Estimation of Hourly Clearness Index and Diffuse Fraction Over Coastal and Sahel Regions of Nigeria Using NCEP/NCAR Satellite Data

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Authors' contributions

This work was carried out in collaboration among all authors. Author AB designed the study, managed the analyses of the study. Author OOV performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors AB and OOV managed the literature searches. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

In this paper, daily satellite data of global and diffuse irradiances obtained from the archives of National Centre for Environmental Prediction (NCEP) and National Centre for Atmospheric Research (NCAR) covering a period of ten years (2005-2014) have been employed to study clearness index (K_T) and diffuse fraction (K_D) distributions over six carefully selected meteorological stations in Nigeria. These stations are Port Harcourt, Akure and Enugu in the coastal region; Kano, Maiduguri and Bauchi in the sahelian region. Results have shown that while global irradiance show double peaks in its mean annual daily variation at both regions, diffuse radiation only show this in the sahelian region. In the coastal region, its values are almost uniform throughout the year .In observing the synoptic hourly distribution of clearness index and diffuse fraction, it was found that while clearness index exhibits minima values at hours close to sunrise and sunset, the reverse is the case for diffuse fraction. Also that in the coastal region, clear sky condition is prevalent in Akure and Enugu at both seasons whereas in Port Harcourt, it seldomly occurs. In the sahelian region, on

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the other hand, clear sky condition is prevalent at both seasons. Using ANOVA method, empirical models were developed for K_T. All the models at the stations and regions gave good and significant coefficient of determination R^2. During the dry season months, it ranges between 0.98 and 0.99 while during the rainy season, it is 0.89 and 0.95. To further test the efficiencies of the developed models, the Mean Bias Error (MBE) and Root Mean Square Error (RMSE) were computed. Values obtained for both MBE and RMSE for most of the stations are low and positive. These are desirable results for good and significant models. It shows that these models can be used to predict clearness index K_T with high accuracy in the selected stations and proximateones.

1. INTRODUCTION

The Sun is considered to be the basic driving force for solar energy in the Earth's climate system with a radius of 6.960×10^{-8} m. Nigeria receives abundant solar energy that can be usefully harnessed with an annual daily average of about 5250 Wm^{-2}. This varies between 3500 Wm^{-2} day^{-1} at the coastal areas and 7000Wm^{-2} day^{-1} at the northern boundary [1,2].This energy emitted by the sun is created by the thermonuclear fusion processes involving oxygen and helium in the core of the sun [3].The Atmosphere consists of some gases and particulate matters such as water vapor and aerosols that cause reflection, absorption and scattering of solar radiation as it is propagating through it. These effects make radiation received on the Earth surface a lot less than what is received at the top of the atmosphere. Inability to have regular and adequate observation data for solar radiation has been a major challenge because of many reasons, part of which are lack of adequate facilities to carry out measurements and paucity of fund to finance good researches in the area of solar radiation.

Iqbal [4] stated that it is important to have solar irradiance separated into various components since it is essential in a wide range of solar engineering tasks. These are (i) direct solar radiation which is that part that travels unobstructed through space and atmosphere to the surface of the Earth; (ii) diffuse radiation which represents the part that is scattered by atmospheric components such as gaseous molecules, aerosols, dust, and clouds [5]. Diffuse radiation has so many factors contributing to it, which includes, the ground condition, changing albedo due to seasonal bare or snow covered surface, variation due to growing seasons and changes in land use (William and Dirmhirn, 1981) and (iii) global solar radiation which is the combination of diffuse and direct solar irradiances. This knowledge is needed by engineers, farmers, and hydrologists for effective managements of day to day activities. For instance, the knowledge of the distribution of the diffuse fraction is required in assessing the climatological potential of a locality for solar energy utilization and in estimating the expected values of the output of concentrating solar collectors [6].

Okogbu et al. [7] in their work on hourly and daily clearness index and diffuse fraction at a tropical station, stated that atmospheric conditions such as turbidity and transparency, air mass, atmospheric water vapor contents and distribution of cloud cover have depleting influences on solar radiation at the earth's surface, mainly through absorption, scattering, and reflection of the incoming solar radiation. The effective utilization of solar radiation is of great importance globally, especially at this time when fossil fuel is depreciating in value globally due to its environmental effects culminating to the climate change problems. One major concern is that, solar radiation, especially the diffuse solar radiation which is very important in terms of utilization and in climate change analysis is less frequently measured compared to other climatic parameters such as temperature and rainfall [8-10]. This has led to dearth of radiation data in almost every part of the world and to worsen it, in Africa, where it is available in abundance [10-12]. The dearth of radiation data has been attributed to high cost of procuring, maintaining and training experts on the necessary radiation equipment.

Clearness index being a veritable tool in the characterization of sky conditions over a particular locality has been studied by some notable researchers over different parts of Nigeria. These include, Ideriah and Suleman [13], Kuye and Jagtap [14], Okogbue and Adedokun [15]. Recently researchers have shifted attention from observations of total amount of solar radiation to its spectral

distribution because of the increment observed in terrestrial application of solar energy (Dimitris et al. 2008). Attentions have also been paid to the study of its ratios [16-21], Adeyefa et al.1997, 2002.

The present study, in consideration of the prevailing atmospheric conditions over the selected stations in Nigeria, investigates the diurnal and seasonal patterns of the synoptic hourly and daily clearness indices and the diffuse fraction (or cloudiness index) calculate dusing the measured synoptic hourly fluxes of global and diffuse solar radiation data obtained from the archives of National Centre for Environmental Prediction (NCEP) and National Centre for Atmospheric Research (NCAR). The characterization of sky conditions over the selected stations using the indices was also investigated.

2. DATA AND DATA ANALYSIS TECHNIQUE

The direct and diffuse solar irradiances satellite data used for this study were obtained from the archives of National Centre for Environmental Prediction (NCEP) and National Centre for Atmospheric Research (NCAR) for a period of 10 years (2005 - 2014) and for 6 stations randomly selected from Sahel and Coastal regions of Nigeria (See Fig.1). The clearness index (K_T) which is the ratio of the global solar radiation (H) obtained at the surface to the total solar radiation at the top of the atmosphere was calculated using

$$K_T = \frac{H}{H_0} \tag{1}$$

The extraterrestrial solar radiation (H_o) was calculated from

$$H_0 = \frac{24 \times 3600}{\pi} I_{SC} \left(1 + 0.033 Cos \frac{360n}{365}\right) \left(Cos \emptyset Cos \delta Sin \omega s + 2\pi \omega s 360 Sin \emptyset Sin \delta\right) \tag{2}$$

where I_{SC} is the solar constant with a value 1367 W/m^{-2}, ωs is the sunset hour angle for the typical day [$c\ os^{-1} (-tan \emptyset .tan\delta)$], δ is the declination angle which is expressed as: 23.45 Sin [360(284+n/365)], $\emptyset$is the latitude of the location in degrees, n is the number of days of the year starting from January 1st.

The diffuse fraction (K_D) was obtained from the ratio of the diffuse solar radiation incident on the horizontal level of earth surface (H_D) to the global solar radiation (H) incident on the surface, that is,

$$K_D = \frac{H_D}{H} \tag{3}$$

Using analysis of variance (ANOVA) method, anempirical relation of the form:

$$K = \beta_1 + \beta_2 t + \beta_3 t^2 + \xi \tag{4}$$

(where β s' are the parameter estimates of the ts' (that is, time of the day) K is $K_T$and ξ is the error term) has been established for each of the stations considered and for the months of December-January representing core dry season period and July and August representing the core rainy season.To ascertain the significance of each of the models, the associated F-ratios and probability values were taken into consideration. Next, K values at each station and for the core dry and rainy season months were calculated using the developed empirical relationsin order to test the applicability of the models.To evaluate the performance of the models,Coefficient of determination (R^2), mean bias error (MBE) and root mean square error (RMSE) were used.

