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ESTIMATING GLOBAL SOLAR RADIATION FROM ROUTINE METEOROLOGICAL PARAMETERS OVER A TROPICAL CITY (7.23^{O}N; 3.52^{O}E) USING QUADRATIC MODELS

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Article Info	Abstract
Received: 31.05.2017 *Accepted: 30.10.2017* **Keywords:** Solar-radiation; Sunshine-hour; Minimum and maximum temperatures; Measured; Estimated.	The need for adequate solar radiation is ever increasing for various applications. However there is an inadequate data of solar radiation in many countries due to the cost of instrument set up. Hence this study investigates two models for estimating solar radiation from routinely measured meteorological parameters. The data were obtained from the International Institute of Tropical Agriculture, Ibadan. The regression coefficients of the quadratic models were determined and used to estimate the global solar radiation for both forward and backward predictions. Their predictive accuracies were compared with four other models and the measured values using standard statistical error indicators. The results showed for forward as compared to backward predictions in bracket root mean square errors 1.2 (1.1); mean bias errors 1.1 (0.8) and mean percentage errors -4.8% (-2.9%) while for backward prediction 1.9 (1.7), 1.7 (1.4) and 7.9% (2.2%) measured in $KJm^{-2}day^{-1}$ respectively. A positive error value shows an over estimation while a negative value shows an under estimation. The models are versatile for estimating global solar radiation at the horizontal surface, fixing missing data and correcting outliers.

1. Introduction

The planet Earth is a member of the Solar System of which the Sun, (having more than 98% of the total mass of the solar system) is the Chief. The Sun behaves like a blackbody which emits energy according to Planck's law at a temperature of 6000 K. The Solar radiation is the set of electromagnetic radiation emitted by the Sun. It provides the energy that powers the Earth's climate and ecosystem. Solar radiation data is required in different fields of endeavours. In power application it is required in photovoltaic, water heater and solar concentrator studies. In agriculture it is required in greenhouse breeders, photosynthetic studies and preservation of agricultural produce while in meteorology it is required in weather and climate studies as well as social life where it determines the type of clothes worn and working periods even for nocturnal animals.

The amount of solar radiation reaching the top of the atmosphere on Earth at a particular location, R_a, is given from FAO [1] by:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[w_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(w_s) \right] \quad (1)$$

where G_{sc}: the solar constant = 0.0820 $MJm^{-2}min^{-1}$; d_r: inverse relative distance earth-sun; δ: solar declination (rad); φlatitude (rad); w_s: sunset hour angle (rad); 1$MJday^{-1}$ = 11.57Js^{-1} = 11.57 W

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} J\right) \quad (2)$$

where J is the Julian day,

$$\delta = 0.409\sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (3)$$

$$w_s = ar\cos\left[-\tan(\psi)\tan(\delta)\right] \quad (4)$$

The maximum possible sunshine hour, N_s, is calculated from

$$N_s = \frac{24}{\pi} w_s \quad (5)$$

However the amount of solar radiation received on a flat surface on Earth is far less than what is available at the top of the atmosphere as a result of extinction by atmospheric constituents. Hence there is the need to accurately evaluate this quantity.

The instruments for measuring solar radiation include: pyrheliometer; Gunn-Bellani integrator and pyranometer; pyranometers; hand held Sun photometers as well as radiometers. Industrial grade devises for measuring solar radiation are delicate and expensive. The foot-print is of the order of a square kilometre. Hence very few meteorological stations measure solar radiation. Thus authors agreed that it is more economical to estimate solar radiation from other routinely measured meteorological parameters.

