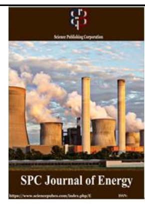
SPC Journal of Energy, 1 (1) (2018) 1-8

SPC Journal of Energy

Website: www.sciencepubco.com/index.php/E
doi: 10.14419/f.v1i1.9991
Research paper



Estimations of photosynthetically active radiation over different climatic zones in Nigeria

Nwokolo Samuel Chukwujindu [1] *, Ogbulezie Julie C. [1], Toge Christal Kabele [2], John-Jaja Sylvia Alwell [3]

[1] *Department of Physics, Faculty of Physical Sciences, University of Calabar, Calabar, Nigeria.*
[2] *Biotechnology Advanced Research Centre, Sheda Science and Technology Complex, Abuja, Nigeria*
[3] *Department of Agriculture, School of Science and Technology, Babcock University, Ilishan Remo, Nigeria.*
**Corresponding author E-mail: nwokolosc@stud.unical.edu.ng*

Abstract

This paper was designed to estimate and model the ratio of photosynthetically active radiation (PAR) to global solar radiation (SR) over different climatic zones in Nigeria in order to assess the feasibility of PAR/SR availability and utilization in agriculture, forestry and oceanography. The measured global solar radiation data was obtained from the Archives of the Nigerian Meteorological Agency, Oshodi, Lagos, over a period of thirteen years (2000-2012). Proven empirical models were used as a baseline for theoretical formulations and estimations of the ratio between PAR to SR over different climatic zones in Nigeria. From the estimated values, the mean ratio of PAR/SR in rainy season recorded 0.5067, 0.4863, 0.4906, 0.4740, 0.4574 and 0.4528 while the mean ratio of PAR/SR in dry season registered 0.4843, 0.4875, 0.4641, 0.4504, 0.4480 and 0.4482 with annual ratio of 0.4974, 0.4868, 0.4811, 0.4651, 0.4535 and 0.4509 for Port Harcourt, Enugu, Abeokuta, Ilorin, Bauchi and Sokoto respectively. The annual ratio of PAR/SR revealed that there is consistent increase in the ratios from North-West (Sokoto) to South-South (Port Harcourt). These variations were mainly due to apparent increase in cloudiness, aerosol particles and associated atmospheric moisture from the South-South to North-West with the apparent movement of the Hadley cell circulation system along the equatorial line form North-West to South-south. The models developed were found to estimate PAR/SR accurately from commonly available SR data and empirical model when tested with statistical indicators and compared with the results of researchers within and beyond tropical locations in Nigeria.

Keywords: *Atmospheric Parameters; Clearness Index; Climatic Zones; Modeling and Photosynthetically active Radiation.*

1. Introduction

Photosynthetically active radiation (PAR) designates the spectral range (wave band) of solar radiation from 400-700nm that photosynthetic organism are able to use in the process of photosynthesis. This spectral region corresponds more or less with the range of light visible to the human eye [1].

Photons at shorter wavelengths tend to be so energetic that they can be damaging to cells and tissues but are mostly filtered out by the ozone layer in the stratosphere while photons with longer wavelengths do not carry enough energy to allow photosynthesis to take place [1-4].

PAR plays an important role in providing energy to support photosynthetic processes that result in the conversion of radiation energy into chemical energy [5]. The accurate determination and clear understanding of the PAR fraction is required for many applications such as radiation forcing effect, energy management, hydrological process and biometeorology, crop production, remote sensing of vegetation, carbon cycle modeling and calculating the euphotic depth in the ocean [1], [6-9].

With the increasing requirement to better understand the Earth's climate systems in the face of global change, more observations of PAR are needed [10].

PAR varies from one geographical location to another. It is a function of the regional sky clearness, which depends on the cloud and aerosol amount; sky brightness, which depends upon the aerosol burden and cloud thickness, solar elevation angle and precipitable water, accounting for the absorption effects that are caused by the water vapour concentration [11-13].

Measurements of PAR have been performed in many parts of the world using a variety of techniques. These techniques have involved the use of Eppley precision spectral pyranometer (PSP), Li-COR quantum sensors (Li-190SZ) and PAR lite to mention but a few.

Unfortunately, a worldwide routine network for the measurement of PAR is not yet established [13]. To overcome these shortcomings, different estimation models have been proposed [14-16], some of them using satellite data [17-18]. In another approach, PAR is often calculated as a constant ratio of the broadband solar irradiance. Different authors have studied this ratio [12], [19-36].The spread of the ratio of photosynthetically active radiation to broadband solar radiation, as reported in these works, suggests the convenience of local calibration for the relationship between photosynthetic photon flux density and solar broadband radiation, to account for local climatic conditions [20]. In fact, many parameters are likely to affect this ratio, e.g. atmospheric pressure, solar elevation, turbidity and precipitable water. It is therefore imperative to develop a model from the existing models that will conveniently estimate the influence of atmospheric conditions on this ratio. This will produce amount of appreciated PAR data without the substantial cost of the instrumentation network that would otherwise be needed.

The aim of this paper, apart from developing empirical models for estimating the relationship between photosynthetically active radiations with global solar radiation using [12] empirical model over selected climatic zones in Nigeria, was to validate and recommend [12] model as a suitable and reliable meteorological model for estimating empirical ratio of PAR/SR in Nigeria and across the globe. Materials and methods

2.1. Data collection

The monthly mean daily global solar radiation used for this study was obtained from the Archives of the Nigeria Meteorological Agency, Oshodi, Lagos. The six cities (locations) studied lie on the latitude, longitude and altitudes of (Lat. 4.40°N, Long. 7.17°E and altitude 19.55m) for Port Harcourt; (Lat. 6.50°N, Long. 7.50°E and altitude 142m) for Enugu; (Lat. 07.05°N, Long. 3.32°E and altitude 66.14m) for Abeokuta; (Lat. 8.50°N, Long. 4.58°E and altitude 303.89m) for Ilorin; (Lat. 10.37°N, Long. 9.80°E and altitude 452m) for Bauchi and (Lat. 13.03°N, Long. 5.26°E and altitude 285.902m) for Sokoto respectively. The data obtained covered a period of thirteen years (2000-2012).

