Theoretical estimation of global solar radiation and its derivatives in Katsina – Nigeria using temperature and relative humidity

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ABSTRACT

In this study, data of global solar radiation for Katsina station (Lat 12° 59' 52" N, Long 7° 35' 5" E) *in Nigeria was used to estimate weather parameters based on monthly mean daily extraterrestrial radiation, on the basis of temperature and relative humidity. The data was obtained from Nigeria Meteorological Agency (NIMET) for a period of five years (2006-2010). Correlation equations were obtained for the estimation of global solar radiation, using minimum to maximum temperature ratio and relative humidity respectively. The estimated values of the radiation parameters and global solar radiation were used to determine the derivatives for the location.*

Keywords: Global solar radiation; Extraterrestrial radiation, Relative humidity; Temperature and correlation equation.

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1.0 Introduction

Solar radiation is the essential ingredient to life on earth. It controls the earth's weather processes which determine the natural environment. Its presence at the earth surface is necessary for the provision of food to mankind. This makes it imperative to be able to understand the physics of solar radiation and in particular, to determine the amount of energy intercepted by the earth's surface. Due to the geometrical nature of the earth, the distribution of solar radiation differs between regions, locations, and seasons. An understanding of these differences is important in the choice of equipment for utilization, planning, and data for every location. Daily solar radiation data are often required in agro-metrological calculations e.g. to compile a water budget for irrigation, running a crop growth simulation model, and solar PV sizing. Data profile of a location such as solar radiation intensity, monthly, daily, or hourly variation in radiation intensity, and sunshine duration are used in the study, design, and prediction of appliance performance as well as the determination of the global solar radiation and its derivatives.

Nigeria lies within a high sunshine belt and thus has enormous solar energy potentials. The mean annual average of total solar radiation varies from about 3.5 $kWhm^{-2}day^{-1}$ in the coastal latitudes to about 7.0 $kWhm^{-2}day^{-1}$ in the semi arid areas far north. On the average, the country receives solar radiation in the region of 19.8 MJm^{-2} day^{-1}. Average sunshine hours are estimated at 6hrs per day. Solar radiation is fairly distributed. The minimum average is about 3.55 $kWhm^{-2}day^{-1}$ in Katsina in January and 3.4 $kWhm^{-2}day^{-1}$ for Calabar in August and the maximum average is 8.0 $kWhm^{-2}day^{-1}$ for Nguru in May [1].

Global solar radiation can be obtained from analysis of metrological data [2,3]. According to [4], 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 [5,6,7].

In the absence of recorded data, an estimate can be made on the basis of satellite remote sensing, spatial interpolation techniques, empirical relation using the measured duration of bright sunshine or cloudiness, or on the basis of correlation found between incoming irradiance and other commonly measured weather variables [8]. Parameters used as input include air temperature, degree-hours of temperature, relative humidity and rainfall. Historical data (mean annual daily solar radiation, amplitude of annual curves of daily solar radiation, etc.) and geographical data (intercorrelations between daily max. and min. temperatures and solar radiation at a geographical area) are also required.

Various models have been proposed for estimating the global solar radiation at different countries and locations. Although solar radiation estimates are available for selected cities in Nigeria, there are still major cities whose estimates are desirable but not available. [9] has reported estimates for eastern and southern Nigeria using metrological data to generate regression equations to estimate global solar radiation. Models based on linear and quadratic equations are also reported for different parts of Nigeria [10]. The aim of this work is to compare two different models for the estimation of the monthly mean daily extraterrestrial radiation and find a correlation for the theoretical estimate of the global solar radiation in Katsina (Lat 12^{o} 59' 52" N, Long 7^{o} 35' 5" E) using minimum to maximum temperature ratio and relative humidity.

2-Theoretical Background

Solar radiation Models

Initial modelling work carried out in many countries involves relating daily horizontal global irradiation to duration of bright sunshine. The first phase of these works is concerned with the development of regression equations from monthly-averaged data. However, work has progressed since then and equations which use data recorded at daily intervals have also been developed [11].

