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Correlations to estimate monthly mean of daily diffuse solar radiation in some selected cities in Nigeria

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ABSTRACT

The successful design and effective utilization of solar energy systems and devices for application in various facets of human needs, such as power and water supply for industrial, agricultural and domestic uses, largely depend on the availability of information on solar radiation characteristic of the location in which the system and devices are to be situated. The diffuse solar radiation for eight stations in Nigeria is estimated using Klein (1977) model. A statistical analysis of monthly mean correlation is examined, using a 16 years achieve (1995-2010) of monthly mean of global and diffuse solar radiation obtained at eight selected meteorological stations over Nigeria area. The accuracy of the candidate correlations are performed in terms of the two widely used statistical indicators, mean bias (MBE) and root mean square errors (RMSE). The results indicate that the correlations relating the diffuse fraction (Kd) with clearness index (KT), the relative sunshine duration (S/Smax), relative humidity and ratio of maximum to minimum daily temperature are more reliable for diffuse radiation predictions in the Nigerian environment than using each variable separately. The study found that the present correlation produced the best estimates of diffuse solar radiation.

Keywords: diffuse fraction, clearness index, temperature, relative humidity and relative sunshine duration.

INTRODUCTION

When we speak of solar radiation, we mean the electromagnetic radiation of the sun. The radiation from the sun is the primary natural energy source of the planet Earth. Other natural energy sources are the cosmic radiation, the natural terrestrial radioactivity and the geothermal heat flux from the interior to the surface of the Earth but these sources are energetically negligible as compared to solar radiation. As the solar radiation passes through the atmosphere, it undergoes absorption and scattering by various constituents of the atmosphere. The amount of solar radiation finally reaching the surface of earth depends quite significantly on the concentration of airborne particulate matter, gaseous pollutants and water (vapour, liquid or solid) in the sky, which can further attenuate the solar energy and change the diffuse and direct radiation ratio. The global solar radiation can be divided into two components: diffuse solar radiation, which results from scattering caused by gases in the Earth's atmosphere, dispersed water droplets and particulates; and direct solar radiation, which have not been scattered. Global solar radiation is the algebraic sum of the two components. Values of global and diffuse radiations are essential for research and engineering applications.

Among the non-conventional energy resources, solar energy, wind energy and Biomass has emerged as most prospective option for the future. Detailed information about the availability of solar radiation on horizontal surface is essential for the optimum design and study of solar energy conversion system. More recently global solar radiation has being studied due to his importance in providing energy for Earth's climatic system. In some places where radiation measurements are scanty, theoretical forecast of the available of solar energy can be used to predict these measurements from standard weather parameters that are extensively measured (air temperature, relative humidity, effective sunshine duration and cloudiness) [1-3].

Several models for estimating the diffuse component based on the pioneer works of [4] and [5] and developed by [6]. These models are usually expressed in either linear or polynomial fittings relating the diffuse fraction (Kd) with the clearness index and combining both clearness index (KT) and relative sunshine duration [7-11] established hourly correlations between KT and Kd under diverse climatic conditions. [12] established correlated the ratio of monthly average hourly diffuse solar radiation to monthly average hourly global solar radiation with the monthly average hourly clearness index in form of polynomial relationships for the city of Izmir, Turkey. [13] used measurements of global and diffuse solar radiations in the City of Sao Paulo (Brazil) to derive empirical models to estimate hourly, daily and monthly diffuse solar radiation from values of the global solar radiation, based on the correlation between the diffuse fraction and clearness index.

This paper presented a comprehensive study of the prediction of the diffuse fraction of solar radiation from other ground variables, including clearness index, relative humidity, relative sunshine duration, ratio of maximum to minimum temperature.

MATERIALS AND METHODS

2.1 Data analysis

The monthly means of daily global solar radiation on horizontal surface, ambient temperature (minimum and maximum), relative humidity and sunshine duration for 16 years (1995-2010) for eight locations in Nigeria listed in Table 1 and displayed in Figure 1, were obtained from the Archives of Nigerian meteorological Agency Oshodi, Lagos State.