2.2. Model development

The study of the seasonal and hourly patterns of the ratio of photosynthetically active radiation and global solar radiation has revealed the variability of this ratio. For this reason, some atmospheric researchers [9, 12, 19, 20, 37-39] have searched out for a set of parameters that could appropriately describe the sky conditions influencing this ratio. The selected sky condition parameters known as the clearness index is given by [19], [39-40] as:

$$k_t = \frac{\bar{H}_m}{\bar{H}_0} \quad (1)$$

Where $\bar{H}_m$ is the measured monthly mean daily global solar radiation, $\bar{H}_0$ is the monthly mean extraterrestrial solar radiation on the horizontal surface, $\frac{\bar{H}_m}{\bar{H}_o}$ is the clearness index. The extraterrestrial solar radiation on the horizontal surface is given by [39, 40] as:

$$\bar{H}_0 = \frac{24}{\pi} I_{SC} E_o \left[\frac{\pi}{180} \omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s \right] \quad (2)$$

Where I_{SC} is the solar constant, E_o is the eccentricity correction factor, ϕ is the latitude of the location, δ is the solar declination and ω_s is the hour angle.

The expression for I_{SC}, E_o ϕ, δ and ω_s are given by the formulae [39], [40]

$$I_{sc} = \frac{1367 \times 3600}{1000000} (MJm^{-2}h^{-1}) \quad (3)$$

$$E_o = 1 + 0.033\cos\left(\frac{360N}{365}\right) \quad (4)$$

Where N is the characteristics day number for each month given by [39, 40] as shown in Table 1.

$$\delta = 23.45 Sin\left[\frac{360(N+284)}{365}\right] \quad (5)$$

$$\omega_s = Cos^{-1}(-\tan\phi\tan\delta) \quad (6)$$

Fig. 1: Map of Nigeria Showing Study Locations (Port Harcourt, Enugu, Abeokuta, Ilorin, Bauchi and Sokoto).

Table 1: Monthly mean daily values of global solar radiation in $MJm^{-2}day^{-1}$ $(\bar{H}_m)$, extraterrestrial solar radiation in $MJm^{-2}day^{-1}$ $(\bar{H}_o)$, clearness index $(\bar{k}_t)$, characteristic day number (N), ratio of observed and predicted photosynthetically active radiation and global solar radiation (PAR/SR) for Port Harcourt, Enugu, Abeokuta, Illorin, Sokoto and Bauchi (2000-2012)

