\sin\delta - 0.045\overline{T}_a + 0.019\overline{T}_s - 0.422\theta(R = 0.999, \sigma = 0.085) \qquad (16)$$

$$\overline{H} = -1.090 + 0.006RH + 44.600\,\overline{n}/\overline{N} + 1.920\sin\delta + 0.001\overline{T}_s - 0.121\theta(R = 1.000, \sigma = 0.054) \qquad (17)$$

$$\overline{H} = -2.020 + 0.007RH + 44.500\,\overline{n}/\overline{N} + 1.840\sin\delta + 0.003\overline{T}_a + 0.022\overline{H_o}\,(R = 1.000, \sigma = 0.058) \quad (18)$$

$$\overline{H} = -1.110 + 0.006RH + 44.600\,\overline{n}/\overline{N} + 1.920\sin\delta + 0.002\overline{T}_a - 0.114\theta(R = 1.000, \sigma = 0.059) \quad (19)$$

$$\overline{H} = -1.690 + 0.006RH + 44.500\,\overline{n}/\overline{N} + 1.850\sin\delta + 0.016\overline{H_o} - 0.056\theta(R = 1.000, \sigma = 0.057) \quad (20)$$

$$\overline{H} = 0.070 + 45.000\,\overline{n}/\overline{N} + 1.890\sin\delta - 0.046\overline{T}_a + 0.018\overline{T_s} + 0.004\overline{H_o} - 0.412\theta \quad (21)$$
$$(R = 0.999, \sigma = 0.093)$$

$$\overline{H} - 1.680 + 0.006RH + 44.600\,\overline{n}/\overline{N} + 1.850\sin\delta + 0.017\overline{H_o} - 0.058\theta(R = 1.000, \sigma = 0.057) \quad (22)$$

$$\overline{H} = -1.680 + 0.006RH + 44.600\,\overline{n}/\overline{N} + 1.850\sin\delta + 0.017\overline{H_o} - 0.057\theta(R = 1.000, \sigma = 0.054) \quad (23)$$

METHODS OF COMPARISON

The performance of the seventeen models was evaluated on the basis of the statistical error tests, (i.e. the mean percentage error (MPE), root mean square error (RMSE) and mean bias error (MBE)) and also tested whether they are statistically significant using t-statistics.

% Error

This is meant to test for the range within which the error of the model equations can be quantified, expressed in percentage form. A lower percentage error interval, $\overline{H}_{error\ interval}$ approaching zero is desirable and a negative value of $\overline{H}_{i,error}$ shows that the result is small than the actual value and vice versa. A desirable value of $\overline{H}_{error\ interval}$ should be between -5% to $+5\%$. Percentage error and percentage error interval are defined as;

$$\overline{H}_{i,error} = \frac{\left(\overline{H}_{i,cal} - \overline{H}_{i,meas}\right)}{\left(\overline{H}_{i,meas}\right)} \times 100 \quad (24)$$

$$\overline{H}_{error,interval} = \left(\overline{H}_{i,error,\max} - \overline{H}_{i,error,\min}\right) \quad (25)$$

The Mean Bias Error

$$MBE = \frac{1}{n}\sum_{1}^{n}\left(\overline{H}_{i,cal} - \overline{H}_{i,meas}\right) \quad (26)$$

This test provides information on long-term performance. A low MBEvalue is desired. A negative value gives the average amount of under-estimation in the calculated value and vice versa. So, one drawback of this test is that over-estimation of an individual observation will cancel under-estimation in a separate observation.

The Mean Percentage Error

$$MPE(\%) = \frac{1}{n}\sum_{1}^{n}\left(\frac{\overline{H}_{i,cal} - \overline{H}_{i,meas}}{\overline{H}_{i,meas}}\right) \times 100 \quad (27)$$

A percentage error between −10% and +10% is considered acceptable.

Table 3: Comparison between measured and estimated values of the correlation equations