Since the publication of original Angstrom equation [2], there have been several modifications proposed by different authors, all aimed at determining the regression coefficients as applicable to a specific climatic zone. Okundimaya and Nzeako in their work proposed a temperature-based model for predicting the monthly mean global solar radiation on horizontal surfaces for some cities in Nigeria [3]. Prior to this time many researchers, Fagbenle, Buhari et al., Akpabio and Etuk, as well as Augustine and Nnabuchi have developed correlations involving global solar radiation and sunshine hours for different locations in Nigeria [4, 5, 6, 7]. Recently, Olatona and Adeleke developed linear models based on sunshine hours and temperature difference for Ibadan [8]. Adegoke and Olatona proposed a hybrid of solar and wind [9] to mitigate the intermittency of solar radiation (in terms of day and night). Also Olatona and Adeleke in their comparative studies of the predictive accuracies of some available sunshine based linear models [10] found that a model developed by them and that of Andretta et al. [11] gave much lower errors than eight other models in their predictive accuracies. Temperature measurement are simple and robust, hence there is a reason for such models to be adapted for estimating daily solar radiation with reasonable accuracy [12]. The criterion based upon sunshine duration is scarce due to limited availability of such data measured concurrently with global solar irradiation [13].

2. Methods and Samples

Twenty years mean monthly measured data of global solar radiation, R_s reaching a horizontal surface at the site, actual sunshine hours, N_a as well as minimum and maximum temperatures T_{min} and T_{max} respectively, measured concurrently were obtained from the International Institute of Tropical Agriculture, (IITA) Ibadan.

The data were sorted to remove incomplete set or outliers and then grouped into eight years each in the first and the last ten years of the data set.

A scattered plot of R_s/R_a against N_a/N_s on one hand and R_s/R_a against T_{min}/T_{max} on the other hand were carried out on the first eight years of data. A polynomial fit of the second order was done on the scattered plot to determine the geographical factors used to derive a forward prediction model. The procedures were repeated for the last eight years for the backward prediction model.

Their predictive accuracies together with four other models found in literatures were compared with the measured values of global solar radiation and the results are shown in Tables 2 and 5 respectively for forward and backward predictions.

The calculated global solar radiations for both forward and backward predictions were compared with the measured values and the corresponding errors evaluated using standard error indicators.

3. Results and Discussion

The regression equation for the sunshine model is given by

$$\frac{R_s}{R_a} = A + B_1\left(\frac{N_a}{N_s}\right) + B_2\left(\frac{N_a}{N_s}\right)^2 \quad (6)$$

while that of the temperature based model is given by

$$\frac{R_s}{R_a} = A + B_1\left(\frac{T_{\min}}{T_{\max}}\right) + B_2\left(\frac{T_{\min}}{T_{\max}}\right)^2 \quad (7)$$

where A, B_1 and B_2 are regression constants otherwise called geographical factors.

Table 1: Geographical factors determined from the First Ten Years for Sunshine Hours and Temperature Based Models

	Sunshine Hours Based Model	Temperature Based Model
Parameter	Value	Value
A	0.122	-1.365
B_1	1.005	5.999
B_2	-0.779	- 4.927
R^2	0.684	0.586
SD	0.036	0.041
P-value	< 0.0001	< 0.0001

$$R_{scS} = \left(0.122 + 1.005\frac{N_a}{N_s} - 0.779\left(\frac{N_a}{N_s}\right)^2\right)R_a \quad (8)$$

$$R_{scT} = \left(-1.365 + 5.999\frac{T_{\min}}{T_{\max}} - 4.927\left(\frac{T_{\min}}{T_{\max}}\right)^2\right)R_a \quad (9)$$

Table 1 shows the values of A, B_1 and B_2, being the coefficient of the polynomial fit which were in turn used for deriving eqs. (8) and (9) being the sunshine and temperature based models respectively.

Thus the two models, eqs. (8) and (9) for sunshine and temperatures based models respectively were compared with four other models, eqs. (10) to (13), two of which are linear and the other two are quadratic, found in the literature for their predictive accuracies.

$$R_{scO} = \left(0.24 + 0.35\frac{N_a}{N_s}\right)R_a$$ Olatona and Adeleke [10] (10)

$$R_{scO} = \left(0.23 + 0.37\frac{N_a}{N_s}\right)R_a$$ Andretta et al [11] (11)

$$R_{scNT} = \left(-0.987 + 5.256\frac{T_{\min}}{T_{\max}} - 4.536\left(\frac{T_{\min a}}{T_{\max}}\right)^2\right)R_a$$