Table 1. Geographical location of the stations

Stations	Locations LAT.	LONG.	Altitudes
Sokoto	13.01N,	05.15E	350.8
Maiduguri	11.51N,	13.05E	353.8
Port-Harcourt	04.51N,	07.01E	19.50
Enugu	06.28N,	07.33E	141.8
Owerri	05.29N,	07.00E	91.0
Abeokuta	07.01N ,	03.20E	104.0
Yola	09.14 N,	12.28E	186.1
Jos	09.52N,	08.45E	192.2

Figure 1: Map of Nigeria

Among the above mentioned linear regression models, the most popular is the Angstrom (1924) type model

$$\frac{H}{H_O} = a + b\left(\frac{S}{S_{\max}}\right) \qquad (1)$$

Where H is the monthly mean of daily total terrestrial solar radiation falling on horizontal surface at a particular location. Ho is the monthly mean of daily total extraterrestrial solar radiation a horizontal surface in the absence of atmosphere. S is the monthly mean daily hours of bright sunshine; S_{max} is the possible daily maximum number of hours of insolation. S_{max} is given by [14] as

$$S_{\max} = \frac{2}{15} Cos^{-1}\left(-\tan\phi \tan\theta\right) \qquad (2)$$

Where θ and ϕ are the latitude and declination angles of the location respectively.

The declination angle δ is given by

$$\delta = 23.45 Sin\left(360\left(\frac{284+n}{365}\right)\right) \qquad (3)$$

$$H_o = \frac{24\times 3600}{\pi} Gsc\left(1+0.033Cos\frac{360n}{365}\right)\left(Cos\phi Cos\delta Sin W_S + \frac{2\pi W_S}{360} Sin\phi Sin\delta\right) \quad (4)$$

Were Ho = monthly mean daily extraterrestrial radiation MJ/m^2
Gsc = Solar constant = 1367 W/m^2
Ws = Sunset hour angle for the typical day n for each month in degrees
= $Cos^{-1}(-\tan\theta\tan\delta)$
$\theta =$ Latitude angle for the location in degrees
δ = declination angle for the month in degree
n = mean day of each months

Then, the monthly mean of daily global radiation H was normalized by dividing with monthly mean of daily extraterrestrial radiation Ho. We can define clearness index (KT) as the ratio of the observation/measured horizontal terrestrial solar radiation (H), to the calculated/predicted horizontal extraterrestrial solar radiation (Ho).

$$K_T = \frac{H}{H_O} \quad (5)$$

2.2 Monthly mean daily diffuse fraction correlations

The diffuse solar radiation Hd can be estimated by an empirical formula which correlates the diffuse solar radiation component Hd to the monthly mean of daily total terrestrial solar radiation (H). The linear regression model which is widely used is developed by [15].

$$\frac{H_d}{H} = 1.00 - 1.13K_T \quad (6)$$

Another commonly used correlation is due to [5]and modified by [6] and is of the form

$$\frac{H_d}{H} = 1.390 - 4.027K_T + 5.53(K_T)^2 - 3.108(K_T)^3 \quad (7)$$

We engaged Klein [3] models to estimate for diffuse solar radiation for eight locations (see Table 1) in Nigeria. Kd is define as the ratio of the observation/measured diffuse solar radiation (Hd) to the observation/measured horizontal terrestrial solar radiation (H).

$$K_d = \frac{H_d}{H} \quad (8)$$

2.2 Method of model evaluation

The accuracy of the correlations was assessed by means of two widely used statistics: root mean square error (RMSE), mean bias error and (MBE). The RMSE (MJ/m^2), MBE (MJ/m^2), for four variables.

$$RMSE = \left\{\left[\frac{1}{n}\sum\left(Kd_{pred} - Kd_{obs}\right)^2\right]\right\}^{\frac{1}{2}} \quad (9)$$

$$MBE = \frac{1}{n}\left[\sum\left(Kd_{pred} - Kd_{obs}\right)\right] \qquad (10)$$

The RMSE test gives the information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the estimated and measured values. The lower the RMSE, the more accurate is the estimate. A positive value of MBE shows an over-estimate while a negative value an under-estimate by the model According to [16], a draw-back with this method is that an over-estimation of an individual observation will cancel an underestimation in a separate observation. The values of the MBE represent the systematic error or bias, while the RMSE is a non-systematic error [17].