Coefficient of determination (R^2) is a sample statistics which gives the numerical descriptive measures of model adequacy and thereby tells us how well the model fits the data.This is calculated from

$$R^2 = \frac{\sum_{j=1}^{N}(Y_j - Y_{Pj}) * (Y_j - Y_{mj})}{\sqrt{\left[\sum_{j=1}^{N}(Y_j - Y_{Pj})^2\right] * \left[\sum_{j=1}^{N}(Y_j - Y_{mj})^2\right]}} \tag{5}$$

Mean bias error (MBE) is the average deviation of predicted values from the actual measured values. It is expressed as

$$MBE = \frac{1}{N}\sum_{j=1}^{N}\left[\frac{Y_{mj} - Y_{pj}}{Y_{mj}} \times 100\right] \tag{6}$$

MBE gives the information on the long term performance of the correlation between predicted values and observed values. Igbal [4] and Almorox et.al (2005) opined that a zero value for MBE is most appropriate and a low value depicts significance. MBE values are either positive or negative; however, negative MBE values shows that the predicted values are underestimated while positive MBE value indicates overestimation.
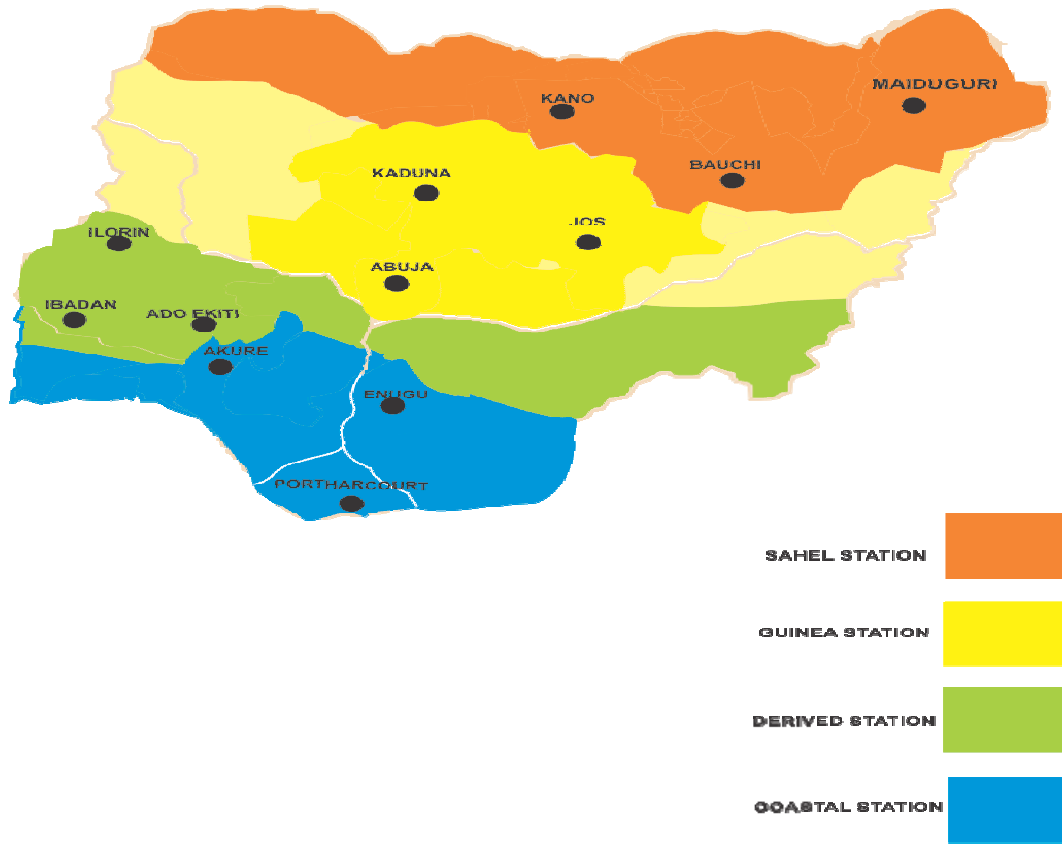
Fig. 1. Map of Nigeria showing the selected meteorological stations

Root Mean Square Error provides measure of the variation between predicted values and observed. This is expressed as

$$RMSE = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(Y_{Pj} - Y_{mj})} \qquad (7)$$

RMSE gives information on a short term performance of the model. RMSE values are usually positive but zero value is desirable. Low values of RMSE also reveal that the model is significant (Adeyemi and Joerg, 2012 , Ajayi and Adeyemi, 2009).

For sky condition characterization, numerous researchers have adopted different values to do this. For example, Reindel et al. [22] gave $K_T <$ 0.6 and $K_T <$ 0.2 for clear sky and cloudy sky respectively. Li and Lam (2001) and Li et al. (2004) using data obtained for Hong Kong, suggested that values of K_T ranging from 0-0.15, > 0.15 -0.7 and > 0.7 to be overcast, partly cloudy and clear skies respectively. Kuye and Jagtap [14] in classifying the sky condition over

Port Harcourt, Nigeria, used $K_T >$ 0.65 and $0.12 \leq K_T \leq 0.35$ for very clear skies and cloudy skies respectively. In this work, the values proposed by Okogbue [7] shall be adopted for sky classification. The importance of a study of this kind can never be overemphasized, most especially, in a country where power generation has remained a serious problem. Hence, the application of solar energy to solve this power problem is inevitable going by the abundance of sunshine that is available throughout the year [23]. Augustine and Nnabuchi [24], in their work, gave the estimation of annual sunshine hour in Nigeria to be 3,000h while Offiong (2003) submitted that average solar radiation received in Nigeria per day is as high as 20MJ/m^2 depending on the time of the year and location. Despite this, the country is still battling with provision of uninterrupted power supply for its teaming population. A very good way of solving the age long challenge is in the application of renewable energy. Although some have discovered this and are already utilizing it at individual levels, but with low performance simply because, over the years,

solar panels used for renewable energy conversion were not designed putting the sky conditions of the area into consideration. Therefore, this study characterizing sky condition, willgive useful information that will be of great help to renewable energy engineers in designing solar energy conversion systems that will perform optimally in the selected regions and the entire country.

3. RESULTS AND DISCUSSION

3.1 Daily Variation of Global and Diffuse Irradiances

Figs. 2 (a & b) show the plots of average over ten years variations of daily mean global and diffuse irradiances at the coastal and sahelian stations. Some features are easily discernible in the variations. Double peaks characterize the variations of global solar radiation at the coastal and sahelian regions, which feature only occurs for diffuse radiation at the sahelian region. Diffuse radiation at the coastal region slightly increases from January to around mid-February after which the values are almost uniform for the rest of the year. The dip observed between the peaks in July/August at both the coastal and sahelian regions for global radiation on one hand, and for diffuse radiation at the sahelian region on the other hand, is in tandem with the period of occurrence of the little dry season (LDS) that is a common phenomenon in the coastal region of West Africa. During this period, cloudiness is high, backed by high humidity and low temperature with absence of rainfall event. Diffuse radiation then increases because the amount of it reaching the earth surface depends largely on the amount, type and distribution of clouds (Kondratyev, 1969); [6]. This may be responsible for the near uniform distribution observed in the diffuse radiation amount observed during the rainy season in the coastal region (Fig. 2a).

3.2 Synoptic Hourly Variations of Clearness Index (K_T) and Diffuse Fraction (K_D)

Figs 3 (a-c) and 4 (a & b) show the plots of monthly mean synoptic hourly variations of K_T and K_D over coastal stations for the months of December, January, and February representing the dry season and July and August representing the rainy season respectively.It is obviously seen from the figures that the clearness index shows a quadraticnormal distribution with a single peak around 10-13HR during the day at all the coastal stations and thereafter drops to its minimum at sunset. This shows that clearness index has lowest values during, and at hours close to sunrise and sunset. Obviously too and during the dry season (Figs. 3a-c), values of K_T are higher at Akure around the peak hours than those of Enugu and Port Harcourt with that of Port Harcourt being the lowest. Since large clearness index implies high global solar radiation and by inference, large direct solar radiation, hence during the day, Akure receives more direct solar radiation than any of Enugu and Port Harcourt. Also, during the dry season months of December-February, values of $K_T$at sunrise range between 0.43- 0.67 at these stations, while at sunset it ranges between 0.00 - 0.05. During the rainy season months of July and August, the observation showing Akure to be leading in direct solar radiation reception persists. The only difference is observed in the sunrise range that has slightly increased to between 0.63- 0.70. The sunset range remains the same. Cloudiness index (diffuse fraction), K_D, on the other hand, during the dry season exhibits a characteristic decrease from sunrise to its minimum during the day around 10-13HR before it rises again to its peak at sunset.This is a reversal of K_T characteristics. The combined effect of K_T and K_D characteristics during the dry season reveals that more direct solar radiation is received during the day at these coastal stations. But at sunrise and sunset hours, solar radiation component that is received at the stations are majorly diffuse as the atmosphere then is cloudier making solar beam passing through the atmosphere to encounter more scattering and reflection constituents [7,25]. Here, K_D ranges between 0.72 and 0.80 at these hours.