Stations	Month	N	$\bar{H}_m$	$\bar{H}_0$	$\bar{k}_t$	$PAR/SR(obs)$	$PAR/SR(pred)$
Port Harcourt							
	JAN	17	18.60	34.46	0.5398	0.4680	0.4682
	FEB	45	19.12	36.21	0.5280	0.4709	0.4712
	MAR	74	17.49	37.52	0.4662	0.4836	0.4838
	APR	105	16.63	37.36	0.4451	0.4882	0.4886
	MAY	135	14.54	36.09	0.4029	0.4980	0.4983
	JUN	161	11.09	35.13	0.3157	0.5197	0.5199
	JUL	191	10.75	35.44	0.3033	0.5224	0.5231
	AUG	239	12.08	36.61	0.3300	0.5160	0.5127
	SEP	261	11.67	37.23	0.3135	0.5202	0.5204
	OCT	292	12.41	36.41	0.3408	0.5133	0.5134
	NOV	322	14.50	34.72	0.4176	0.4946	0.4949
	DEC	347	17.30	33.75	0.5126	0.4736	0.4738
Enugu							
	JAN	17	16.09	35.85	0.4492	0.4874	0.4880
	FEB	45	17.65	37.01	0.4769	0.4812	0.4820
	MAR	74	18.05	37.54	0.4808	0.4804	0.4811
	APR	105	18.56	36.44	0.5093	0.4743	0.4751
	MAY	135	17.93	34.41	0.5211	0.4719	0.4726
	JUN	161	15.59	33.15	0.4703	0.4827	0.4833
	JUL	191	14.23	34.85	0.4083	0.4968	0.4974
	AUG	239	14.37	35.47	0.4051	0.4976	0.4982
	SEP	261	15.24	36.95	0.4124	0.4959	0.4965
	OCT	292	14.58	37.73	0.3864	0.5020	0.5027
	NOV	322	17.29	35.83	0.4826	0.4800	0.4807
	DEC	347	16.46	35.22	0.4673	0.4833	0.4841
Abeokuta							
	JAN	17	19.87	35.35	0.5621	0.4570	0.4542
	FEB	45	20.28	35.43	0.5724	0.4615	0.4601
	MAR	74	20.72	37.24	0.5564	0.4646	0.4640
	APR	105	18.62	37.64	0.4947	0.4774	0.4780
	MAY	135	17.75	36.79	0.4825	0.4800	0.4814
	JUN	161	15.56	36.03	0.4319	0.4914	0.4925
	JUL	191	13.46	36.25	0.3713	0.5057	0.5047
	AUG	239	12.67	37.06	0.3419	0.5129	0.5103
	SEP	261	14.09	37.16	0.3792	0.5037	0.5032
	OCT	292	16.26	35.77	0.4544	0.4862	0.4877
	NOV	322	18.32	33.69	0.5438	0.4670	0.4643
	DEC	347	19.39	32.54	0.5959	0.4570	0.4542
Ilorin							
	JAN	17	20.62	32.12	0.6420	0.4485	0.4486
	FEB	45	21.59	34.54	0.6251	0.4515	0.4520
	MAR	74	23.01	36.89	0.6208	0.4523	0.4559
	APR	105	21.82	37.84	0.5766	0.4624	0.4614
	MAY	135	20.22	37.44	0.5518	0.4655	0.4663
	JUN	161	18.29	36.88	0.4959	0.4772	0.4713
	JUL	191	16.27	37.00	0.4397	0.4898	0.4884
	AUG	239	15.17	37.44	0.4052	0.4976	0.4953
	SEP	261	17.44	36.00	0.4844	0.4796	0.4795
	OCT	292	19.31	35.06	0.5508	0.4657	0.4665
	NOV	322	20.80	32.55	0.6393	0.4490	0.4433
	DEC	347	21.18	31.22	0.6784	.4421	0.4414
Sokoto							
	JAN	17	19.43	30.33	0.6406	0.4487	0.4492
	FEB	45	22.46	33.35	0.6741	0.4429	0.4438
	MAR	74	24.78	36.30	0.6832	0.4413	0.4419
	APR	105	25.71	37.98	0.6767	0.4424	0.4430
	MAY	135	25.46	38.15	0.6679	0.4439	0.4444
	JUN	161	24.06	37.84	0.6361	0.4495	0.4500
	JUL	191	22.11	37.84	0.5843	0.4591	0.4596
	AUG	239	19.83	37.82	0.5245	0.4771	0.4715
	SEP	261	21.46	36.69	0.5849	0.4590	0.4595
	OCT	292	20.83	34.07	0.6114	0.4540	0.4545
	NOV	322	20.61	31.08	0.6631	0.4447	0.4453
	DEC	347	19.08	29.55	0.6457	0.4477	0.4483
Bauchi							
	JAN	17	19.55	30.57	0.6394	0.4489	0.4489
	FEB	45	21.09	32.76	0.6438	0.4482	0.4481
	MAR	74	21.65	34.90	0.6204	0.4524	0.4523
	APR	105	22.99	38.45	0.5978	0.4565	0.4566
	MAY	135	24.06	39.18	0.6141	0.4535	0.4535
	JUN	161	23.36	38.01	0.6147	0.4534	0.4534
	JUL	191	20.89	37.21	0.5613	0.4636	0.4636
	AUG	239	21.72	38.29	0.5672	0.4625	0.4625
	SEP	261	22.65	38.92	0.5820	0.4596	0.4596
	OCT	292	23.36	36.98	0.6319	0.4502	0.4502
	NOV	322	21.44	32.86	0.6524	0.4466	0.4466
	DEC	347	19.25	29.56	0.6511	0.4468	0.4463

The average day length for each month was calculated using the expression by [39], [40], thus;

$$\bar{N} = \frac{2}{15} Cos^{-1}\left(-\tan\phi\tan\delta\right) \quad (7)$$

This was the basis for the model development of [12] model given as:

$$\frac{PAR}{SR} = 0.121{k_t}^2 - 0.334k_t + 0.613 \quad (8)$$

Where $\frac{PAR}{SR}$ is the ratio of photosynthetically active radiation to global solar radiation, k_t is the clearness index

To develop the models for estimating the ratio of photosynthetically active radiation to global solar radiation, PAR/SR, SPSS computer software was used to obtain various regression constants of the three parameters ($\frac{PAR}{SR}$, ${k_t}^2$ and k_t) evaluated using [12] model, and ${k_t}^2$ and k_t were calculated from ratio of global solar radiation to extraterrestrial solar radiation obtained using different sets of meteorological variables. Therefore, the sets of models developed for estimating PAR/SR ratio in the six climatic zones in Nigeria are given as:

Port Harcourt (South-South);

Model 1:

$$\frac{PAR}{SR} = 0.614 - 0.338k_t + 0.126{k_t}^2 \quad R = 0.999 \quad (9)$$

Enugu (South-East);

Model 2:

$$\frac{PAR}{SR} = 0.616 - 0.345k_t + 0.134{k_t}^2 \quad R = 0.999 \quad (10)$$

Abeokuta (South-West);

Model 3:

$$\frac{PAR}{SR} = 0.557 - 0.088k_t - 0.142{k_t}^2 \quad R = 0.997 \quad (11)$$

Ilorin (North-Central);

Model 4:

$$\frac{PAR}{SR} = 0.576 - 0.201k_t + 0.007{k_t}^2 \quad R = 0.992 \quad (12)$$

Sokoto (North-West);

Model 5:

$$\frac{PAR}{SR} = 0.616 - 0.343k_t + 0.129{k_t}^2 \quad R = 0.999 \quad (13)$$

Bauchi (North-East);

