The African Review of Physics (2017) **12**: Special Issue on Applied Physics in Africa 0009

Estimation of Global Solar Radiation and its Derivatives at Nguru, Nigeria

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The estimation of global solar radiation at Nguru, latitude12°53'N, 10°28'E was carried out. The data was obtained from Nigeria Meteorological Agency (NIMET) for a period of five years (2004-2008).The minimum temperature, maximum temperature and relative humidity data within the Sudan savannah climatic zone of northern Nigeria were used to compute the correlation coefficients (a&b) of correlation equations as -0.143+1.183 (Tmin/Tmax) and 0.563-0.003(RH)for estimation of global solar radiation using ratio of minimum temperature to maximum temperature and relative humidity respectively, with the values of 26.02MJday^{-1}and 25.85 MJday^{-1},as the peak values of the global solar radiation (H), corresponding to the months of April and October respectively in the station and hence its derivatives were also derived.

1. Introduction

Fossil fuel being the major source of energy is continuously depleting and access to it is extremely being politicized. Coupled with its negative effect on the environment, dependence on fossil fuel sources is a strong recipe for a devastating environment on which the entire human and all other living organisms rely on. Seeking refuge in other alternative sources is inevitable, whose sustainability, safety, natural abundance and unhindered access is reliable, classified as renewable. Prime among the alternatives is a renewable source that readily surmount the above mentioned criterion, which also has been in use from stone-age to date; solar energy [1-3].

Solar energy can be used directly as in cookers, dryers, heaters or boilers it can also be used indirectly by involving the use of conversion systems as in photovoltaic cells to generate electricity. Although in the latter case there is the need to have an insight into the feasibility of installations/applications need to be ascertained, hence profile of the solar radiation in the location is unavoidable [3-6].

To achieve this profiling, measurement and/or records are examined and analyzed. Yet, these measurements and/or records are rarely available due to high cost of solar energy measuring devices and maintenance. And where available, their accuracy or overall reliability is questionable, especially in the developing countries. To ease the challenge of absolute lack or inaccuracy of measured data on solar energy/radiation in different locations, models have been advanced to estimate solar energy/radiation using meteorological data, with affordable and reliable instruments for measuring other meteorological elements [5-10].

This article explores this avenue and use the values of clearness index (H/H_0), minimum and maximum temperature ratio and relative humidity to derive a correlation that is used to theoretically estimate solar radiation and its derivatives in Nguru (12°53'N, 10°28'E).

2. Theoretical Framework

2.1. Solar radiation models and equations

The first correlation proposed for estimating the monthly mean daily global solar radiation on a horizontal surface (MJ m-2 day-1) using the sunshine duration data is due. Angstrom (1924) and Prescott (1940) have put the Angstrom correlation in more convenient form [10,11]:

$$\hat{H} = \left(a + bn/N\right)\hat{H}_o \qquad (1)$$

Where

$\hat{H}$ = the monthly average daily global radiation on a horizontal surface;

$\hat{H}_0$ = the monthly average daily extraterrestrial radiation on a horizontal surface;

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n = the monthly average daily number of hours of bright sunshine;

N = the monthly average daily maximum number of hours of possible sunshine.

a, *b* = the regression constant to be determined.

2.2. Computation of extraterrestrial solar radiation (H_0)

Model 1

The extraterrestrial solar radiation (H_0), for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year according to the relation employed by [12]:

$$H_o = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s sin(\phi) sin(\delta) + cos(\phi) cos(\delta) sin(\omega_s) \right] \quad (2)$$

Where, G_{sc} is solar constant (0.0820 $MJm^{-2}min^{-1}$), d_r is the inverse relative Sun-Earth distance, ω_s = sunset hour angle [rad], ϕ = latitude [rad], δ = solar declination [rad].

The latitude ϕ expressed in radians is positive for the northern hemisphere, and negative for the southern hemisphere. The inverse relative distance Earth-Sun, d_r is given in [12];

$$d_r = 1 + 0.033\ cos\left(\frac{2\pi J}{365}\right) \quad (3)$$

The declination angle (δ) can be calculated from the equation

$$\delta = 0.409\ sin\left(\frac{2\pi J}{365} - 1.39\right) \quad (4)$$

Where, J is the number of the day in the year between 1 January and 31 December

The sunset hour angle ω_s is given by

$$\omega_s = arc\ \cos\left[-\tan(\phi) \tan(\delta) \right] \quad (5)$$

The daylight hours, N, are computed from Cooper's formula

$$N = \frac{24}{\pi}\omega_s \quad (6)$$

Model 2

In this model, the mean daily extraterrestrial solar radiation on a horizontal surface is calculated following the equation given by [13,14]

$$H_o = \frac{24 \times 3600}{\pi} I_{SC} \left[1 + 0033\ \cos\left(360 \frac{dn}{365}\right) \right] \left[\left(\frac{2\pi\omega_s}{360} \right) \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s \right] \quad (7)$$