Figs. (5a-c) and 6 (a & b) show the monthly mean synoptic hourly variations of K_T and K_D over sahelian stations for the months of December, January, and February representing the dry season and July and August representing the rainy season respectively. Similar features with that of the coastal stations are discernible here at both seasons. However, some notable differences appeared in the minimum and maximum values as the case may be. All the stations selected gave maximum values of $K_T \approx 0.8$ and $K_T \approx 0.6$.

During the dry season and rainy season respectively, during the day. Minimum values of $K_D \approx 0.3$ during the day for Kano and Bauchi at

both seasons are discernible mostly between 9 and 12hrwhile that of Maiduguri comes up around 12 noon (with K_D ranging between 0.3 and 0.5). Its sunrise and sunset values for all the stations and at both seasons are ≈ 0.8.Diffuse fractionis a factor that determines the effectiveness of the sky in scattering the incoming radiation as expressed by Falayi et al. (2011), hence, the radiation that is mostly available during the day at these sahelian stations at both the dry and the rainy season, is the direct solar radiation same as what obtains in the coastal stations. This implies that, in solar energy utilization, solar thermal technologies using solar concentrators shall put up very high performance during the day in these months and at the two regions. Photovoltaic, on the other hand, that directly convert photon energy into electricity will be effective from sunrise till the afternoon period but will be less effective at sunset at the coastal stations and at both seasons of the year. At the sahelian stations, it will be effective throughout the day (GCEP, 2006); [7].

Using Table 1 which represents the monthly averages of the synoptic hourly clearness index K_T for both coastal and sahelian regions, some clearly defined features in K_T distribution are easily discernible. In the coastal region and between the months of November and January depicting the early dry season period, partially cloudy condition is prevalent at Port Harcourt in the morning and afternoon hours whereas in the evening hours, overcast condition prevails. Enugu and Akure on the other hand, presented clear sky condition in the morning and in the afternoon and overcast condition in the evening hours during this period.In the months of February-April representing transitional months to rainy season, all the stations presented partially cloudy condition in the morning hours, overcast in the evening hours whereas in the afternoon hours, clear sky condition is prevalent in Enugu and Akure while in Port Harcourt, partially cloudy condition prevails.In the months of May to October representing the rainy season months,partially cloudy condition is prevalent at all the stations during the morning and afternoon hours whereas in the evening hours, overcast condition is prevalent. Clear sky condition seldomly occurs, when it does, it occurs in the afternoon at Akure and Enugu only during the rainy season. From the foregoing, clear sky condition is scarcely available in Port Harcourt whereas at Akure and Enugu it is prevalent in the afternoon throughout the year. The implication of

this is that solar energy concentrating devices that use incident beam radiation that is dependent on how clear the sky is will not be effective in Port Harcourt but will be, at Akure and Enugu in the afternoon hours. In the sahelian region and at all the selected stations of Bauchi, Maiduguri and Kano, sky condition in the morning and afternoon hours during the dry season is clear whereas overcast condition is prevalent in the evening. During the rainy season, the situation is different. Sky condition in Bauchi is mostly partially cloudy in the morning and afternoon hours whereas in the evening it is overcast. But in Kano and Maiduguri, clear sky condition frequently occurs in the morning and afternoon hours, whereas in the evening period, overcast condition prevails.The difference in sky condition observed in Bauchi may be because it is at the brink of sahelian region (being very close to Jos that is in the guinea savannah region).The above shows that photovoltaic systems for solar conversion and solar concentrating devices are going to be very effective in this region during the morning and afternoon hours throughout the year.

The mean diffuse fraction for months of similar atmospheric and sky conditions for the stations and regions under consideration in this paper are shown in Table 2. From Table 2 and at all stations and regions, the morning and evening hours are characterized by high cloudiness index (diffuse fraction of between 0.78 and 0.80) whereas between sunrise and midday, value is between 0.33 and 0.49 all the year round. Another very conspicuous observation is the fact that cloudiness index is latitudinal dependent. It decreases from low latitude to high latitudinal region. The obvious implication from the former observation where cloudiness index is highin the morning and evening hours is that solar radiation received at these periods will consist mainly of diffuse component. This is because diffuse solar radiation reaching the surface is dependent upon solar elevation angle, atmospheric turbidity, water vapour content of the atmosphere, air mass and distribution of cloud cover [25,7]. The average daily values of diffuse fraction at the months with relative similar atmospheric and sky conditions at all the stations (both coastal and sahel) range between 55% and 57% for dust-hazy months, 55% and 60% for the set of partly cloudy, partly hazy and partly clear sky months, 58 and 61% for the set of less cloudy, cloudy and wet months. Iziomon and Aro [6] and Okogbue et al. [7] reported for Ilorin and Ile-Ife in Nigeria respectively. The values they reported are

6

closely related to the ones we reported here with the exception of the very cloudy months of July, August and September. For instance, during for dust-haze months, they both got 58%, and for the set of partly cloudy, partly hazy and partly clear sky months, they got 59 and 53% respectively. But for the set of very cloudy months, their values range between 72 and 78%. The large differences between their values and that of the present study during the very cloudy months could be due to the fact that in this study, satellite data were employed. Satellites do overestimate or underestimate data values depending on the region in context.

3.3 Model Development for Clearness Index, Testing and Efficiency

Using statistical method, an analysis of variance (ANOVA) table (not shown) was worked out for the months of December-February representing the dry season and the months of July and August representing the rainy season. This was done for all the stations selected taking into cognizance the coefficient of determination (R^2)

and the standard error of estimation. The obtained parameter estimates are as shown in Table 3. In order to determine the efficacy of the predictive equations (models) for the different months and seasons at the observed stations across the regions, mean bias error (MBE) and root mean square error (RMSE) as have been defined previously in equations 1.5 and 1.6 were used. Positive and negative values indicate overestimation and underestimation respectively. The results are as shown in Table 4. From Table 3, low standard error and very high R^2 are discernible at all the stations and at both seasons. This attests to the fact that the models are significant. Taking critical look at the R^2 values at both seasons and for all stations, the level of association is higher during the dry season than in the rainy season period. Using Table 4, low and positive MBE and RMSE values characterized the observations at all the stations and regions across the seasons. This is an indication that the developed models are good enough to estimate clearness index values at the observed stations, regions and proximate ones to between 90-96% accuracy with mean uncertainty of about 7%.
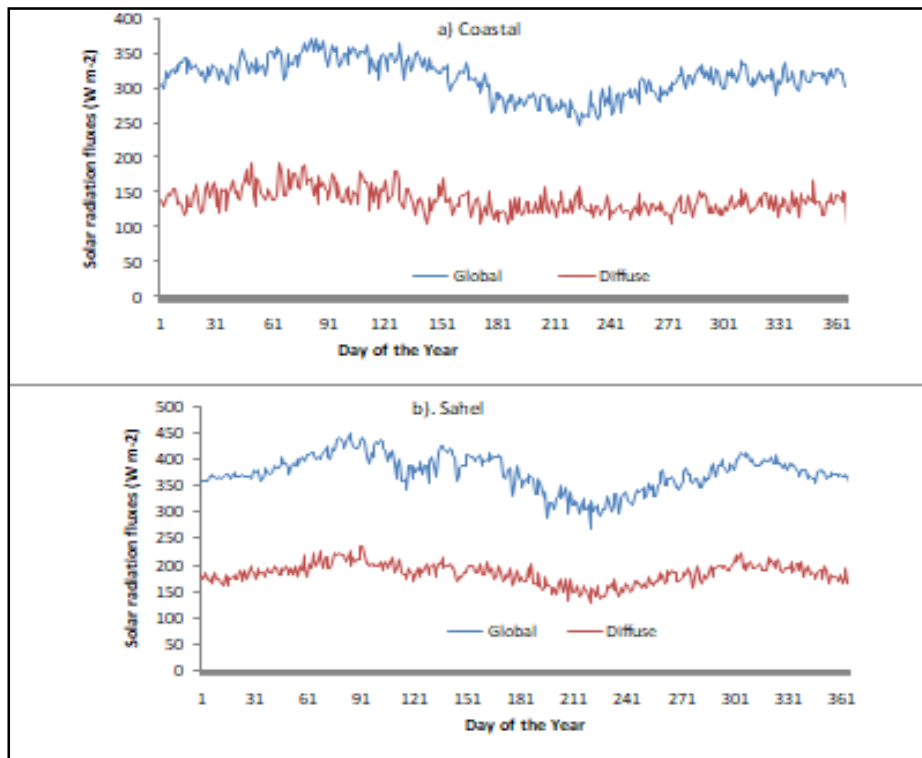