Model 6:

$$\frac{PAR}{SR} = 0.615 - 0.341k_t + 0.127{k_t}^2 \quad R = 0.999 \quad (14)$$

2. Results analysis

The calculated values of monthly mean global solar radiation $(\bar{H}_m)$, extraterrestrial solar radiation $(\bar{H}_o)$, clearness index $(\bar{k}_t)$, characteristic day number (N), observed and predicted ratio PAR/SR using [12] model and different sets of meteorological parameters over climatic zones in Nigeria are presented in Table 1 and shown in Figs. 2a -2g. The minimum values of the monthly mean PAR/SR ratio are 0.4682, 0.4726, 0.4542, 0.4414, 0.4463, 0.4438 for Port Harcourt, Enugu, Abeokuta, Ilorin, Bauchi and Sokoto respectively and they occur within the months of December, January, March and April. These values are within what is expected of a tropical site [41-42]. These months of occurrence are expected for Port Harcourt (January), Abeokuta (December), Ilorin (December) and Bauchi (December) because the harmattan season when aerosol mass loading, dry atmosphere and the presence of clear skies greatly reduces the intensity of PAR/SR [43-44]. But the months of occurrence for Enugu (April) and Sokoto (March) is not expected which could be attributed to prolonged dry seasons annually in the two locations. These minimum values obtained in this study are similar to 0.42-0.47 observed by [41]; for Ilorin, Nigeria; 0.43-0.45 reported by [45], for Lhasa, Tibet; 0. 46- 0.48 recorded by [24], USA; 0.41-0.46 reported by [46], for Anthen, Greece.

While the maximum values of the monthly mean PAR/SR ratio are 0.5231, 0.5027, 0.5103, 0.4953, 0.4636, 0.4715 for Port Harcourt, Enugu, Abeokuta, Ilorin, Bauchi and Sokoto respectively and they occur within the months of July, August, and October. According to [41-42] these months of occurrence is expected for of a tropical site for Port Harcourt (July), Abeokuta (August), Ilorin (August), Bauchi (July) and Sokoto (August) because they are characterized by heavy rainfalls, cloudy skies, absence of harmattan dust and presence of pyrogenic aerosols from regional biomass burning. But the months of occurrence for Enugu (October) is not expected. However it could be attributed to prolonged dry seasons annually in the location. These factors attenuate PAR/SR ratio through absorption by the precipitated water vapour and through reflection and absorption by clouds [43-44].

The mean monthly PAR/SR ratios are 0.4843, 0.4875, 0.4641, 0.4504, 0.4480 and 0.4482 for the dry season in Port Harcourt, Enugu, Abeokuta, Ilorin, Bauchi and Sokoto respectively. This is because, primarily, cloudiness conditions occur frequently during the dry season. This could be attributed to influence of the Inter-Tropical Convergence Zone (ITCZ), producing Tropical Continental (TC) associated with dry and dusty North-East winds (easterlie) which blow from the Sahara desert and finally prevail over Nigeria, thus producing the dry season conditions. These values are within the range of what is expected of a tropical site [41-42]. The range of values obtained is comparable to 0.42 - 0.47 reported by [41], Ilorin, Nigeria.

However, the mean monthly PAR/SR ratios of 0.5067, 0.4863, 0.4906, 0.4740, 0.4480 and 0.4528 for the rainy season for Port Harcourt, Enugu, Abeokuta, Ilorin, Bauchi and Sokoto respectively, are higher than the values for dry season because the absorption of solar radiation in the intend portion of the solar spectrum is enhanced whereas absorption in the PAR wavelength does not vary significantly. Thus an increase in the PAR/SR ratio under cloudy skies. Also, with the movement of the ITCZ into the Northern hemisphere, the rain-bearing South westerlies prevail as far inland as possible to bring rainfall during the rainy season. The implication is that there is a prolonged rainy season in the far South, while the far North undergoes long dry periods annually. These values are within the range of what is expected of a tropical site [41-42]. The range of values obtained is equally comparable to 0.42-0.47 reported by [41]. Ilorin, Nigeria.

The annual mean values of PAR/SR ratio of 0.4974, 0.4868, 0.4798,0.4647, 0.4535 and 0.4509 for Port Harcourt, Enugu, Abeokuta, Ilorin, Bauchi and Sokoto respectively in different locations under different climatic zones indicate an evidence increase from 0.4509 in Sokoto, North-West to 0.4974 in Port Harcourt, South-South. These evidence variations were mainly due to trends in cloudiness and associated atmospheric moisture with the movement of the Hadley cell circulation system along the equatorial line.

Researchers [12], [23], [28] reported that PAR/SR was greater than 0.6 under very cloudy skies. In this paper, PAR/SR predicted from Port Harcourt (South-South), Enugu (South-East) and Abeokuta (South-West) also recorded higher values up to 0.5 when clearness index had extremely low values between the months of June to October.

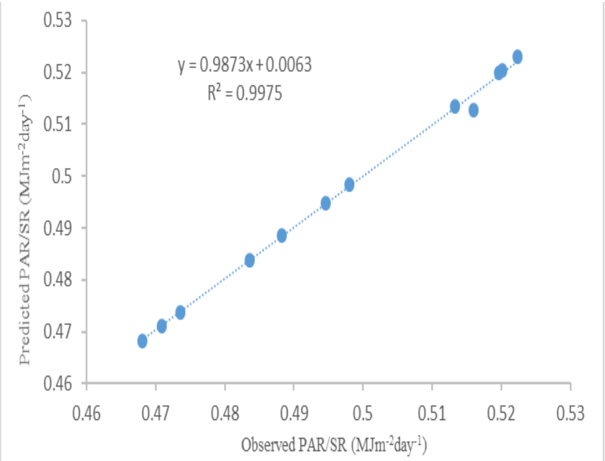


Fig. 2: Comparison between Predicted and Observed Par/Sr for Port Harcourt.