We analyze the regression and correlations between the monthly mean of diffuse solar radiation, clearness index, relative sunshine duration, relative humidity and ratio of maximum to minimum temperature. The linear regressions are expressed in Table 2 below.

Table 2. Shows equation with regression and statistical indicators for eight stations

Stations	r	R^2	MBE	RMSE
Sokoto	0.9989	0.9979	-5.0E-07	0.00473
Maiduguri	0.9989	0.9977	- 7.08E-07	0.00372
Port Harcourt	0.9994	0.9988	1.2E-07	0.00234
Owerri	0.9962	0.9927	-1.66E-07	0.00664
Enugu	0.9984	0.9969	1.17E-06	0.00404
Abeokuta	0.9943	0.8879	-1.66E-07	0.00891
Yola	0.9952	.9905	1.02E-07	0.01261
Jos	0.9963	0.9926	8.33E-07	0.01133

This regression is derived from the databases of Nigerian meteorological Agency Oshodi and the same databases were used in the comparisons of the models (Figure 2). Therefore, the regression obviously gave the best results. The comparisons between the predicted and observed values clearly indicate that the diffuse fraction Kd at all the eight stations are relatively large at high clearness index values as demonstrated in Table 2 and Figure 2. It is accepted that seasonal, location differences and moisture content incur substantial influences on the diffuse fraction

Based on the results obtained in Table 2, forecasting model has been proposed for estimating the monthly mean daily diffuse solar radiation on a horizontal surface using relative sunshine duration, clearness index, relative humidity, and ratio of maximum to minimum temperature. From Table 2, the forecasting model investigated in this study is stated as follows:

For Sokoto

The correlation of coefficient of 0.9989 exists between the diffuse fraction, clearness index, relative sunshine duration, ratio of maximum to minimum daily temperature, relative humidity. The coefficient of determination of 0.9979 implies 99.79% of diffuse fraction can be accounted by clearness index, relative sunshine, ratio of minimum to maximum daily temperature, relative humidity.

$$Kd = 1.055-0.815\,(K_T)\,-0.0353\,(S/Smax)\,+0.142(\theta)\,+0.00078\,(RH) \qquad (11)$$

For Maiduguri

The correlation of coefficient of 0.9989 exists between the diffuse fraction, clearness index, relative sunshine duration, ratio of maximum to minimum daily temperature, relative humidity.

The coefficient of determination of 0.9988 implies 99.88% of diffuse fraction can be accounted by clearness index, relative sunshine, ratio of minimum to maximum daily temperature, relative humidity.

$$Kd = 0.7795 – 0.830(K_T) – 0.0364\ (S/Smax) + 0.0152(\theta) + 0.00023(RH) \quad (12)$$

For Port Harcourt

The correlation of coefficient of 0.9994 exists between the diffuse fraction, clearness index, relative sunshine duration, ratio of maximum to minimum daily temperature, relative humidity. The coefficient of determination of 0.9979 implies 99.79% of diffuse fraction can be accounted by clearness index, relative sunshine, ratio of minimum to maximum daily temperature, relative humidity.

$$Kd = 0.684 - 0.735(KT) - 0.095\ (S/Smax) + 0.0248(\theta) + 0.00065(RH) \quad (13)$$

For Owerri

The correlation of coefficient of 0.9962 exists between the diffuse fraction, clearness index, relative sunshine duration, ratio of maximum to minimum daily temperature, relative humidity. The coefficient of determination of 0.9927 implies 99.27% of diffuse fraction can be accounted by clearness index, relative sunshine, ratio of minimum to maximum daily temperature, relative humidity.

$$Kd = 0.775 - 0.954(K_T) - 0.056\ (S/Smax) - 0.000042(\theta) + 0.0762(RH) \quad (14)$$

For Enugu

The correlation of coefficient of 0.9984 exists between the diffuse fraction, clearness index, relative sunshine duration, ratio of maximum to minimum daily temperature, relative humidity. The coefficient of determination of 0.9969 implies 99.69% of diffuse fraction can be accounted by clearness index, relative sunshine, ratio of minimum to maximum daily temperature, relative humidity.

$$Kd = 0.642 - 0.851(K_T) - 0.016\ (S/Smax) + 0.087(\theta) + 0.00057(RH) \quad (15)$$