Fig. 2. Daily distribution of global and diffuse solar irradiances averaged over ten years (2005-2014) in a) Coastal b) Sahelian regions
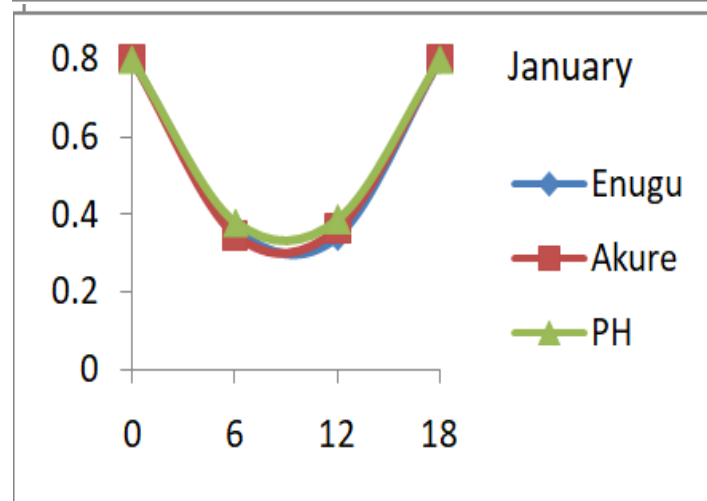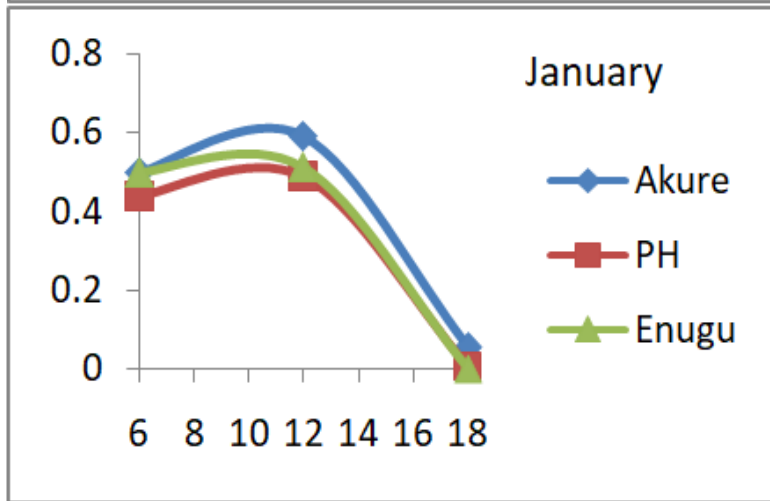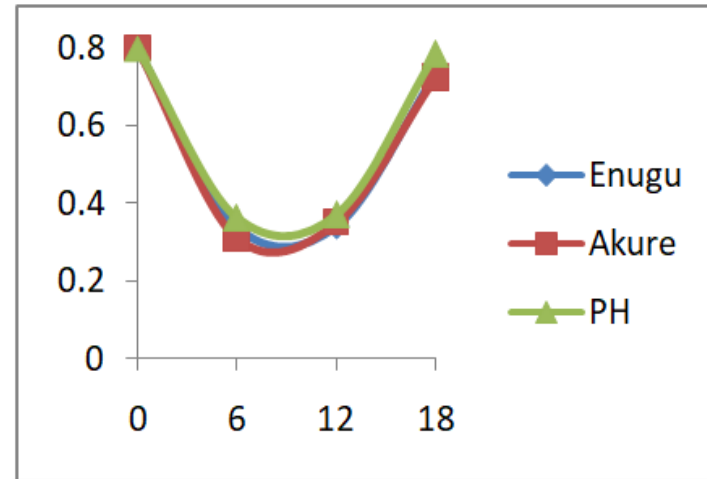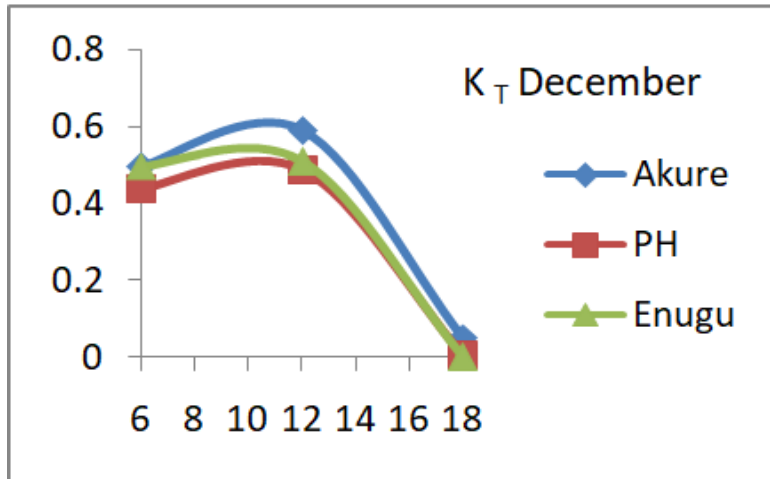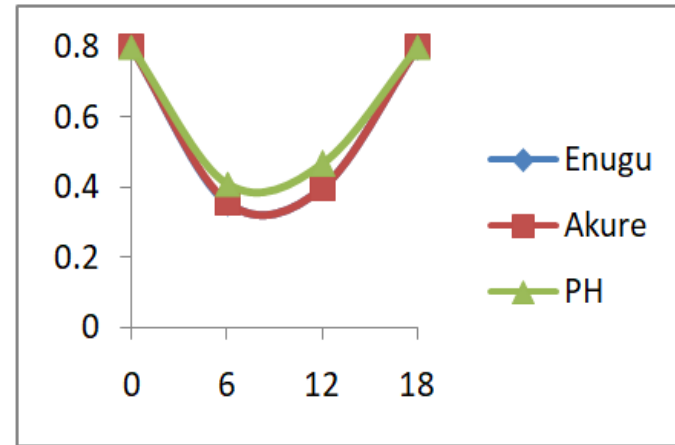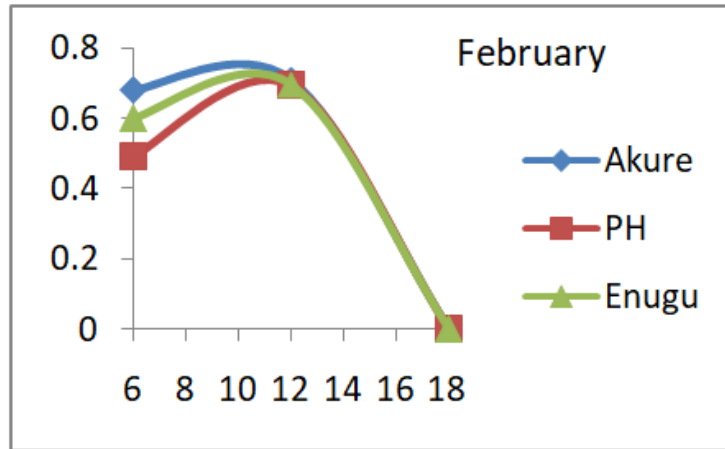
Figs. 3 (a-c). Plots of monthly mean synoptic hourly variations of K_T and K_D over coastal stations for the months of December, January and February