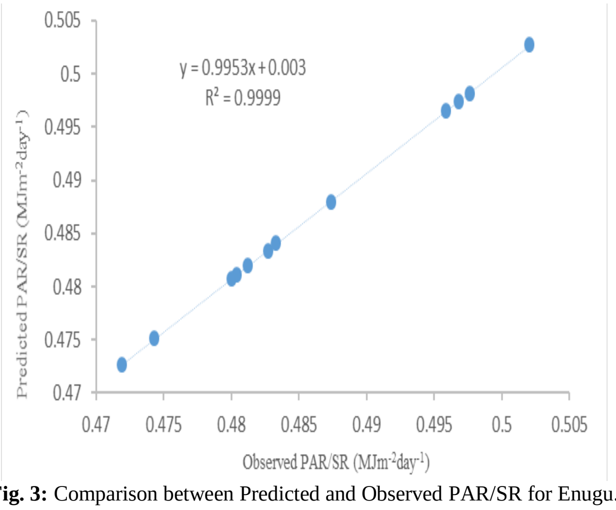


Fig. 3: Comparison between Predicted and Observed PAR/SR for Enugu.

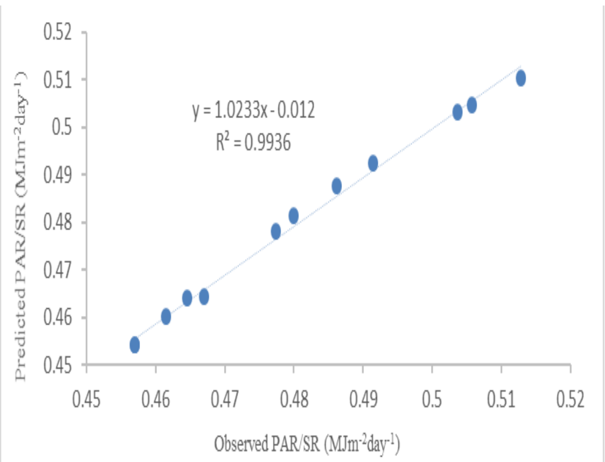


Fig. 4:.Comparison between Predicted and Observed PAR/SR for Abeokuta.

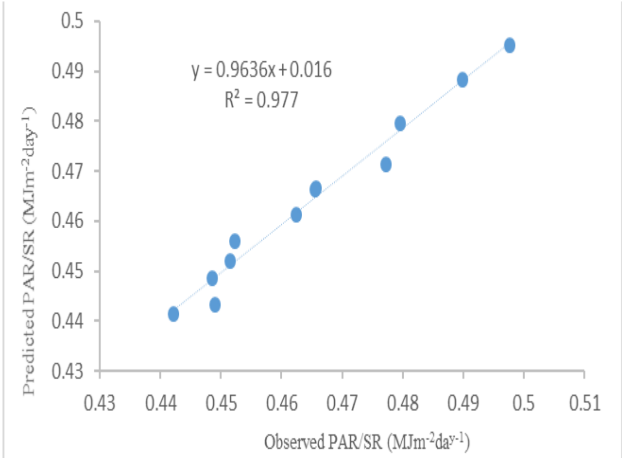


Fig. 6: Comparison between Predicted and Observed PAR/SR for Ilorin.

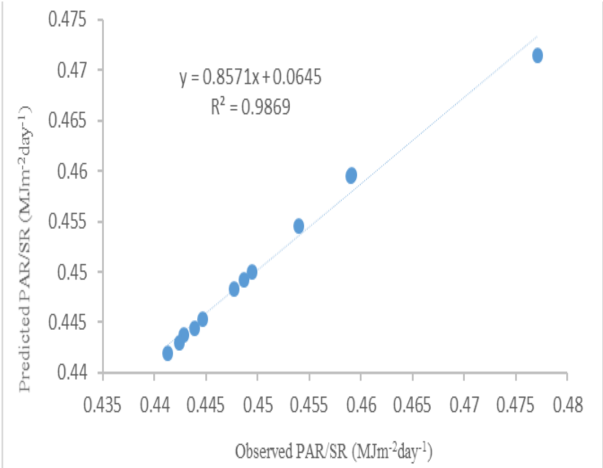


Fig. 8: Comparison between Predicted and Observed PAR/SR for Sokoto.

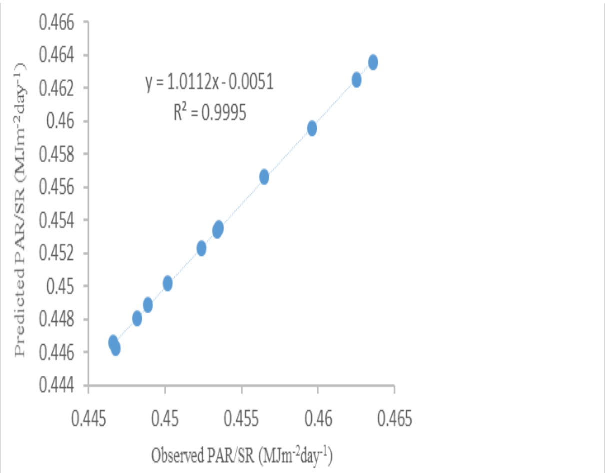


Fig. 5: Comparison between Predicted and Observed PAR/SR for Bauchi.

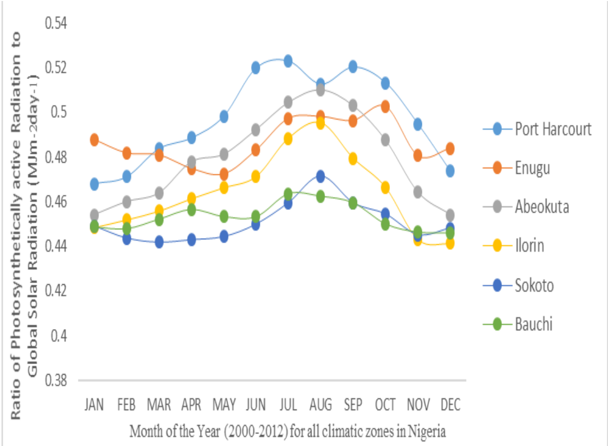


Fig. 7: Comparison between the Ratios of Predicted PAR/SR for Port Harcourt, Enugu, Abeokuta, Ilorin, Sokoto and Bauchi.