The value of 1367Wm^{-2} has been recommended for solar constant I_{sc}

The hour angle ω_s for horizontal surface is given as

$$\omega_s = \cos^{-1}(-\tan\phi \tan\delta) \quad (8)$$

Declination is calculated as

$$\delta = 23.45\ sin\left(360 \frac{284+d}{365}\right) \quad (9)$$

Where, d is the day of the year from 1 January to December 31. Usually, the 15th of each month is the day of the month in which the solar declination is calculated [10].

The day length N_0 is the number of hours of sunshine within the 24 hours in a given day. For a horizontal surface it is given by [13]

$$N_o = \frac{2}{15}\cos^{-1}(-\tan\phi \tan\delta) = \frac{2}{15}\omega_s \quad (10)$$

2.3. Global solar radiation

While, global solar radiation for a particular location can be estimated using various empirical models, using meteorological data, using similar variation of the Angstrom formula.

These include either linear models, with single variable or multiple variables, according to [1,4]

i- $$H = \left[a + b\left(\frac{n}{N_0}\right) - c(\theta) + d(RH) + e(T) \right] H_0 \quad (11)$$

ii- or,

$$H/H_0 = a + b\left(\frac{n}{N_0}\right) + c(\theta) + d(RH) + e(T) \quad (12)$$

iii- $$H/H_0 = a + b\left(\frac{n}{N}\right) + c(\theta) + d(RH) \quad (13)$$

iv- $$\frac{H}{H_0} = a + b\left(\frac{n}{N}\right) + c(RH) \quad (14)$$

v- $$H/H_0 = a + b\left(\frac{n}{N}\right) \quad (15)$$

and higher order equations, like;

vi- $$H/H_0 = a + b\left(\frac{n}{N}\right) + c\left(\frac{n}{N}\right)^2 \quad (16)$$

Although it is found that the second and third order correlations do not improve the accuracy of estimation of global solar radiation [1].

3. Methodology

In this research, the extraterrestrial solar radiation (H_0) at Nguru (12°53'N, 10°28'E) was estimated, using two (2) Models for estimation of monthly mean daily extraterrestrial solar radiation (H_0).

The compatibility of the two (2) models for estimation of monthly mean daily extraterrestrial solar radiation (H_0) was tested by comparing with values of measured monthly mean daily global solar radiation (H) at the locations to determine best-fit model for estimation of extraterrestrial solar radiation, using the mean bias error (MBE), root mean square error (RMSE) and the mean percentage error (MPE). Low values of RMSE and MPE are desirable. Positive MBE shows overestimation while negative MBE indicates underestimation [8,9].

The statistical analysis was carried-out purely to select a better model between the two (2) models, no matter what the statistical indicators may portray magnitude wise.

The MBE, RMSE and MPE are defined as in the following equations [1,4]

a- $$\text{MBE} = \sum(\text{Hest} - \text{Hmeas})/n \quad (17)$$

b- $$\text{RMSE} = \{[\sum(\text{Hest} - \text{Hmeas})^2/n]\}^{0.5} \quad (18)$$

c- $$MPE = \frac{\sum\left(\frac{H_{est} - H_{meas}}{H_{meas}}\right) \times 100}{n} \quad (19)$$

Using the determined values of the monthly mean daily extraterrestrial solar radiation (H_0) from the best fit model, data for five years from Nguru station (2004-2008) for the values of the measured monthly mean daily global solar radiation, minimum and maximum temperatures, sunshine hours and relative humidity in the station, as in Figure 1, the clearness indices (H/H_0) were determined, to enable the computation of the empirical constants (a & b). Hence, the separate correlation equations for estimation of monthly mean daily global solar radiation (H), using ratio of minimum temperature to maximum temperature, sunshine hours and relative humidity were formulated.