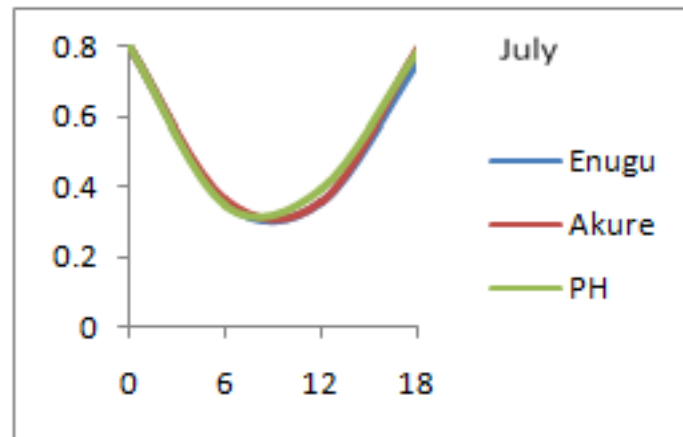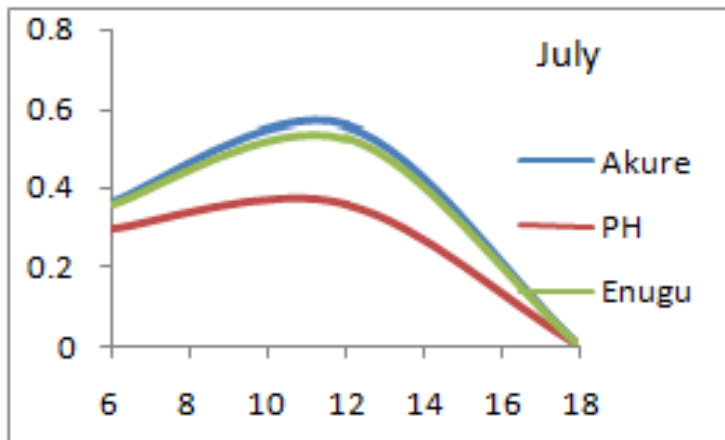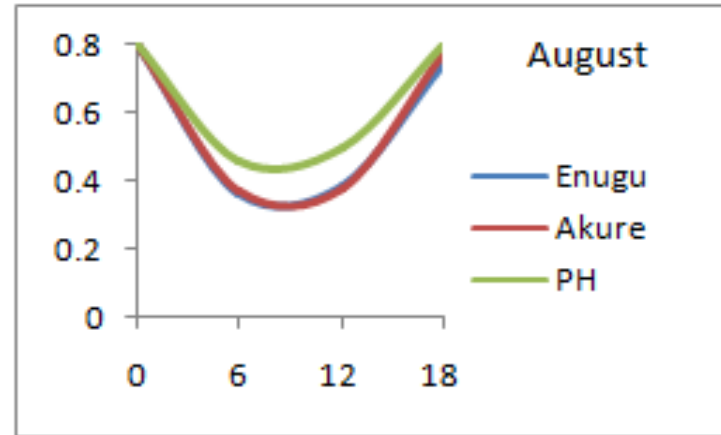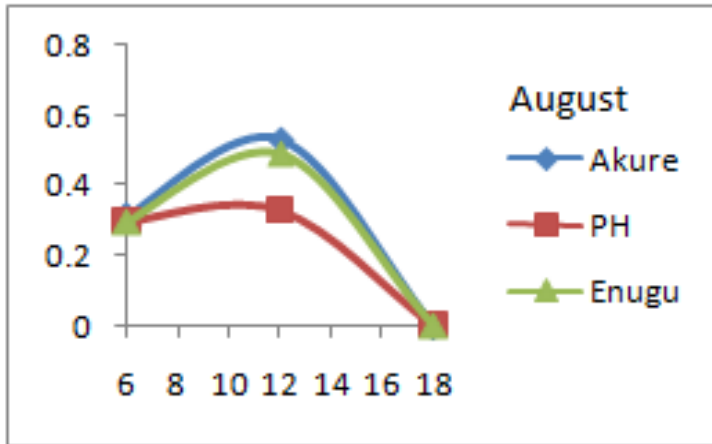
Figs. 4 (a-b). Plots of monthly mean synoptic hourly variations of K_T and K_D over coastal stations for the months of July And August
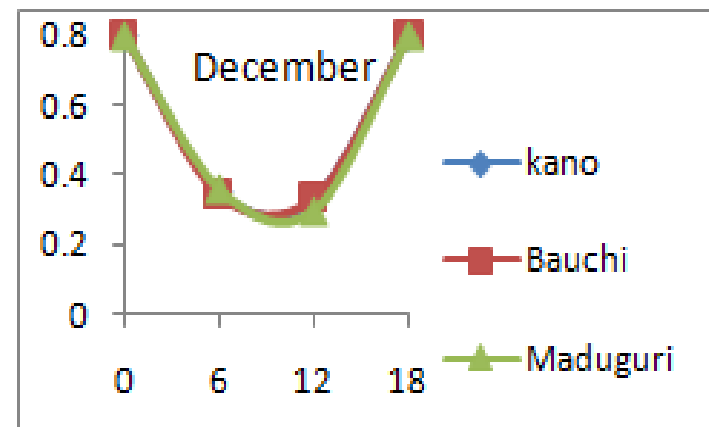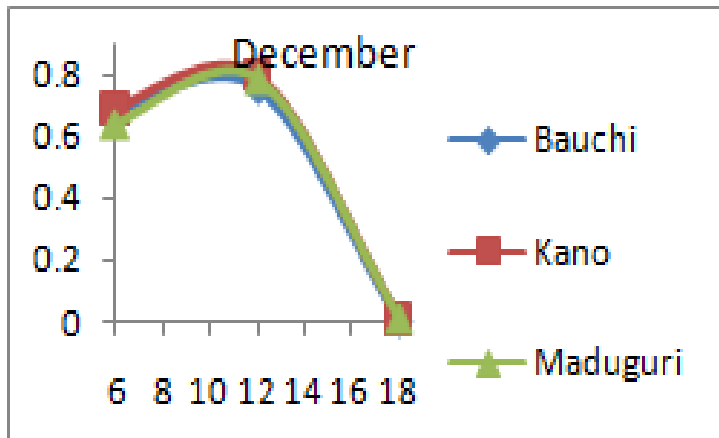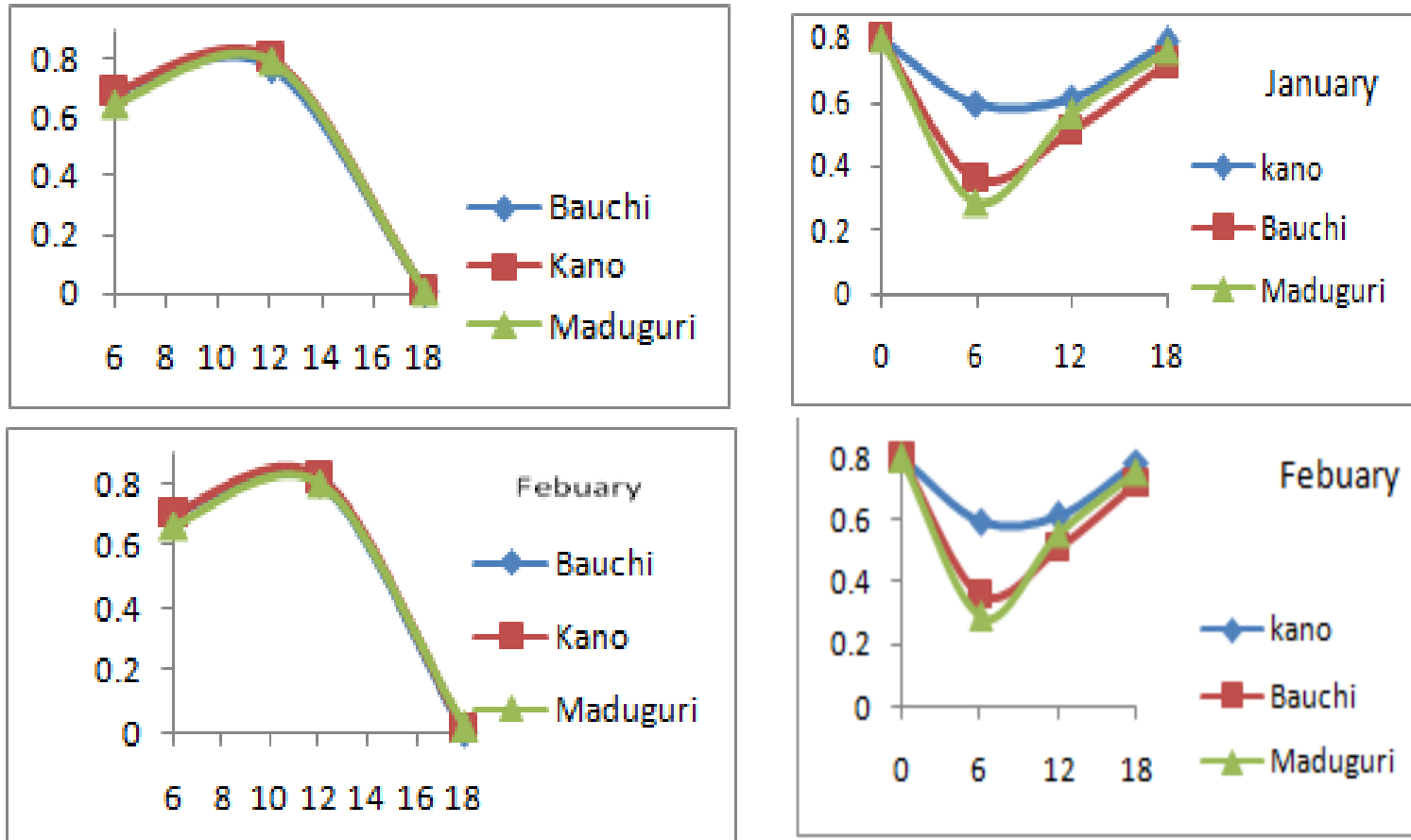
Figs. 5 (a-c). Plots of monthly mean synoptic hourly variations of K_T and K_D over Sahelian stations for the months of December, January and February