Table 2 contains summaries of various linear regression analysis obtained from the application of model 9-14 for various climatic zones in Nigeria.

The correlation coefficient (R) of 0.992 – 0.999 exist between the clearness index and monthly mean hourly ratio of PAR/SR indicating that there was high positive correlation between the observed and predicted values of ratio of PAR/SR. However, this range of values are comparable to 0.999 recorded in Spain by [13]; range of 0.998-0.999 reported by [47] in Spain and 0.998 registered by Tsubo and Walker [12] in Bloemfontein, South Africa. The values of coefficient of determination (R^2) ranged from 0.984 – 0.998 implying that 98.4% to 99.8% of clearness index can be accounted using ratio of PAR/SR. These values is in agreement with the record of 99.6% by [12] in Bloemfontein, South Africa; 99.8% registered by [13] in Spain as well as 99.6% to 99.8% reported by [47] in Spain. The estimated value of adjusted coefficient of determination of 0.981 – 0.996 from the models developed (9-14) shows they are fit for making generalization in any location in Nigeria and across the globe at large.

The range of values of the regressions constants (a = 0.557 to 0.616, b = -0.088 to -0.345 and c = -0.142 to 0.134) are found to be different from [12] who reported a = 0.121, b = -0.334 and c = 0.613 in Bloemfontein, South Africa. These differences suggest that regression coefficients are associated with the skies clearness and brightness which is a function of the clearness index within a location. [12] reported that PAR/SR was greater than 0.6 under very cloudy skies implying, as more cloudy skies were experienced in some locations, it causes the regression constant to vary from the record obtained in Nigeria where greatest value of PAR/SR was 0.5224 in Port Harcourt (South-South) which is the most cloudy location in this paper.

3. Model performance

We have analyzed the performance of the different models. The procedure followed consist of testing each model using multiple linear regression analyses between the observed and the predicted values of the radiometric fluxes. Table 2 shows the result obtained for the direct ratio model, including correlation coefficient R, slopes (b and c) and intercepts, a, of the linear regression of observed versus predicted ratio of photosynthetically active radiation to global solar radiation.

For the model validation, as recommended by [48], mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE), index of agreement (d), as well as χ^2 square and Nash-Sutcliff equation (NSE) as recommended by [49] were employed to determine the performance of the model for estimating the ratio PAR/SR for the selected locations in the six climatic zones in Nigeria as given in equations 15 - 20.

Table 2: Statistical Results for the Validation of the Models of the Ratio of Photosynthetically Active Radiation to Global Solar Radiation PAR/SR in Terms of Their Capability for Estimating the Photosynthetically Active Radiation for Sokoto, Bauchi, Ilorin, Abeokuta, Enugu and Port Harcourt (2000-2012)

Locations	a	b	c	R	R^2	Adjusted R^2
Port Harcourt Model 1	0.614	-0.338	0.126	0.999	0.998	0.996
Enugu Model 2	0.616	-0.345	0.134	0.999	0.998	0.996
Abeokuta Model 3	0.557	-0.088	-0.142	0.997	0.994	0.992
Ilorin Model 4	0.576	-0.201	0.004	0.992	0.984	0.981
Sokoto Model 5	0.616	-0.343	0.129	0.999	0.998	0.996
Bauchi Model 6	0.615	-0.341	0.127	0.999	0.998	0.996

Where R the coefficient of correlation of the linear regression of observed versus predicted ratio of photosynthetically active radiation to global solar radiation, R^2 is the coefficient of determination, adjusted $R^2$is the adjusted value coefficient of determination, a is the intercept, b and c are slope and all units are in $MJm^{-2}day^{-1}$.

$$MBE = \sum_{i=1}^{n}(O_i - P_i)/n \qquad (15)$$

$$MPE = \left[\sum_{i=1}^{n}\left(\frac{O_i - P_i}{O_i}\right)\times 100\right]/n \qquad 16)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(O_i - P_i)^2\right]^{1/2} \qquad (17)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{ave})^2} \qquad (18)$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{P_i} \qquad (19)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - O_{ave}| + |O_i - O_{ave}|)^2}\right] \qquad (20)$$

Where O_i represents summation of observed values of PAR/SR, P_i represents summation of predicted values of PAR/SR, O_{ave} represents average values of observed PAR/SR and other symbols retain their usual meaning.

A good observation of Table 3 shows a perfect harmony with the recommendation of [49-52] that MBE, RMSE and χ^2 square should be close to zero while R and NSE should be close to unity for better estimation. [53] Recommended low value of MPE for optimal performance while [54-56] have recommended that a zero value for MBE is ideal and a low RMSE is desirable. [12] Reported values close to unit for index of agreement (d). The performance of the models was equally tested with theoretical recommended values. Theoretically, PAR/SR is 0.4 because energy in the wavebands between 0.4 and 0.7 μm is 40% of the solar constant [21]. Substituting PAR/SR=1 into all the models recorded approximate value of 0.4 for Model 1, 2, 4, 5 and 6 except model 3 that recorded 0.33. These are in agreement with the theoretical

PAR/SR ratio of 40% and 0.40 registered by [12] in Bloemfontein, South Africa.