Okonkwo and Nwokoye [14] (12)

$$R_{scS} = \left(0.145 + 0.845\frac{N_a}{N_s} - 0.280\left(\frac{N_a}{N_s}\right)^2\right)R_a$$ Akinoglu and Ecevit [15] (13)

Table 2: Comparison of Calculated Solar Radiation (Forward Prediction) with Measured Values

Month	**Rsm/ MJm^{-2}day^{-1}**	**RscS/ MJm^{-2}day^{-1}**	**RscT/ MJm^{-2}day^{-1}**	**RscO/ MJm^{-2}day^{-1}**	**RscA/ MJm^{-2}day^{-1}**	**RscNT/ MJm^{-2}day^{-1}**	**RscSA/ MJm^{-2}day^{-1}**
January 2002	12.6	14.0	15.2	13.4	13.4	17.7	16.0
February 2002	14.0	15.7	16.3	16.7	16.8	18.6	20.6
March 2002	16.3	16.2	16.1	15.8	15.8	18.1	19.0
April 2002	16.8	16.2	15.5	15.6	15.6	17.3	18.7
May 2002	15.9	16.4	15.4	16.2	16.2	17.2	19.6
June 2002	13.8	15.9	14.6	15.7	15.7	16.3	19.0
July 2002	12.8	13.5	12.9	13.0	12.9	14.3	14.4
August 2002	12.0	11.4	11.7	11.8	11.6	13.0	11.9
September 2002	13.4	14.4	13.9	13.7	13.6	15.5	15.5
October 2002	13.7	15.4	14.3	15.0	15.0	16.0	18.1
November 2002	13.6	14.8	13.8	16.2	16.3	15.4	20.0
December 2002	15.5	14.1	14.9	16.4	16.5	17.2	20.2

The results are shown in Table 2. Rsm is the measured global solar radiation reaching a horizontal surface; RscS, is the global solar radiation reaching a horizontal surface estimated from measured sunshine hours based model; RscT is the global solar radiation reaching a horizontal surface estimated from measured temperature based model. RscO and RscA are global solar radiations estimated from linear models developed by Olatona and Adeleke [10] and Andretta et al [11] respectively. RscNT is a global solar radiation estimated from temperature based quadratic model as developed by [14] and RscSA is a sunshine hour based quadratic model as developed by [15]

Table 3: Error Indicator (Forward Prediction, 2002)

Modelled Solar Radiation / $MJm^{-2}day^{-1}$	RMSE	MBE	MPE
RscS	1.2	1.1	-4.8
RscT	1.1	0.8	-2.9
RscO	1.4	1.1	-0.5
RscA	1.4	1.1	-5.6
RscNT	2.6	2.2	-15.9
RscSA	4.1	3.6	-25.0

where RMSE is the root mean square error, MBE is the mean bias error and MPE is the mean percentage error.

Table 4: Geographical factors Determined from the Last Ten Years for Sunshine Hour and Temperature Based Models

	Sunshine Hours Based Model	Temperature Based Model
Parameter	Value	Value
A	0.168	- 2.949
B_1	0.654	10.586
B_2	- 0.374	- 8.246
R^2	0.637	0.641
SD	0.036	0.036
P-value	< 0.0001	< 0.0001