Figs. 6 (a-b). Plots of monthly mean synoptic hourly variations of K_T and K_D over coastal stations for the months of July and August

Table 1. Monthly averages of synoptic hourly clearness index k_t for (a) coastal and (b) sahelian stations

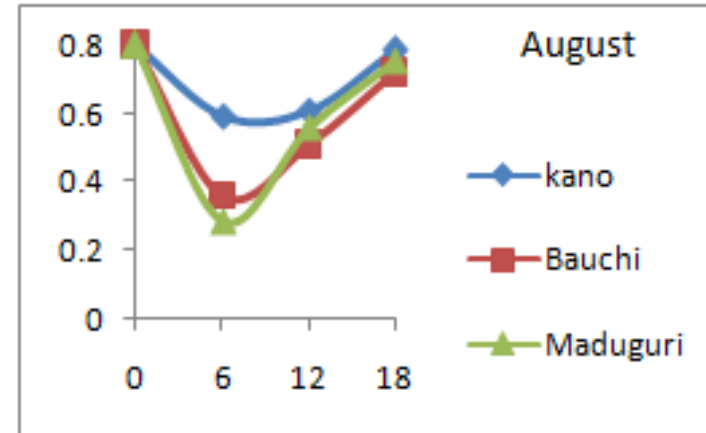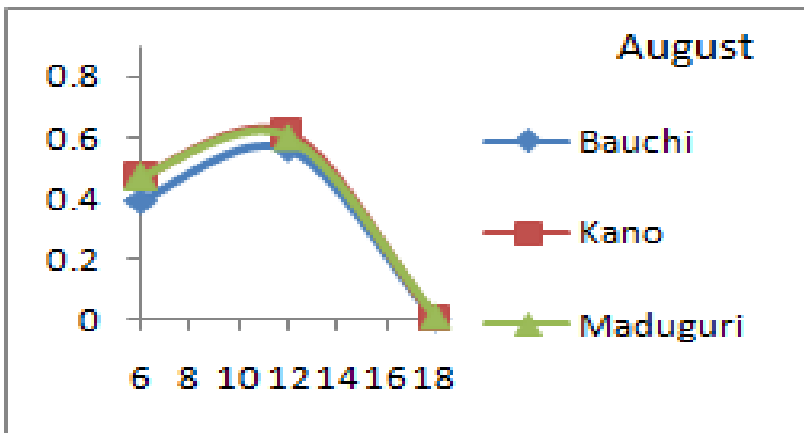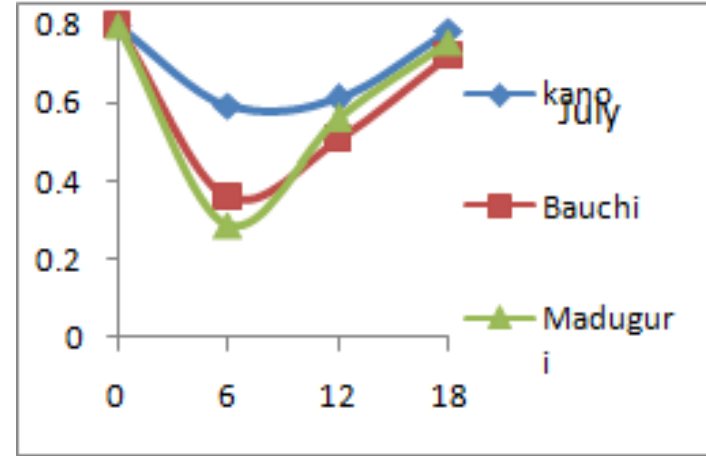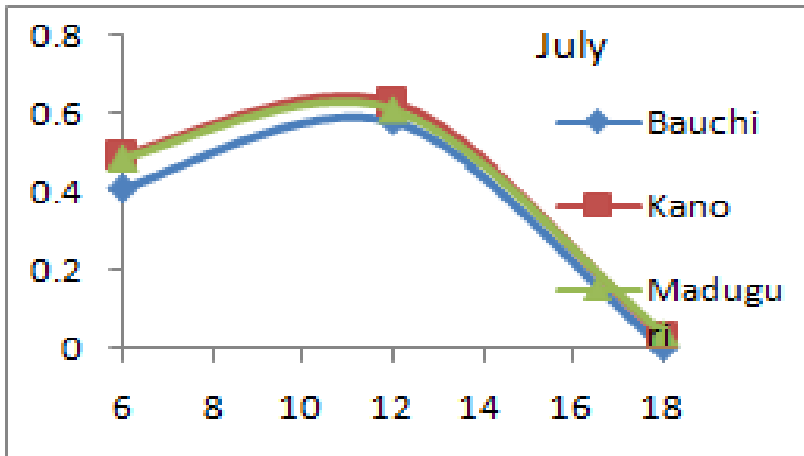| a) Coastal		Port- Harcourt		Type of sky	Enugu		Type of sky	Akure		Type of sky
Dry Months		Value	Ave.		Value	Ave.		Value	Ave	
Nov, Dec, Jan	$K_{T\,06Hr}$	0.40,0.43, 0.49	0.44	Partially cloudy	0.40,0.43,0.57	0.46	Partially cloudy	0.39,0.49,0.59	0.49	Partially cloudy
	$K_{T\,12Hr}$	0.49,0.48,0.49	0.48	Partially cloudy	0.59.0.60,0.66	0.61	Clear sky	0.60,0.69,0.70	0.66	Clear sky
	$K_{T\,18\,Hr}$	0.00,0.00,0.00	0.00	Overcast	0.00,0.00,0.00	0.00	Overcast	0.00,0.00,0.00	0.00	overcast
Feb, Mar, April,	$K_{T\,06Hr}$	0.49,0.49,0.47	0.48	Partially cloudy	0.60,0.53,0.47	0.53	Partially cloudy	0.67,0.52,0.49	0.56	Partially cloudy
	$K_{T\,12Hr}$	0.50,0.48,0.48	0.48	Partially cloudy	0.69,0.68,0.56	0.64	Clear sky	0.71,0.64,0.63	0.66	Clear sky
	$K_{T\,18\,Hr}$	0.00,0.00,0.00	0.00	Overcast	0.00,0.00,0.00	0.00	Overcast	0.00,0.00,0.00	0.00	overcast
July , Aug	$K_{T\,06Hr}$	0.30,0,30	0.30	Cloudy	0.35,0,33	0.34	Partially cloudy	0.36,0,31	0.35	Partially cloudy
	$K_{T\,12Hr}$	0.35,0.49,	0.33	Partially cloudy	0.52, 0.49	0.50	Partially cloudy	0.55, 0.52	0.53	Partially cloudy
	$K_{T\,18\,Hr}$	0.00,0.00	0.00	Overcast	0.00,0.00	0.00	Overcast	0.00,0.00,0.00	0.00	overcast
Sept, Oct,	$K_{T\,06Hr}$	0.40,0.38	0.39	Partially cloudy	0.40,0,42	0.41	Partially cloudy	0.42,0,45	0.43	Partially cloudy
	$K_{T\,12Hr}$	0.48,0.49	0.48	Partially cloudy	0.59,0.62	0.60	Clear sky	0.61,0.61	0.61	Clear sky
	$K_{T\,18\,Hr}$	0.00,0.00	0.00	Overcast	0.00,0.00	0.00	Partially cloudy	0.00,0.00	0.00	overcast
May June	$K_{T\,06Hr}$	0.44,0.41	0.43	Partially cloudy	0.45,0.44	0.44	Partially cloudy	0.45,0.49	0.47	Partially cloudy
	K_{T12Hr}	0.46,0.40	0.43	Partially cloudy	0.56,0.56	0.56	Partially cloudy	0.63,0.58	0.60	Clear sky
	$K_{T\,18\,Hr}$	0.00,0.00,0.00	0.00	Overcast	0.00,0.00	0.00	Overcast	0.00,0.00,0.00	0.00	overcast