M	H (MJ/m^2)	MODELS																
		Eqn. 7	Eqn. 8	Eqn. 9	Eqn. 10	Eqn. 11	Eqn. 12	Eqn.1 3	Eqn. 14	Eqn. 15	Eqn. 16	Eqn. 17	Eqn. 18	Eqn. 19	Eqn. 20	Eqn. 21	Eqn. 22	Eqn. 23
Jan	19.65	19.64	19.60	19.62	19.62	19.60	19.61	19.63	19.62	19.64	19.77	19.62	19.64	19.63	19.61	19.76	19.65	19.66
Feb	20.01	20.06	20.08	20.05	20.05	20.06	20.08	20.09	20.07	20.10	20.12	20.07	20.10	20.09	20.07	20.11	20.11	20.11
Mar	21.95	21.85	21.85	21.82	21.82	21.85	21.86	21.87	21.86	21.89	21.90	21.86	21.90	21.88	21.86	21.90	21.90	21.91
Apr	22.35	22.35	22.34	22.35	22.35	22.34	22.34	22.33	22.32	22.38	22.31	22.32	22.38	22.33	22.33	22.31	22.37	22.38
May	21.83	21.84	21.82	21.83	21.83	21.80	21.81	21.82	21.81	21.84	21.84	21.81	21.84	21.82	21.80	21.84	21.84	21.85
Jun	19.76	19.81	19.79	19.79	19.79	19.75	19.79	19.78	19.77	19.78	19.78	19.77	19.79	19.79	19.76	19.78	19.79	19.80
Jul	18.42	18.42	18.40	18.40	18.40	18.38	18.40	18.40	18.39	18.41	18.42	18.39	18.41	18.41	18.38	18.42	18.42	18.42
Aug	16.37	16.38	16.38	16.37	16.37	16.38	16.38	16.38	16.37	16.42	16.41	16.37	16.41	16.39	16.38	16.41	16.42	16.42
Sep	17.43	17.37	17.36	17.36	17.36	17.38	17.36	17.38	17.37	17.41	17.42	17.37	17.41	17.38	17.38	17.42	17.41	17.42
Oct	21.36	21.40	21.36	21.37	21.37	21.37	21.37	21.39	21.38	21.41	21.40	21.38	21.41	21.39	21.37	21.39	21.42	21.42
Nov	17.95	17.94	17.94	17.93	17.93	17.90	17.94	17.93	17.92	17.93	17.88	17.92	17.93	17.93	17.90	17.87	17.94	17.94
Dec	18.77	18.80	18.77	18.78	18.78	18.75	18.78	18.74	18.73	18.79	18.69	18.73	18.79	18.75	18.74	18.69	18.78	18.78
TOTAL	**235.85**	**235.86**	**235.69**	**235.67**	**235.67**	**235.54**	**235.71**	**235.74**	**235.61**	**236.01**	**235.93**	**235.61**	**236.01**	**235.78**	**235.60**	**235.89**	**236.06**	**236.12**

The Root Mean Square Error

The value of *RMSE* is always positive, representing zero in the ideal case. The normalized root mean square error gives information on the short term performance of the correlations by allowing a term by term comparison of the actual deviation between the predicted and measured values. The smaller the value, the better is the model's performance.

$$RMSE = \left[\frac{1}{n} \sum_{1}^{n} \left(H_{i,cal} - H_{i,meas} \right)^2 \right]^{1/2} \tag{28}$$

t-statistics

The random variable t with $n-1$ degrees of freedom may be written here as follows:

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2} \right]^{1/2} \tag{29}$$

The smaller the value of t the better is the model's performance in approaching the real value. To determine whether a model's estimates are statistically significant, one simply has to determine, from standard statistical tables, the critical t value, i.e. $t_{\alpha/2}$ at α level of significance and $(n-1)$ degrees of freedom. For the model's estimates to be judged statistically significant at the $(1-\alpha)$ confidence level, the calculated t value must be less than the critical value. The t-statistic used in addition to the MBE and RMSE give more reliable and explanatory results [25].

RESULTS AND DISCUSSION

A total of 127 model equations were formed and % error analysis were perfomed on them. Seventeen model equations were then extracted based on the %error interval of -1% to +1%. The applicability of the proposed correlations in predicting $\bar{H}$ is tested by estimating $\bar{H}$ values for Wa Polytechnic location used in the analysis. Estimated values of $\bar{H}$ along with measured data, are shown in Table 3.

The resulting equations were then taken through statistical error tests. The results are shown in Table 4.

Table 4: Error values (in MJ/m^2) for the developed correlation models

ERRO R	MODELS																
	Eqn. 7	**Eqn. 8**	**Eqn. 9**	**Eqn. 10**	**Eqn. 11**	**Eqn. 12**	**Eqn.13**	**Eqn. 14**	**Eqn. 15**	**Eqn. 16**	**Eqn. 17**	**Eqn. 18**	**Eqn. 19**	**Eqn. 20**	**Eqn. 21**	**Eqn. 22**	**Eqn. 23**
MBE	0.001	-0.014	-0.015	-0.015	-0.026	-0.011	-0.009	-0.020	0.013	0.007	-0.020	0.014	-0.006	-0.021	0.004	0.017	0.022
MPE	0.000	-0.006	-0.006	-0.006	-0.011	-0.005	-0.004	-0.008	0.006	0.003	-0.008	0.006	-0.002	-0.009	0.002	0.007	0.009
RMSE	0.004	0.047	0.051	0.051	0.089	0.040	0.032	0.069	0.045	0.024	0.069	0.047	0.020	0.073	0.013	0.059	0.077
t-Stat	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

The t-statistics values obtained were all less than the critical t for each equation implying that the equations were all statistically significant. Based on MBE tests, equations (7), (13), (16), (19) and (21) qualified. The result shows that Equation (7) is the best while Equation (13) is the worst. With respect to MPE test, all equations qualified. Equation (7) is the best while Equation (11) is the worst. For the RMSE test, Equation (7) is the best while Equation (11) is the worst. Since the test on RMSE conveys information on the short-term performance of different equations, it enables a term-by-term comparison of the actual variations between the estimated and measured values and since Equation (7) passes all tests, our model is then that equation. Figure 3 shows plots of the measured $\bar{H}$ and Equation (7).