Table 3: Statistical Results for the Validation of the Models of the Ratio of Photosynthetically Active Radiation to Global Solar Radiation PAR/SR in Terms of Their Capability for Estimating the Photosynthetically Active Radiation for Sokoto, Bauchi, Ilorin, Abeokuta, Enugu and Port Harcourt (2000-2012)

Locations	NSE	MBE	RMSE	MPE	χ^2	d
Port Harcourt Model 1	0.999999991	0.000042	0.000144	0.000698	4.19×10^{-8}	0.9999999
Enugu Model 2	0.999997647	0.000683	0.002367	-0.011714	1.15×10^{-5}	0.9999994
Abeokuta Model 3	0.999998194	0.000708	0.054010	0.010264	8.76×10^{-6}	0.9999995
Ilorin Model 4	0.999999902	0.000133	0.000462	0.000239	4.49×10^{-7}	0.9999999
Sokoto Model 5	0.999998194	-0.000475	0.001645	-0.008789	6.01×10^{-6}	0.9999997
Bauchi Model 6	0.999999979	0.000058	0.000202	0.001071	9.09×10^{-8}	0.9999999

Where NSE is the Nash-Sutcliffe equation, MBE is the mean bias error, RMSE is root mean square error, MPE is the mean bias error, χ^2 is the chi square, d is the index of agreement and all units are in $MJm^{-2}day^{-1}$

4. Conclusion

Higher mean values of PAR/SR ratio were observed during rainy season with increasing sequence from North-West to South-South climatic zones while in dry season, the mean values were lower with increasing sequence from South-South to North-West climate zones. This evidence variation is due to the movement of the ITCZ into the Northern hemisphere, the rain-bearing South westerlies prevail as far inland as possible to bring rainfall during the rainy season. This result in prolonged rainy season in the far South, while the far North undergoes long dry period's annually. The average annual values of PAR/SR ratio equally increased from North-West to South-South climatic zones. These variations were mainly due to trends in cloudiness and associated with atmospheric moisture with the movement of the Hadley cell circulation system along the equatorial line. As observed PAR is however, not measured at standard weather stations but solar radiation (SR) is often observed in Nigeria, it becomes imperative for us to develop a set of models for estimating the ratio of PAR/SR and PAR from SR data with their corresponding extraterrestrial solar radiation calculated values. Therefore, the proposed sets of models in this paper can be used to estimate both the ratio of PAR/SR and PAR in any location within Nigeria and across this continent since this study revealed that the ratio of PAR/SR relationship were similar in all the climatic zones in Nigeria.

5. Competing interests

Authors have declared that no competing interests exist.

References

[1] McCree K. Test of current definitions of photosynthetically active radiation against leaf photosynthesis data. Agric Meteorol 1972b; 10:443–453. https://doi.org/10.1016/0002-1571(72)90045-3.

[2] McCree LJ. The active spectrum absorption and quantum yield of photosynthesis in crop plants. Agricultural and Forestry, Meteorology. 1972a; 9:191-216. https://doi.org/10.1016/0002-1571(71)90022-7.

[3] McCree KJ. Photosynthetically active radiation In: Encyclopedia of plant physiology, Springer-Verlag, Berlin, 1981; Pp. 41-55 https://doi.org/10.1007/978-3-642-68090-8_3.

[4] Gates DM. Biophysical Ecology, Springer-Verlag, New York, 1980; Pp. 611. https://doi.org/10.1007/978-1-4612-6024-0.

[5] Wortman E, Tomaszewski T, Waldner P, Schleppi P. Atmospheric nitrogen deposition and canopy retention influences on photosynthetic performance at two high nitrogen deposition Swiss forests. Tellus B 2012; 64:17216. https://doi.org/10.3402/tellusb.v64i0.17216.

[6] Loutzenhiser PG., Manz H, Felsmann C, Strachan PA, Frank T. Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation. Sol Energ 2007; 81:254–267. https://doi.org/10.1016/j.solener.2006.03.009.

[7] Hoyle CR, Myher G, Isaksen I. Present-day contribution of anthropogenic emissions from China to the global burden and radiative forcing of aerosol and ozone. Tellus B 2009; 61:618–624. https://doi.org/10.1111/j.1600-0889.2009.00424.x.

[8] Frouin R, Pinker RT. Estimating photosynthetically active radiation (PAR) at the earth's surface from satellite observations. Remote Sens Environ 1995; 51:98–107. https://doi.org/10.1016/0034-4257(94)00068-X.

[9] Wang LC, Gong W, Ma YY, Zhang M. Modeling regional vegetation NPP variations and their relationships with climatic parameters in Wuhan, China. Earth Interact, International of Physical sciences, 2013; 88(3):1–20.

[10] Clay GD. Worrall F, Rose R. Carbon budgets of an upland blanket bog managed by prescribed fire. J Geophys Res 115: G04037, pp. 2010; 225-234.

[11] Gonzalez JA, Calbo J. Modeled and measured ratio of PAR to global radiation under cloudless skies. Agric For Meteorol 2002; 110:319–325 https://doi.org/10.1016/S0168-1923(01)00291-X.

[12] Tsubo M, Walker S. Relationships between photosynthetically active radiation and clearness index at Bloemfontein, South Africa. Theor ApplClimatol., 2005; 80:17–25 https://doi.org/10.1007/s00704-004-0080-5.

[13] Alados I, Moreno IF, Arboledas LA. Photosynthetically active radiation: measurements and modelling. Agric Fores. Meteorol 1996; l78:121–131

[14] Gueymard C. An atmospheric transmittance model for the clear sky beam, diffuse and global photosynthetically active radiation. Agric. For. Meteorol, 1989a; 45: 215-229. https://doi.org/10.1016/0168-1923(89)90045-2.