And finally, the derivatives of the global solar radiation were calculated using the below mentioned equations [11]

a- clear-sky radiation, Hso

When calibrated values for a_s and b_s are not available:

$$\text{Hso} = (0.75 + 2\ 10\text{-}5z)\ H_0 \quad (20)$$

b- Relative shortwave radiation (H/Hso)

$$H_{ns} = H/H_{so} \quad (21)$$

c- Net solar or net shortwave radiation (Hns)

The net shortwave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$\text{Hns} = (1\text{-}\alpha)\ H \quad (22)$$

d- Net long-wave radiation (Hnl)

The rate of long-wave energy emission is proportional to the absolute temperature of the surface raised to the fourth power. This relation is expressed quantitatively by the Stefan-Boltzmann law. The net energy flux leaving the earth's surface is, however, less than that emitted and given by the Stefan-Boltzmann law due to the absorption and downward radiation from the sky. Water vapour, clouds, carbon dioxide and dust are absorbers and emitters of long-wave radiation. Their concentrations should be known when assessing the net outgoing flux. As humidity and cloudiness play an important role, the Stefan-Boltzmann law is corrected by these two factors when estimating - the net outgoing flux of long-wave radiation. It is thereby assumed that the concentrations of the other absorbers are constant:

$$Hnl = \sigma\frac{[Tmaxk4 + Tmin4]}{2}(0.34 - 0.14\sqrt{Ea})[1.35\frac{Rs}{Ra} - 0.35] \quad (23)$$

σ =Stefan-Boltzmann constant [4.903 10-9 MJ K-4 m-2 day-1], i.e., (5.68 x 10-8 W m-2 K-4)]

$$E_a = \frac{RHmean}{100}[\frac{e0(Tmax)+e0(Tmin)}{2}] \quad (24)$$

e- Net radiation (Hn)

The net radiation (Hn) is the difference between the incoming net shortwave radiation (Hns) and the outgoing net long-wave radiation (Hnl):

$$Hn = Hns - Hnl \quad (25)$$

Research Location

Nguru (or N'Gourou) is a Local Government Area in Yobe State, Nigeria. Its headquarters are in the town of Nguru near the Hadejia Komadugu River at 12°52′45″N 10°27′09″E, see Fig. 1 below. It has an area of 916 km² and a population of 150,632 at the 2006 census.

Fig.1: Map of Nigeria showing Nguru Station

http://www.onlinenigeria.com/links/adv.asp?blurb=70

4. Results and Discussion

The best-fit model for calculating the extraterrestrial solar radiation (H_0) (Table 1), was found to be Model 2, by its desirably low values of RMSE and MPE, as in Table 2. This was derived using the available records (2004-2008), for the Station.

While, by linear correlation analysis on the clearness index (H/H_0) of the station, using ratio of recorded values of minimum temperature to maximum temperature (TMIN/TMAX) and relative humidity (RH), as in Fig. 2, the coefficients (a & b), were determined.

Furthermore, the correlation relations for estimating global solar radiation using ratio of minimum temperature to maximum temperature (H/H_0), sunshine hours and relative humidity (RH) at those stations, as in Tables 3 (a) & (b).

The values of 26.02MJday^{-1}and 25.85MJday^{-1} are the peak values of the global solar radiation (H), corresponding to the months of April and October respectively in the station, as in Table 4.

Also, the global solar radiation derivatives also show similar pattern as that of global solar radiation (H), given in Table 5.

Table 1:- Extraterrestrial Solar Radiation for Models 1 & 2 in Nguru station

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Model 1	30.41	33.26	36.32	37.99	38.13	37.77	37.75	37.84	36.98	34.59	31.53	29.61
Model 2	34.98	36.30	36.94	35.94	33.94	32.56	32.86	34.55	36.17	36.44	35.44	34.51

Table 2: The results of statistical analyses of the models (MBE, RMSE and MPE) values for Nguru station

Stations	MBE 1	MBE 2	RMSE 1	RMSE 2	MPE 1	MPE 2
Nguru	15.17	16.14	16.52	16.24	-87.76	-91.75

Table 3(a): Linear Correlation coefficients for estimation of global solar radiation (H) using ratio of minimum to maximum temperature (Tmin/Tmax) value for six (6) years (2004-2008) in Nguru station.

Station	a	b
Nguru	-0.142	1.183

Table 3(b): Linear Correlation coefficients for estimation of global solar radiation (H) using Relative Humidity (RH) value for six (6) years (2004-2008) in Nguru station.