For Abeokuta

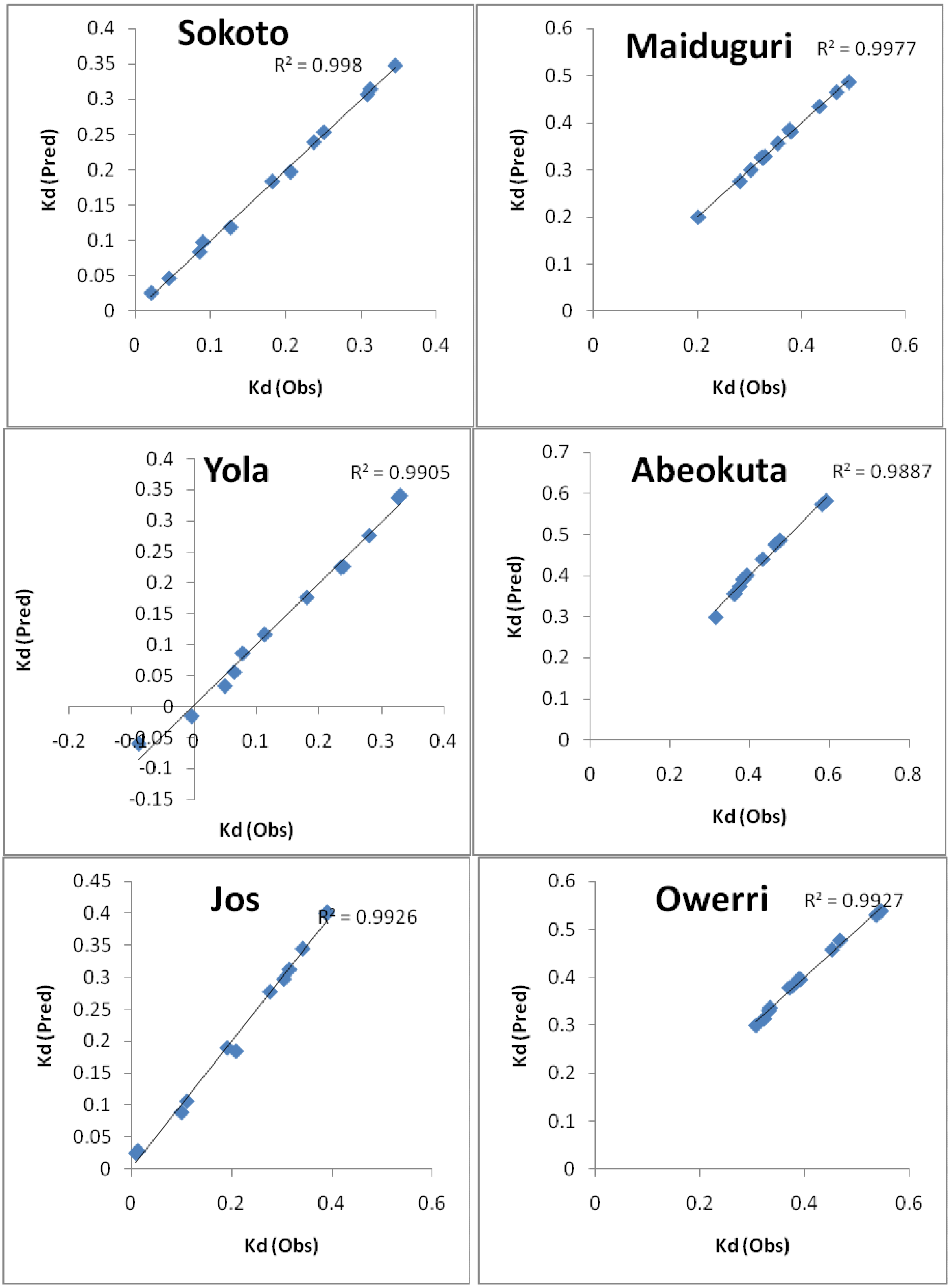
The correlation of coefficient of 0.9943 exists between the diffuse fraction, clearness index, relative sunshine duration, ratio of maximum to minimum daily temperature, relative humidity. The coefficient of determination of 0.8879 implies 88.79% of diffuse fraction can be accounted by clearness index, relative sunshine, ratio of minimum to maximum daily temperature, relative humidity.