The original Ångström regression equation relates monthly-averaged daily irradiation to clear day irradiation. However, this method poses the difficulty of defining a clear day. To overcome this difficulty several workers, [11, 13] have modified the original Angstrom relation into a form given by the following equation;

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

where $\hat{H}$ is the monthly average global radiation on a horizontal surface, $\hat{H}_0$ is the monthly average extraterrestrial radiation on a horizontal surface, a, b are the regression constant to be determined, n is the monthly average daily number of hours of bright sunshine, and N is the average daily maximum number of hours of possible sunshine. Second, third, and fourth order correlations of the Angstrom relation have also been reported [11] and considered valid for the estimation of the global radiation.

Computation of Extraterrestrial Solar Radiation (H_0)

Model 1

The extraterrestrial radiation, H_o, 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 January 1 and December 31

The sunset hour angle, ω_s, is given by:

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

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

$$N = \frac{24}{\pi}\omega_s \tag{6}$$

Model 2

In this model, the mean daily extraterrestrial solar radiation on a horizontal surface is calculated following the equation given by [13,14,15,6,16]

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

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

The hour angle ω_s for horizontal surface is given as

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

Declination is calculated as

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

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]

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

Global solar radiation

The global solar radiation for a particular location can be estimated using various empirical models, using meteorological data, calculation using equation 1, or using the modified Angstrom formula with either linear regression approach, [14], involving minimum ratio of daily temperature ratio (θ), and relative humidity (RH) ratio;

$$H/H_o = a + b(\theta) \quad (11)$$

$$H/H_o = a + b(RH) \quad (12)$$

and a combination of the minimum daily temperature, relative humidity, and the monthly average daily temperature (T);

$$H/H_o = a + b\left(\frac{n}{N}\right) + c(\theta) + d(RH) + e(T) \quad (13)$$

or using quadratic regression approach [11], given as;

;

$$H/H_0 = a + b\left(\frac{n}{N}\right) + c\left(\frac{n}{N}\right)^2 \quad (14)$$

The ration H/Ho known as the clearness index expresses the percentage deflection by the sky of the incoming global radiation which gives an indication of the level of available solar radiation and changes in atmospheric conditions at a particular location [10].

The accuracy of the estimated global radiation results is usually tested by calculating the mean bias error (MBE), the root mean square error (RMSE), and the mean percentage error (MPE).

The MBE, RMSE and MPE are defined as follows;

$$MBE = \sum\left(H_{est} - H_{meas}\right)/n \quad (15)$$

$$RMSE = \left(\left[\sum\left(H_{est} - H_{meas}\right)^2/n\right]\right)^{0.5} \quad (16)$$

$$MBE = \left(\sum \left(\frac{H_{est} - H_{meas}}{H_{meas}} \times 100 \right) \right) / n \qquad (17)$$

Low values of RMSE and MPE are desirable. Positive MBE shows overestimation while negative MBE indicates underestimation [15].

The derivatives of the global solar radiation can be evaluated according to the relations given in [12] as follows;

a- clear-sky radiation, H_{so},

The calculation of the clear-sky radiation H_{so}, when n = N is required for computing the longwave radiation.

1. For near sea level when a_s and b_s are available,

   $$H_{so} = (a_s+b_s)H_o \qquad (18)$$

   where
   H_{so} clear-sky solar radiation [MJ m^{-2} day^{-1}], a_s+b_s fraction of extraterrestrial radiation reaching the earth on clear-sky days (n = N).

2. When calibrated values for a_s and b_s are not available:

   $$H_{so} = (0.75 + 2 \times 10^{-5} z)\ H_0 \qquad (19)$$

   where z is station elevation above sea level (in metres)

b- Relative shortwave radiation (H/Hso)

The relative shortwave radiation is the ratio of the solar radiation (H) to the clear-sky solar radiation (H_{so}). H is the solar radiation that actually reaches the earth's surface in a given period, while H_{so} is the solar radiation that would reach the same surface during the same period but under cloudless conditions.

$$H_{rs} = H/H_{so} \tag{20}$$

c- Net solar or net shortwave radiation (H_{ns})

The net solar radiation, H_{ns}, is the fraction of the solar radiation H that is not reflected from the surface. Its value is:

$$H_{ns} = (1-\alpha)\, H \tag{21}$$

where α is the albedo, the fraction of the solar radiation that is reflected by the surface.

d- Net long-wave radiation (H_{nl})