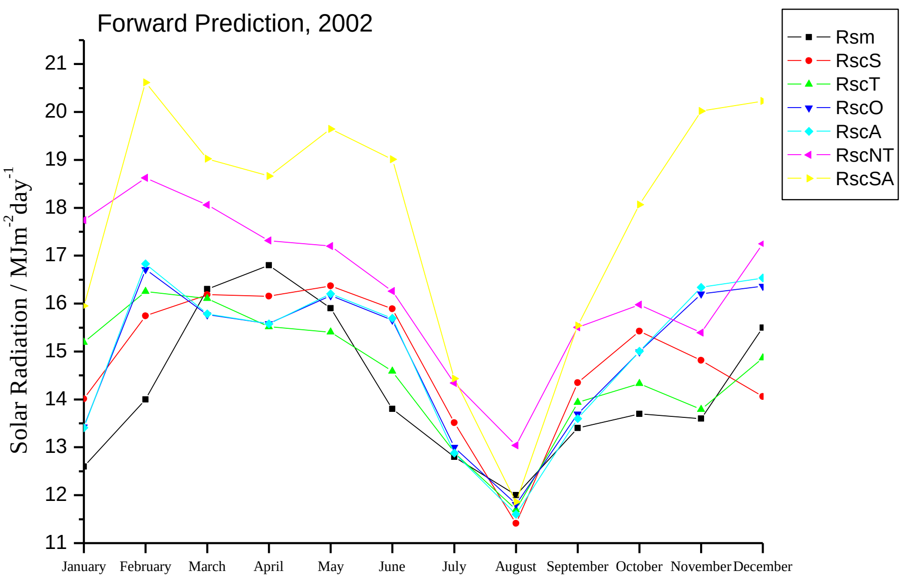

Fig. 1. Comparison of the measured and forward predicted values for both sunshine and temperature based models.

These two models, equations (14) and (15), were also compared with equations (10) to (13) for their predictive accuracies.

$$R_{scS} = \left(0.168 + 0.645\frac{N_a}{N_s} - 0.374\left(\frac{N_a}{N_s}\right)^2\right)R_a \tag{14}$$

$$R_{scT} = \left(-2.949 + 10.586\frac{T_{\min}}{T_{\max}} - 8.246\left(\frac{T_{\min}}{T_{\max}}\right)^2\right)R_a \tag{15}$$

Table 2 shows the values of A, B_1 and B_2, being the coefficient of the polynomial fit which were in turn used for deriving eqs (14) and (15) being the sunshine and temperature based models respectively. The two models, eqs (14) and (15) for sunshine and temperatures based models respectively were also compared with four other models, eqs (10) to (13) and the results shown in Table 5 below.

Table 5: Comparison of Calculated Solar Radiation (Backward Prediction) with Measured Values

Month	**Rsm / MJm^{-2}day^{-1}**	**RscS / MJm^{-2}day^{-1}**	**RscT / MJm^{-2}day^{-1}**	**RscO / MJm^{-2}day^{-1}**	**RscA / MJm^{-2}day^{-1}**	**RscNT / MJm^{-2}day^{-1}**	**RscSA / MJm^{-2}day^{-1}**
January 1992	15.40	13.1	12.3	13.6	13.5	17.6	16.2
February 1992	18.10	15.3	14.5	16.4	16.5	18.9	20.2
March 1992	15.70	14.0	16.4	14.3	14.3	18.4	16.7
April 1992	17.70	15.5	16.2	16.2	16.2	18.1	19.6
May 1992	16.80	14.7	15.4	15.1	15.1	17.2	18.0
June 1992	15.70	13.1	14.6	13.5	13.4	16.4	15.4
July 1992	11.40	10.0	11.8	11.0	10.8	13.8	10.5
August 1992	10.30	9.1	9.7	10.5	10.3	12.2	9.1
September 1992	11.80	10.5	12.6	11.5	11.3	14.5	11.2
October 1992	12.50	14.5	14.3	15.1	15.1	16.0	18.2
November 1992	14.00	14.3	14.9	15.1	15.2	17.0	18.5
December 1992	13.40	14.1	14.5	15.3	15.4	16.8	18.8

Table 6: Error Indicator (Backward Prediction, 1992)

Modelled Solar Radiation / $MJm^{-2}day^{-1}$	RMSE	MBE	MPE
RscS	1.9	1.7	7.9
RscT	1.7	1.4	2.2
RscO	1.6	1.4	2.0
RscA	1.6	1.4	2.5
RscNT	2.3	2.0	-15.3
RscSA	2.8	2.1	-11.1