$$Kd = 0.6796 - 1.099(K_T) + 0.044\ (S/Smax) + 0.079(\theta) + 0.0014(RH) \quad (16)$$

For Yola

The correlation of coefficient of 0.9952 exists between the diffuse fraction, clearness index, relative sunshine duration, ratio of maximum to minimum daily temperature, relative humidity. The coefficient of determination of 0.9905 implies 99.05% of diffuse fraction can be accounted by clearness index, relative sunshine, ratio of minimum to maximum daily temperature, relative humidity.

$$Kd = 1.1007 - 0.9844(K_T) + 0.0214\ (S/Smax) - 0.1117(\theta) - 0.0001(RH) \quad (17)$$


Sokoto
R² = 0.998
Kd (Pred)
Kd (Obs)
Maiduguri
R² = 0.9977
Kd (Pred)
Kd (Obs)
Yola
R² = 0.9905
Kd (Pred)
Kd (Obs)
Abeokuta
R² = 0.9887
Kd (Pred)
Kd (Obs)
Jos
R² = 0.9926
Kd (Pred)
Kd (Obs)
Owerri
R² = 0.9927
Kd (Pred)
Kd (Obs)

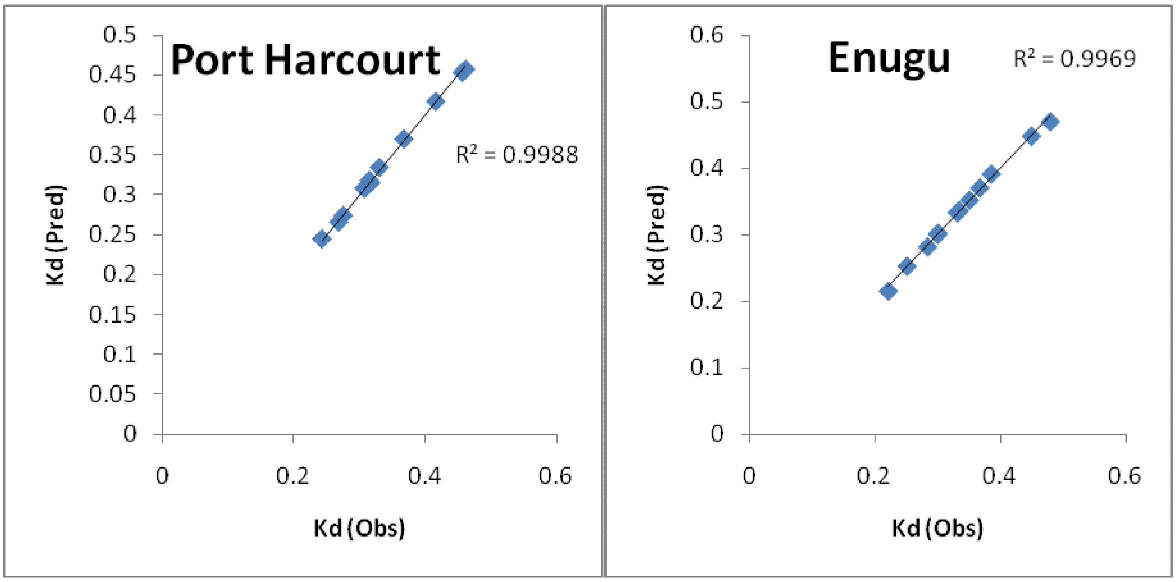


Figure 2: Comparison of the predicted and observed monthly average of diffuse fraction of global solar radiation data for eight stations in Nigeria.