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:

$$H_{nl} = \sigma\frac{[Tmaxk4 + Tmin4]}{2}(0.34 - 0.14\sqrt{Ea})[1.35\frac{Rs}{Ra} - 0.35] \tag{22}$$

$$E_a = \frac{RHmean}{100}\left[\frac{e0(Tmax)+e0(Tmin)}{2}\right] \quad (23)$$

e- Net radiation (H_n)

The net radiation (H_n) is the difference between the incoming net shortwave radiation (Hns) and the outgoing net long-wave radiation (H_{nl}):

$$H_n = H_{ns} - H_{nl} \quad (24)$$

3. Methodology

Metrological data for five years from Katsina station were used to estimate the extraterrestrial solar radiation using model 1 (equ. 2) and model 2 (equ. 7) to evaluate the monthly mean daily extraterrestrial solar radiation (H_0).

The compatibility of models 1 and 2 for estimation of monthly mean daily extraterrestrial solar radiation (H_0) was tested by calculating the mean bias error (MBE), root mean square error (RMSE) and the mean percentage error (MPE) of the models.

The evaluated monthly mean daily extraterrestrial solar radiation (H_0) obtained from the two models was used with the measured monthly mean daily global solar radiation, minimum and maximum temperatures and relative humidity in the station to extract the regression constants a and b. The derivatives of the global solar radiation were evaluated using equations (18 – 24).

4.0- Results and Discussions

There is a little difference in the estimated monthly mean daily extraterrestrial solar radiation (H_0), between the two models as shown in Table 1. However, the difference was not that significant for the yearly average as seen in Table 2. The average extraterrestrial radiation in this work is in agreement with values obtained from first and second order quadratic type Angstrom equations reported by [10] for the same station. The bias errors were considered to be moderately small from both models. Although the MBE is positive, which indicates an overestimation, the lower MBE suggest a reasonable estimate as shown in Table 3. The metrological elements of the station for the five year period are shown in Fig. 1. The following correlation equations using ratio of minimum to maximum temperature and relative humidity were obtained respectively for the estimation of the global solar radiation of the station;

$$H/H_o = 0.6161 + 0.04187(\left(T_{\min}/T_{\max}\right) \text{ and } H/H_o = 0.5595 - 0.00219(RH)$$

The regression constants are of the order of values reported by [17] for Katsina station. There is a very close agreement of the mean bias errors using the two models which implies their compatibility.

Table 1:- Extraterrestrial solar radiation for Models 1 & 2 in Katsina station.

Months	$\overline{H}$	$\overline{H}_o$	
		Model 1	Model 2
Jan	23.7	30.39	34.99
Feb	26.2	33.30	36.32
Mar	25.6	36.20	36.99
Apr	24.2	38.00	35.92
May	20.8	38.17	33.92
June	19.8	37.81	32.51
July	18.2	37.81	32.88
Aug	18.2	37.85	34.66
Sep	20.2	36.80	36.25
Oct	21.6	34.23	36.35
Nov	24.0	31.09	35.25
Dec	23.8	29.43	34.44

Table 2: Mean values of the extraterrestrial radiation, regression constants, and clearness index from the two models (H), using ratio of minimum to maximum temperature and relative humidity for Katsina station.

Year	H	H_o		T_{max} (^oC)	T_{min} (^oC)	a	b	H/H_o	
		Model 1	Model 2					Model 1	Model 2
2006	23	35.09	35.03	34	20	1.067	-0.709	0.655	0.657
2007	22	35.09	35.03	35	21	1.445	-1.35	0.627	0.628
2008	22	35.09	35.03	33	21	1.359	-1.131	0.627	0.628
2009	22	35.09	35.03	34	21	1.50	-1.36	0.627	0.628
2010	22	35.09	35.03	34	21	1.508	-1.42	0.627	0.628

Table 3: The values of the statistical indicators (MBE, RMSE and MPE) of the 2 models for Katsina station

Year	**MBE**		**RMSE**		**MPE**	
	Model 1	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**
2006	0.411	0.409	2.362	2.295	-1.87	-1.86
2007	0.432	0.430	2.614	2.422	-2.148	-2.066
2008	0.419	0.418	2.553	2.339	-2.011	-1.945
2009	0.426	0.424	2.521	2.366	-2.027	-1.971
2010	0.431	0.430	2.614	2.419	-2.143	-2.060