b) Sahelian Stations		Bauchi			Maiduguri		Type of sky	Kano		Type of sky
Dry Months		Value	Ave.		Value	Ave.		Value	Ave	
Nov, Dec, Jan	K_{T06Hr}	0.67,0.67,0.68	0.67	Clear sky	0.63,0.63,0.64	0.63	Clear sky	0.67,0.68,0.69	0.68	Clear sky
	K_{T12Hr}	0.75,0.75,0.76	0.75	Clear sky	0.72,0.78,0.79	0.76	Clear sky	0.76,0.78,0.80	0.78	Clear sky
	$K_{T\,18\,Hr}$	0.00,0.00,0.00	0.00	overcast	0.12,0.14,0.10	0.12	overcast	0.16,0.19,0.15	0.00	overcast
Feb, Mar, April,	K_{T06Hr}	0.69, 0.60,0.55	0.61	Clear sky	0.66,0.64,0.60	0.65	Clear sky	0.70,0.69,0.61	0.66	Clear sky
	K_{T12Hr}	0.79,0.73,0.69	0.73	Clear sky	0.80,0.76,0.76	0.77	Clear sky	0.81,0.79,0.74	0.78	Clear sky
	$K_{T\,18\,Hr}$	0.00,0.00,0.00	0.00	overcast	0.00,0.00,0.01	0.00	overcast	0.00,0.00,0.01	0.00	overcast
July , Aug	K_{T06Hr}	0.40, 0.39	0.39	Partially cloudy	0.48, 0.46,	0.47	Partiallycloudy	0.49,0.47	0.48	Partially cloudy
	K_{T12Hr}	0.58,0.59,	0.59	Partially cloudy	0.61, 0.60	0.60	Clear sky	0.62, 0.61	0.60	Clear sky
	$K_{T\,18\,Hr}$	0.00,0.00	0.00	overcast	0.00,0.00	0.00	overcast	0.00,0.00	0.00	overcast
Sept, Oct,	K_{T06Hr}	0.45,0.50,	0.47	Partially cloudy	0.62,0.65	0.63	Clear sky	0.65,0.69	0.67	Clear sky
	K_{T12Hr}	0.60,0.70	0.65	Clear sky	0.69 ,0.70	0.69	Clear sky	0.67,0.77	0.72	Clear sky
	$K_{T\,18\,Hr}$	0.00,0.00	0.00	overcast	0.00,0.00	0.00	overcast	0.00,0.00	0.00	overcast
May ,June	K_{T06Hr}	0.55,0.59,	0.57	Partially cloudy	0.62, 0.59	0.61	Clear sky	0.67,0.60	0.63	Clear sky
	K_{T12Hr}	0.67,0.66	0.66	Clear sky	0.70, 0.69	0.69	Clear sky	0.72,0.70	0.71	Clear sky
	$K_{T\,18\,Hr}$	0.00,0.00	0.00	overcast	0.00,0.00	0.00	overcast	0.00,0.00	0.00	overcast

Table 2. Average monthly cloudiness index K$_D$ for months with relatively similar atmospheric and sky condition for (a) coastal and (b) sahelian stations

a) COASTAL		Port-Harcourt		Type of sky	Enugu		Type of sky	Akure		Type of sky
Dry Months		Value	Ave.		Value	Ave.		Value	Ave	
Dec, Jan	K$_{D06Hr}$	0.80,0.80	0.80	Bust/Hazy	0.80,0.80	0.80	Bust/Hazy	0.80,0.80	0.80	Bust/Hazy
	K$_{D06Hr}$	0.36,0.37	0.36		0.34,0.36	0.35		0.31,0.34	0.32	
	K$_{D12Hr}$	0.35,0.38	0.36		0.35, 0.34	0.34		0.35,0.36	0.35	
	K$_{D18 Hr}$	0.78,0.80	0.78		0.73,0.80	0.75		0.72, 0.80	0.75	
Average Daily	0.58				0.56			0.55		
Feb, March, November	K$_{D06Hr}$	0.80, 0.80,0.80	0.80	Partly hazy,	0.80, 0.80,0.80	0.80	Partly hazy,	0.80, 0.80,0.80	0.80	Partly hazy,
	K$_{D06Hr}$	0.41, 0.39,0.37	0.39	partly cloudy	0.35,0.35,0.333	0.35	partly cloudy	0.35.0.34,0.30	0.34	partly cloudy
	K$_{D12Hr}$	0.40, 0.39,0.36	0.38	and partly	0.39,0.38,0.34	0.38	and partly	0.39,0.37,0.32	0.38	and partly
	K$_{D18 Hr}$	0.80, 0.80,0.77	0.78	clear sky	0.80,0.78,0.73	0.79	clear sky	0.80,0.80, 0.73	0.80	clear sky
Average Daily	0.78				0.58			0.58		
April, May June, October	K$_{D06Hr}$	0.80, 0.80, 0.80, 0.80	0.80	Less cloudy	0.80, 0.80, 0.80,0.80	0.80	Less cloudy	0.80, 0.80, 0.80, 0.80	0.80	Less cloudy
	K$_{D06Hr}$	0.38, 0.36, 0.38, 0.39	0.37	sky	0.35, 0.34, 0.35, 0.37	0.35	sky	0.34, 0.36, 0.34,0.36	0.35	sky
	K$_{D12Hr}$	0.39, 0.43, 0.49, 0.49	0.45		0.38, 0.37,0.38	0.38		0.36, 0.36,0.37,0.37	0.37	
	K$_{D18 Hr}$	0.80, 0.80, 0.80,0.80	0.80		0.80,0.80, 0.80 0.80	0.80		0.80,0.80, 0.80 0.80	0.80	
Average Daily	0.60				0.58			0.58		
July , Aug, September	K$_{D06Hr}$	0.80, 0.80,0.80	0.80	Very cloudy	0.80, 0.80,0.80	0.80	Very cloudy	0.80, 0.80,0.80	0.80	Very cloudy
	K$_{D06Hr}$	0.34, 0.39,0.38	0.37	sky	0.35, 0.35,0.35	0.35	sky	0.36, 0.35,0.36	0.36	sky
	K$_{D12Hr}$	0.45, 0.49,0.46	0.46		0.36,0.38,0.36,	0.37		0.37,0.37,0.36	0.37	
	K$_{D18 Hr}$	0.79, 0.80 0.80	0.79		0.78, 0.80, 0.80,	0.79		0.79,0.80,0.80	0.80	
Average Daily	0.60				0.57			0.58		

b) SAHELIAN		Bauchi			Maiduguri			Kano		Type of sky
Dry Months		Value	Ave.		Value	Ave.		Value	Ave	
Dec, Jan	K$_{D06Hr}$	0.80,0.80	0.80	Dust/ hazy	0.80,0.80	0.80	Dust/ hazy	0.80,0.80	0.80	Dust/ hazy
	K$_{D06Hr}$	0.34,0.34	0.34		0.35,0.36,	0.34		0.34,0.34	0.34	
	K$_{D12Hr}$	0.33, 0.30	0.31		0.29, 0.30	0.29		0.32, 0.30	0.31	
	K$_{D18 Hr}$	0.80,0.80	0.80		0.80,0.80	0.80		0.72, 0.80	0.80	
Average Daily	0.56				0.55			0.56		
Feb, March, November	K$_{D06Hr}$	0.80, 0.80,0.80	0.80	Partly hazy,	0.80, 0.80,0.80	0.80	Partly hazy, partly	0.80, 0.80,0.80	0.80	Partly hazy,
	K$_{D06Hr}$	0.34,0.33,0.35	0.34	partly cloudy	0.34,0.33,0.32	0.34	cloudy and partly	0.32,0.33,0.30	0.32	partly cloudy
	K$_{D12Hr}$	0.32,0.30,0.32	0.33	and partly	0.32,0.34,0.28	0.34	clear sky	0.29,0.30,0.32	0.30	and partly
	K$_{D18 Hr}$	0.78, 0.80,0.78	0.78	clear sky	0.80,0.80,0.80	0.79		0.80,0.80, 0.80	0.80	clear sky
Average Daily	0.56				0.57			0.48		
April, May June, October	K$_{D06Hr}$	0.80, 0.80, 0.80, 0.80	0.80	Less cloudy	0.80, 0.80, 0.80,0.80	0.80	Less cloudy	0.80, 0.80, 0.80, 0.80	0.80	Less cloudy
	K$_{D06Hr}$	0.33,0.38,0.39,0.35	0.36		0.34,0.38,0. 38,0.34,	0.36		0.32,0.39,0.38,0.33,	0.35	