For Jos

The correlation of coefficient of 0.9963 exists between the diffuse fraction, clearness index, relative sunshine duration, ratio of maximum to minimum daily temperature, relative humidity. The coefficient of determination of 0.9926 implies 99.26% of diffuse fraction can be accounted by clearness index, relative sunshine, ratio of minimum to maximum daily temperature, relative humidity.

$$Kd = 1.028 - 1.0081(K_T) - 0.0229\,(S/Smax) - 0.031(\theta) - 0.0011(RH) \quad (18)$$

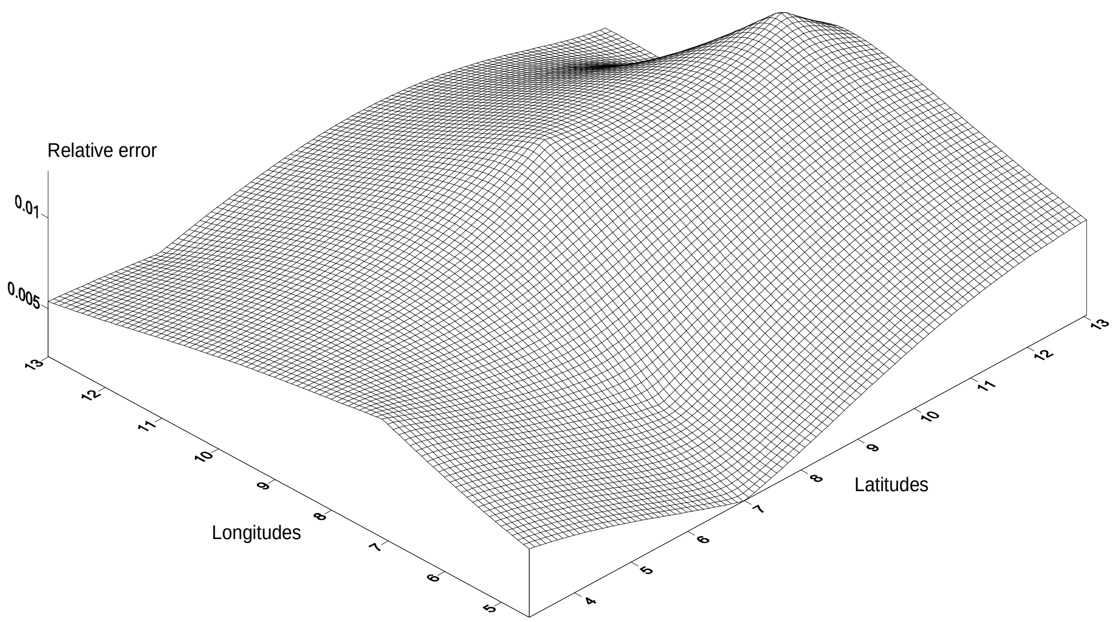


Figure 3: Dependence on latitude and longitude of the relative error associated to Eq. (2) for eight stations in Nigeria.

Fig. 3 is based on monthly average values of the diffuse fraction of solar radiation obtained by using measurements and Eq. (7), respectively, for all the eight stations of Table 1. A positive relative error means that Eq. (7) overestimates the value of the diffuse fraction of solar radiation. Generally, the relative error associated to Eq. (7) slightly depends on latitude (Fig. 3).

DISCUSSION

Table 2 contain summaries of multiple regression analyses, obtained from equation (7) to the monthly mean value for four variables were examined. The correlation coefficient r, coefficient of determination R^2, MBE (MJ/m^2), RMSE (MJ/m^2) varies from one station to another station.

Generally, correlation coefficients (0.9989 - 0.943) are high for all the stations. This implies that, there are statistically significant relationships between the diffuse solar radiation, clearness index, relative sunshine duration, the relative humidity, the ratio of maximum to minimum daily temperature and this is further demonstrated by high values of coefficient of determination R^2 (0.9988 - 0.8879) across the eight stations.

To compare visually between observed and estimated Kd values, Fig. (2) is provided. As it appears from Fig. 2, the agreement between observed and estimated values is quite good. The variability of weather conditions and aerosol mass concentration may be the reason for the observed scatter of the daily values shown in Fig. 2. The accuracy of the predicted data is tested by calculating the MBE and RMSE for each of the stations with standard techniques. The MBE and RMSE values are given in Table 2. The model used produced the low MBE and RMSE values.