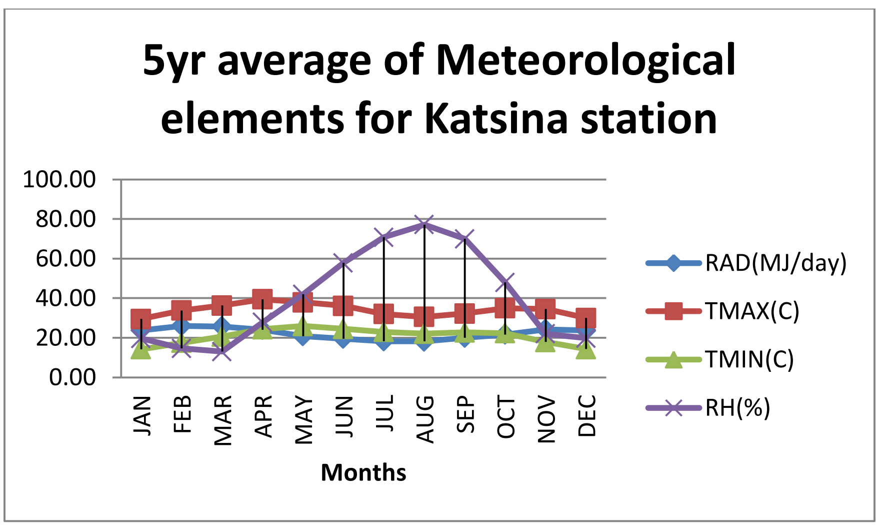

Fig 1: 5yr average of Meteorological elements for Katsina station

The derivatives of the global solar radiation show a similar pattern in the course of the year over the monthly period except for the clear-sky radiation which remains constant over the monthly periods as shown in Fig. 2. This is thought to be a consequence of using monthly mean daily extraterrestrial radiation values in our estimate, which also affects the relative shortwave radiation.

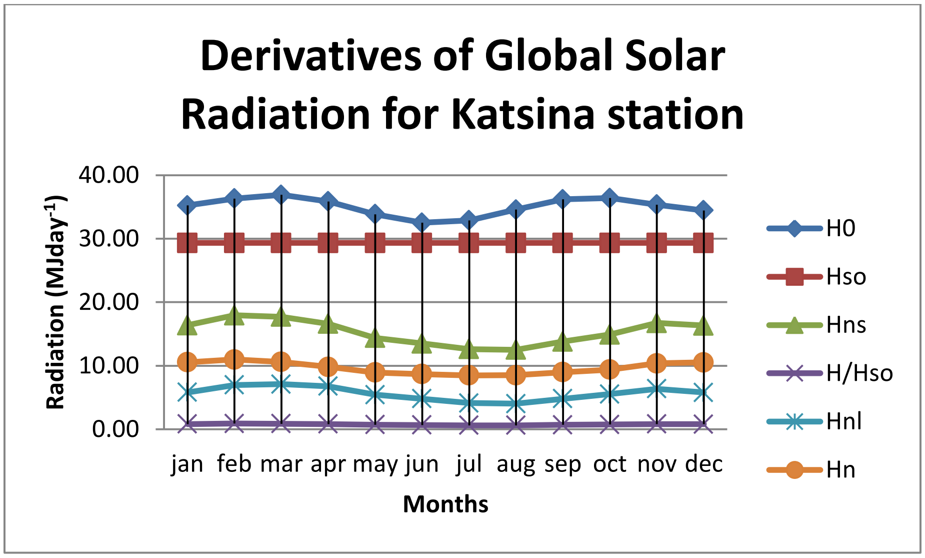

Fig 2: Derivatives of Global Solar Radiation for Katsina station

5.0- Conclusion

The mean monthly measured global solar radiation, ratio of minimum to maximum temperature and relative humidity records for five (5) years (2006-2010) of Katsina station of Nigeria Meteorological Agency (NIMET), have been employed in this study to evaluate the mean monthly extraterrestrial solar radiation using two different models, and other derivatives of the global solar radiation. A good agreement was observed between the two models. The mean bias errors are low and within the range of reported values. Correlation equations were also obtained for theoretical estimation of global solar radiation, using the ratio of minimum to maximum temperature and relative humidity..

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