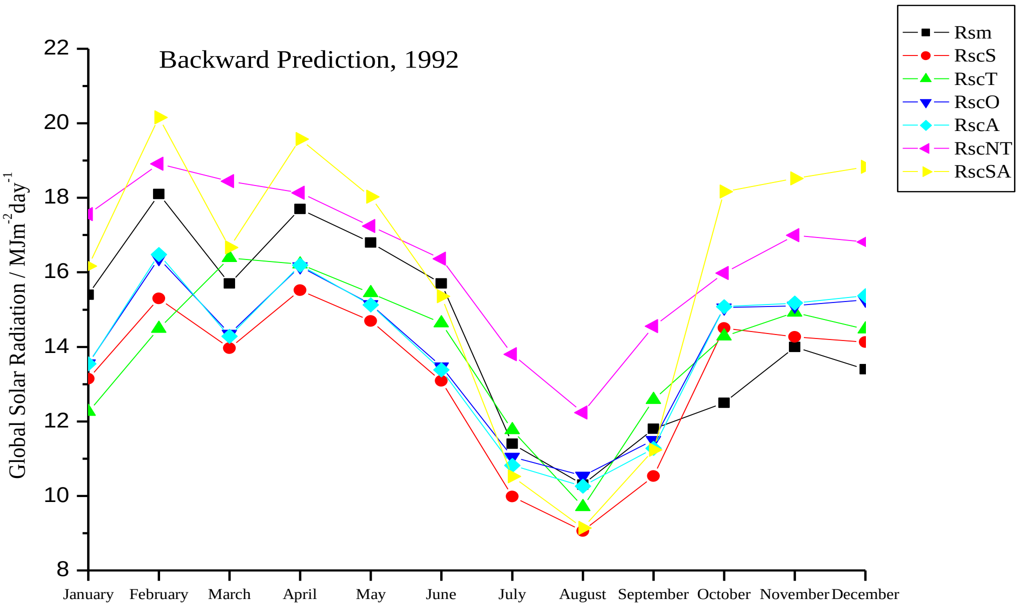

Fig. 2. Comparison of the measured and backward predicted values for both sunshine and temperature based models.

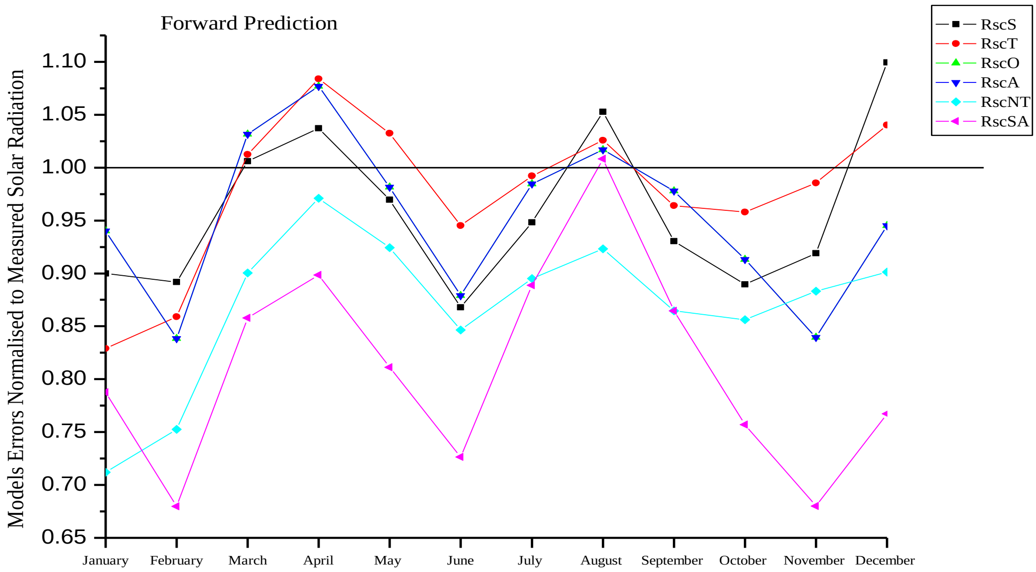

Fig. 3. Comparison of models errors normalised to the measured solar radiation for forward prediction.