b) SAHELIAN		Bauchi			Maiduguri			Kano		Type of sky
Dry Months		Value	Ave.		Value	Ave.		Value	Ave	
	K_{D12Hr}	0.35,0.39,0.39,0.35	0.37		0.35,0.39,0. 37,0.35	0.36		0.30,0.38,0.39,0.35	0.35	
	$K_{D18\,Hr}$	0.80, 0.78, 0.80,0.80	0.80		0.80,0.80, 0.80, 0.80	0.80		0.80,0.80, 0.80 0.80	0.80	
Average Daily		0.58			0.58			0.58		
July , Aug, September	K_{D06Hr}	0.80, 0.80,0.80	0.80	Very Cloudy	0.80, 0.80,0.80	0.80	Very Cloudy	0.80, 0.80,0.80	0.80	Very Cloudy
	K_{D06Hr}	0.36,0.36,0.35,	0.36		0.36,0. 34,0.35	0.35		0.36,0.33,0.37	0.35	
	K_{D12Hr}	0.36,0.36,0.35	0.36		0.36,0. 34,0.35	0.35		0.36,0.33,0.36	0.35	
	$K_{D18\,Hr}$	0.77, 0.80 0.78	0.79		0.78, 0.80, 0.80,	0.79		0.79,0.80,0.80	0.80	
Average Daily		0.60			0.57			0.58		

Table 3. Values of parameter estimates β_1, β_2 and β_3 in the parabolic equation for K_T, for the selected months and for all the stations in the coastal and sahelian regions

Station	December					January					February				
	β1	β2	β3	R2	S.E	β1	β2	β3	R2	S.E	β1	β2	β3	R2	S.E
Akure	-0.008	0.138	-0.015	0.986	0.066	-0.009	0.164	-0.016	0.998	0.072	-0.010	0.174	-0.006	0.999	0.072
PH	-0.006	0.118	-0.009	0.993	0.040	-0.007	0.130	-0.009	0.994	0.039	-0.007	0.132	-0.009	0.995	0.039
Enugu	-0.007	0.127	-0.002	0.982	0.010	-0.009	0.156	-0.012	0.992	0.055	-0.009	0.164	-0.012	0.993	0.055
Bauchi	-0.010	0.181	-0.012	0.995	0.053	-0.010	0.183	-0.012	0.994	0.056	-0.010	0.189	-0.015	0.992	0.056
Maiduguri	-0.010	0.180	-0.022	0.981	0.099	-0.010	0.181	-0.021	0.982	0.096	-0.010	0.184	-0.019	0.986	0.096
Kano	-0.010	0.187	-0.016	0.991	0.070	-0.010	0.189	-0.017	0.990	0.076	-0.011	0.198	-0.024	0.982	0.065

Stations	July					August				
	β1	β2	β3	R2	S.E	β1	β2	β3	R2	S.E
Akure	-0.006	0.117	-0.029	0.925	0.129	-0.006	0.108	-0.032	0.895	0.143
PH	-0.004	0.082	-0.008	0.987	0.370	-0.004	0.079	-0.004	0.996	0.020
Enugu	-0.006	0.112	-0.025	0.940	0.110	-0.005	0.102	-0.029	0.902	0.131
Bauchi	-0.007	0.125	-0.025	0.951	0.11	-0.007	0.123	-0.027	0.938	0.123
Maiduguri	-0.007	0.137	0.017	0.981	0.075	-0.007	0.135	0.020	0.973	0.088
Kano	-0.007	0.137	-0.028	0.949	0.124	-0.007	0.135	-0.031	0.936	0.138

Table 4. Results of MBE and RMSE tests on measured and model predicted values of Clearness Index K_T for all the stations during (a) dry months of December, January and February (b) wet months of July and August

(A) Dry season monthsClearness Index K_T

Stations	December					January					February				
	Measured	Predicted	Residual	MBE	RMSE	Measured	Predicted	Residual	MBE	RMSE	Measured	Predicted	Residual	MBE	RMSE
Akure	0.59	0.48	0.11	0.11	0.0120	0.70	0.69	0.01	0.01	0.0001	0.70	0.58	0.12	0.12	0.0144
PH	0.49	0.46	0.03	0.07	0.0065	0.54	0.55	-0.01	0.01	0.0001	0.49	0.48	0.01	0.065	0.0073
Enugu	0.51	0.53	-0.02	0.04	0.0045	0.66	0.62	0.04	0.013	0.0006	0.69	0.68	0.01	0.047	0.0049
Bauchi	0.75	0.65	0.10	0.06	0.006	0.76	0.76	0.00	0.00	0.0001	0.79	0.68	0.11	0.068	0.00694
Maiduguri	0.78	0.76	0.02	0.05	0.0553	0.79	0.84	-0.04	-0.004	0.00051	0.80	0.70	0.10	0.0709	0.00667
Kano	0.78	0.76	0.02	0.05	0.0051	0.80	0.83	-0.03	-0.006	0.00054	0.81	0.77	0.04	0.0683	0.00625

(B) Wet season months					Clearness Index K_T				
Stations	July					August				
	Measured	Predicted	Residual	MBE	RMSE	Measured	Predicted	Residual	MBE	RMSE
Akure	0.55	0.53	0.02	0.02	0.0004	0.55	0.53	0.02	0.02	0.0004
PH	0.35	0.45	-0.1	-0.04	0.01	0.35	0.45	-0.1	-0.04	0.01
Enugu	0.53	0.52	0.01	0.023	0.0051	0.53	0.52	0.01	0.023	0.0051
Bauchi	0.58	0.56	0.02	0.001	0.0016	0.58	0.56	0.02	0.001	0.0016
Maiduguri	0.61	0.60	0.01	0.0001	0.0014	0.61	0.60	0.01	0.0001	0.0014
Kano	0.62	0.60	0.02	0.0001	0.0013	0.62	0.60	0.02	0.0001	0.0013

4. CONCLUSION

The synoptic hourly data of direct and diffuse solar radiation reanalyzed satellite data used for this study were obtained from the archives of National Centre for Environmental Prediction (NCEP) and National Centre for Atmospheric Research (NCAR). The data, whichcovers a period of 10 years (2005-2014) were obtained for six selected stations distributed evenly between coastal and sahelian regions of Nigeria. Result shows that global and diffuse irradiances' distribution gave two peaks in the sahelian region while only global irradiance shows similar characteristics in the coastal region. Diffuse radiation here, is almost uniform throughout the year. The sky conditions in the selected stations were characterized using clearness index and diffuse fraction. Estimations of average daily clearness index and diffuse fraction for all the selected stations and for the months of December, January and February representing dry seasons months together with those of July and August representing the rainy season period show thatsynoptic hourly distribution of clearness index K_T gave a single peak (maximum) during the day around 10-13 hrs where as diffuse fraction on the other hand, shows a minimum at that hour. This shows that while clearness index exhibits minimum at hours close to sunrise and sunset, reverse is the case for diffuse fraction. Result also shows that Akure receives more direct solar radiation than any of Enugu and Port Harcourt during the dry and rainy seasons. In general, direct solar radiation has been found to be mostly available in all the stations and at both seasons between hours of sunrise and sunset.

In the coastal stations, Port Harcourt exhibits partly cloudy condition in the morning and afternoon periods whereas in the evening period, sky condition is overcast. Akure and Enugu on the other hand exhibit clear sky condition in the morning and afternoon hours during the dry months. In the rainy months, partly cloudy and overcast condition prevails at all the stations.In the sahelian region and in the morning and afternoon hours, clear sky condition is prevalent at all the stations. Evening period is characterized with cloudy or overcast condition. Using Table 2, cloudiness index shows a decrease from the coast inland. Also, morning and evening hours, at all the stations, are characterized by high cloudiness index whereas in the afternoon period, the cloudiness is low (ranging between 0.33-0.49) at all the stations and regions all the year round. Analyses have shown that diffuse fraction for dust-hazy months range between 55 and 57%, for the set of partly cloudy, partly hazy and partly clear sky months, it ranges between 55 and 60% and the set of less cloudy, cloudy and wet months, it is between 58 and 61%. These values are closely related to what obtains in literature with the exception of the very cloudy months of July, August and September where values have been notably different from literature.

Using ANOVA method empirical equations have been obtained that useful in predicting clearness index at the selected locations at the coastal and sahelian regions. Considering the coefficient of determination, the MBE and RMSE values, the equations have performed well and at the various stations, will estimate clearness index to about 96% accuracy with mean uncertainty of about 7%.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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