Station	a	b
Nguru	0.563	-0.003

Table 4: Global Solar radiation for Nguru satation using both temperature ratios and relative humidity

Months	GSR for Sudan Savannah (a) $MJday^{-1}$ using Tmin/Tmax	GSR for Sudan Savannah (a) $MJday^{-1}$ using (RH)
Jan.	24.98	22.36
Feb.	25.56	23.74
Mar.	25.47	24.27
Apr.	26.02	22.76
May	22.05	20.27
Jun.	20.28	17.80
Jul.	20.93	17.62
Aug.	22.13	17.25
Sep.	24.75	18.46
Oct.	25.85	19.89
Nov.	25.59	21.23
Dec.	24.83	21.63

Table 5:- Extraterrestrial and Global Solar Radiation Derivatives, in $MJday^{-1}$, for Sudan Savannah (a)

Months	H_0	Hso	Hns	H/Hso	Hnl	Hn
Jan.	35.05	29.07	17.24	0.86	6.45	10.79
Feb.	36.38	29.07	17.64	0.88	6.74	10.90
Mar.	36.97	29.07	17.58	0.88	6.97	10.61
Apr.	35.92	29.07	17.95	0.90	7.43	10.53
May	33.91	29.07	15.22	0.76	5.96	9.26
Jun.	32.57	29.07	14.00	0.70	5.10	8.90
Jul.	32.94	29.07	14.44	0.72	5.35	9.10
Aug.	34.65	29.07	15.27	0.76	5.60	9.67
Sep.	36.24	29.07	17.08	0.85	6.62	10.47
Oct.	36.45	29.07	17.84	0.89	6.96	10.87
Nov.	35.43	29.07	17.66	0.88	6.81	10.85
Dec.	34.53	29.07	17.14	0.85	6.49	10.64

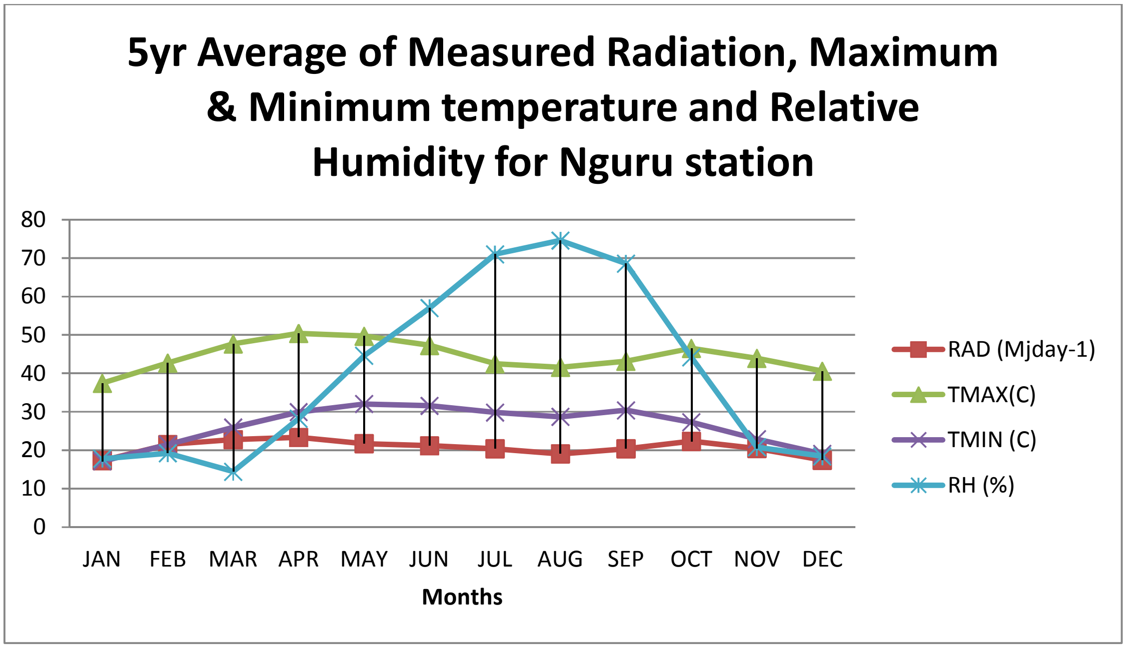

Fig.2: 5yr Average of Measured Radiation, Maximum & Minimum temperature and Relative Humidity for Nguru station

5. Conclusion

The mean monthly extraterrestrial solar radiation, mean monthly measured global solar radiation, ratio of minimum to maximum temperature and relative humidity for Nguru station of Nigeria Meteorological Agency (NIMET), has been employed in this study to develop several correlation equations, for theoretical estimation of global solar radiation, using the ratio of minimum to maximum temperature and relative humidity. The values of 26.59565108MJday^{-1}and 23.11020966 MJday^{-1}are the peak values of the global solar radiation (H), corresponding to the months of April and September respectively in the station. Also, derivatives of the global solar radiation were determined.

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Received: 5 September, 2015
Accepted: 25 December, 2016