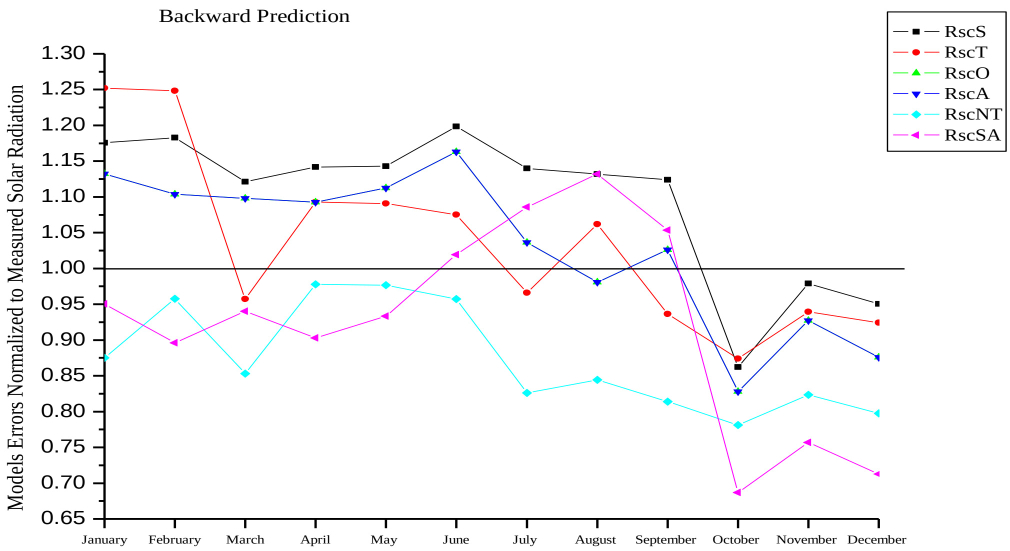

Fig. 4: Comparison of models errors normalised to the measured solar radiation for backward prediction.

The calculated global solar radiations from measured sunshine hours and temperature based models, RsCS and RsCT respectively derived from the two models compared favourably with the measured value either for forward or backward predictions.

The error indicators show higher values for the sunshine hours based model than the temperature based model. For instance 2002 forward prediction: RMSE 1.2 (1.1); MBE 1.1 (0.8) and MPE -4.8% (-2.9%) while for 1992 backward prediction: RMSE 1.9 (1.7); MBE 1.7 (1.4) and MPE 7.9% (2.2%). A positive error value shows an over estimation while negative value shows an under estimation. The linear models showed lesser error values than the remaining quadratic models.

The two newly developed models RscS and RscT for forward prediction have lower RMSE and MBE errors than the other four models, but the errors associated with the temperature model are the least. This might not be unconnected with the fact that temperature is easier to measure more accurately than the sunshine hours. However the linear model gave a least percentage error of -0.5% while RscSA gave the highest of -25%.

In the case of the global solar radiation estimated for backward predictions, the two linear models showed lower RMSE than the newly developed models, their MBE are the same with the temperature based model but RscO has the least MPE.

The other two quadratic models have errors much higher than the rest of the models.

Hence the two forward models are quite handy for estimating global solar radiation when the measured data are not feasible or when there is an instrument error or outliers.

Figures 1 and 2 show the variation of the measured values compared to the values estimated from the models. All the models followed nearly the same trend. However in Figure 1 RscNT and RscSA have widest variations from the measured data. The variations decrease gradually with the least July to September and slightly increase again from October to December. On the other hand Figure 2 shows that RscNT and RscSA over estimated the measured data by other models under estimated it. However the trends are very close.

The comparison of the models errors normalized to the measured solar radiation are for the forward and backward predictions are depicted in Figures 4 and 5 respectively.

4. Conclusions

When resources are not enough to mount sophisticated solar radiation equipment in this era of economic recession, researchers can make do with a lot of robust and rugged minimum and maximum thermometers to determine the minimum and maximum temperatures from which using this models the global solar radiation can be estimated. The models are handy to estimate missing data that can occur during power outages or equipment failure as well as fixing outliers. The models' predictive accuracies for location differing much in latitude and perhaps longitude from the station whose data were used to design the models will be investigated in a future work.

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