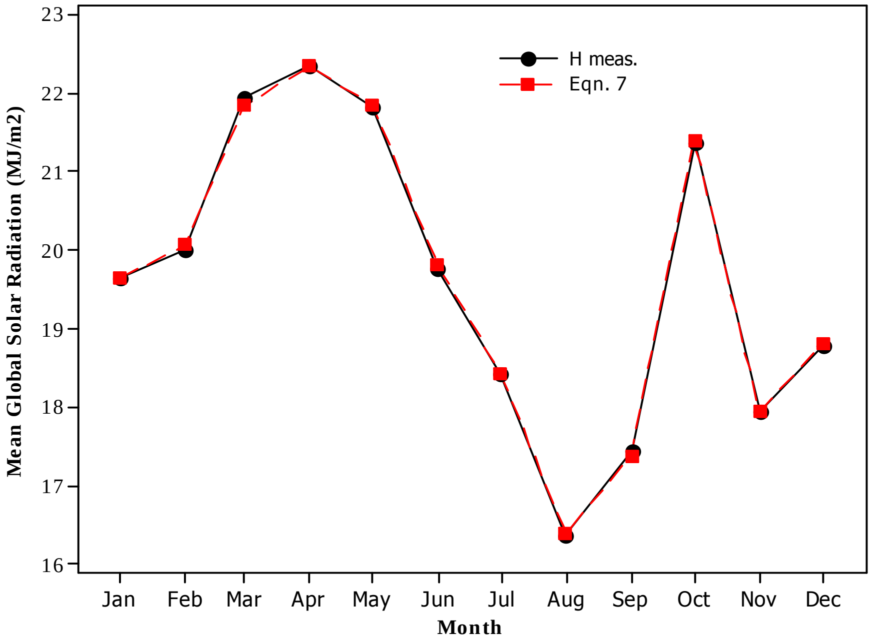

Figure 3: Comparison of measured and estimated(Eqn. 7) of mean monthly global solar radiation

CONCLUSION

The objective of this study was to evaluate various models for the estimation of monthly average daily global radiation on a horizontal surface from sunshine hours, relative humidity, ambient temperature and soil temperature and to select the most appropriate model for Wa Polytechnic weather station. One hundred and twenty seven equations in different combinations were obtained. Seventeen models having the best %errors were compared using the statistical routine. Even though up to seven variable corrrelations have been developed, it was observed that the best correlation involved only three variables namely Relative Humidity, declination and monthly percent possible sunshine. The MBE, MPE, RMSE and %error values of the selected equation (Eqn. 7) are 0.01, 0, 0.004 and -0.047 to 0.272, which are within the range of acceptable values.

Hence, the multiple linear regression model that could be employed for the purposes of estimating global solar radiation of locations that have the same climate, latitude and altitude as Wa Polytechnic station is the correlation equation with the least value of RMSE as

$$\overline{H} = -1.350 + 0.007RH + 44.800\,\overline{n}/\overline{N} + 2.000\sin\delta$$

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NOMENCLATURE

$\beta_0 - \beta_7$	multiple linear regression coefficients
$x_1 - x_{10}$	correlated parameters in regression equations
MBE	mean bias error
MPE	mean percent error
RMSE	root mean square error
t-stat	t-statistics
G_{sc}	solar constant [1367 W/m^2]

$\bar{H}$	monthly mean daily global radiation [MJ/m^2]
$\bar{H}_0$	monthly mean daily extraterrestrial radiation [MJ/m^2]
$\bar{n}$	monthly average daily hours of bright sunshine [hour]
$\bar{N}$	monthly average of maximum possible daily hours of bright sunshine [hour]
$\bar{T}_a$	monthly mean ambient temperature, ºC
$\bar{T}_s$	monthly mean ambient temperature, ºC
R^2	determination coefficient
RH	relative humidity, %
w_s	sunset hour angle (in degrees)
δ	declination angle
θ	ratio of the difference between the maximum and minimum monthly mean ambient temperature to the minimum monthly mean ambient temperautre
$\emptyset$	latitude, the angular location north or south of the equator, north positive
σ	standard deviation

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