As observed from Fig. 4 (a and b), the stations experienced a decrease in the clearness index from March through September (during rainy season) with increase in diffuse solar radiation. This wet season minimum is expected due to poor sky conditions caused by atmospheric controls as the atmosphere is partly cloudy and part of solar radiation are scattered by air molecules, some absorbed directly by the dust particles, ozone and water vapour of cloud. Increased cloud cover and precipitation water, associated with the Inter-Tropical Convergence Zone (ITCZ), result to the low value of clearness index in the wet season they have likely contributed to the decrease in clear days in the stations under analysis.

During the commencement of dry season in October some stations like Yola, Jos, Sokoto and Maiduguri experienced a rapid increase in their solar radiation than other stations like Port-Harcourt, Abeokuta, Enugu and Owerri maintained a gradual decrease in global radiation with high diffuse fraction. The diffuse ratio can be regarded as the cloudiness index. The value of diffuse ratio is essential in assessing the climatologically potential solar energy utilization for a region and in estimating the secular averages or expected values of the output of concentrating solar collectors. The diffuse coefficient is a factor that reflects the effectiveness of the sky in scattering the incoming radiation. This may also be as a result of geographical stations.

Generally the maximum values of clearness index occurred during dry season, although varying with months, across the eight stations. Clear skies and low precipitation water enhanced the clearness index values. High values of clearness index indicate great availability of solar irradiation during dry season as the cloud is free from sky condition like cloud, aerosol and water vapour. [18-20] and [3] used the peculiar variability of sky condition in tropical region to explain the variation of clearness index

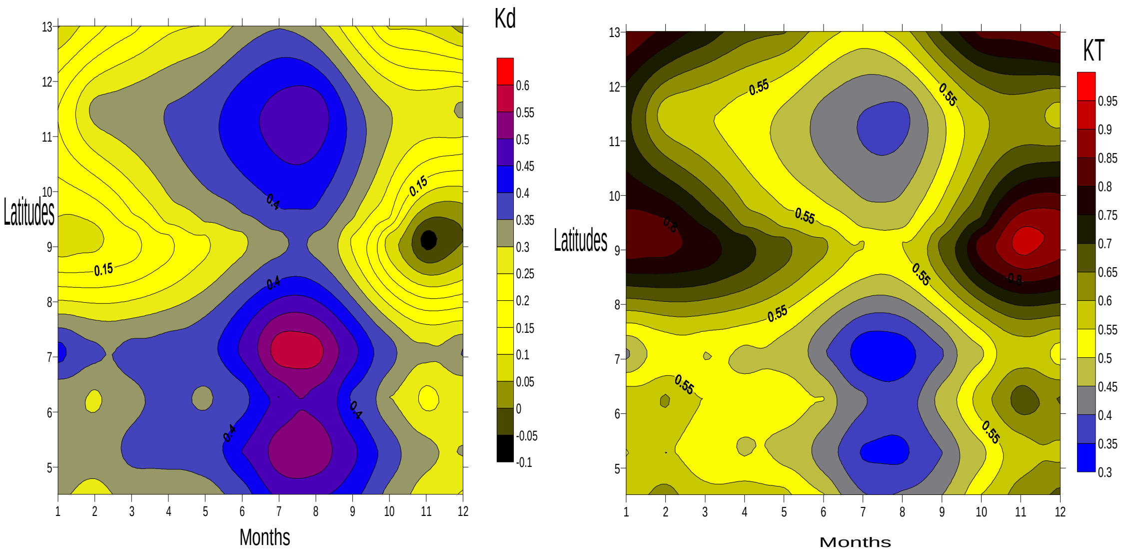


Fig.4: (a) Variation of Monthly means of daily diffuse fraction (Kd) and (b) Variation of Monthly means of clearness index (KT) for eight locations in Nigeria.

CONCLUSION

The diffuse solar radiation for eight stations in Nigeria is estimated using [6] model, as Nigerian meteorological Agency, Oshodi, has no diffuse solar radiation measurement. From the estimated result, it is seen that contribution of diffuse solar radiation is low throughout the month. The performances for the model for eight stations have been done in terms of widely used statistical indicators, Mean Bias Error (MBE) and Root Mean Square Error (RMSE). It was observed from statistical indicator that Klein models provided reasonably high degree of precision in the forecast of monthly average of diffuse solar radiation on the horizontal surfaces. The estimated values of global and diffuse solar radiation reveals that solar radiation can be very efficiently used to compensate for energy inadequacy

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