[15] Gueymard C. A two-band model for the calculation of clear sky solar irradiance, illuminance, and photosynthetically-active radiation at the Earth's surface. Solar Energy. 1989b; 43: 253-265. https://doi.org/10.1016/0038-092X(89)90113-8.

[16] Olseth JA, Skartveit A. Luminous efficacy models and their application for calculation of photosynthetically-active radiation. Solar Energy, 1993; 52: 391-399.

[17] Eck TF, Dye DG. Satellite estimation of incident photosynthetically-active radiation using ultraviolet reflectance. Remote Sens. Environ. 1991; 38: 135-146. https://doi.org/10.1016/0034-4257(91)90075-H.

[18] Pinker RT, Laszlo I. Global distribution of photosynthetically-active radiation as observed from satellites, J. Climate, 1992; 5: 56-65. https://doi.org/10.1175/1520-0442(1992)005<0056:GDOPAR>2.0.CO;2.

[19] Li R, Zhao L, Ding YJ. Monthly ratios of PAR to global solar radiation measured at northern Tibetan Plateau, China. Sol. Energ. 2010; 84: 964–973. https://doi.org/10.1016/j.solener.2010.03.005.

[20] Jacovides CP, Timvios FS, Papaionanuou G, Asimakopoulos DN, Theofilou CM. Ratio of PAR to Broadband solar radiation measured in cyprous. Agric and For Meteoro. 2004; 121: 135-140 https://doi.org/10.1016/j.agrformet.2003.10.001.

[21] Moon P. Proposed standard solar radiation curves for engineering use. J. Franklin Inst., 1940; 230: 583-618. https://doi.org/10.1016/S0016-0032(40)90364-7.

[22] Yocum CS, Allen, LH, Lemon ER. Photosynthesis under field conditions, Part VI: Solar radiation balance and photosynthetic efficiency. Agron. J., 1969; 56:249-253 https://doi.org/10.2134/agronj1964.00021962005600030001x.

[23] McCree KJ. A solarimeter for measuring photosynthetically-active radiation. Agric. Meteorol., 1966; 3: 189-202. https://doi.org/10.1016/0002-1571(66)90017-3.

[24] Britton CM, Dodd JD. Relationships of photosynthetically-active radiation and shortwave irradiance. Agric. Meteorol., 1976; 17: 1-7. https://doi.org/10.1016/0002-1571(76)90080-7.

[25] McCartney HA. Spectral distribution of solar radiation. Part II: Global and diffuse. Q. J. R. Meteorol. 1978; 33: 89-98.

[26] Ross J. The radiation regime and architecture of plant stands. W. Junk, The Hague. Soc., 1981; 104:911-926.

[27] Stigter CJ, Musabilha MM. The conservative ratio of photosynthetically-active to total radiation in the tropics. J. Appl. Ecol., 1982; 19: 853-858. https://doi.org/10.2307/2403287.
[28] Rodskjer N. Special daily insolation at Uppsala, Sweden. Arch. Meteorol. Geophys. Bioclim., Ser. B, 1983; Pp. 353-366.
[29] Howell TA., Meek DW. Hatfield JL. Relationship of photosynthetically active radiation to shortwave radiation in the San Joaquin Valley. Agric For Meteorol 1983; 28:157–175 https://doi.org/10.1016/0002-1571(83)90005-5.
[30] Rao CR. Photosynthetically-active components of global solar radiation: Measurements and model computations. Arch. Meteorol. Geophys. Bioclim., Set. B, 1984; 33: 89-98.
[31] Karalis JD. Characteristics of direct photosynthetically-active radiation. Agric. For. Meteorol., 1989; 48: 406–415 https://doi.org/10.1016/0168-1923(89)90070-1.
[32] Papaioannou G, Papanikolaou N, Retails D. Relationships of photosynthetically-active radiation and shortwave irradiance. Theor. Appl. Climatol., 1993; 48: 23-27. https://doi.org/10.1007/BF00864910.
[33] Gunn R, Wang LC., Lin AW, Zhang M. Evaluating the monthly and interannual variation of net primary production in response to climate in Wuhan during 2001 to 2010. Solar Energy 1969; 13:347–355
[34] Gunn R, Ineichen P, Seals R, Michalsky J. Modeling daylight availability and irradiance components from direct and global irradiance. Solar Energy 1951; 2:271–289
[35] Pereira H C. Practical field instruments for the estimation of radiation and evaporation, Meteorology. Sci. 1959; 85:253-261.
[36] Cheng SJ, Bohrer G, Steiner, AL, Hollinger DY, Suyker A, Philips RP, Nadelhoffer KJ. Variations in the influence of diffuse light on gross primary productivity in temperate ecosystems. Agricultural and Forest Meteorology 2015; 201: 98-110 https://doi.org/10.1016/j.agrformet.2014.11.002.
[37] Cruse MJ, Kncharik CJ, Norman JM. Using a simple apparatus to measure direct and diffuse Photosynthetically active radiation at remote location. PLOS ONE 10 (2): 2015. e0115633. doi:101371/journal.pone.0115633.
[38] Iqbal M. An introduction to solar radiation. Academy press. New York. 1983; pp. 6-51.
[39] Bulent Y, Yasin AG, Establishing new model for predicting the global solar radiation in horizontal surface. International Journal of Hydrogen Energy. 2015; 40: 15278-15283. https://doi.org/10.1016/j.ijhydene.2015.02.064.
[40] Udo SO, Aro TO. Global PAR related to global solar radiation for Central Nigeria. Agric For Meteorol 1999; 97:21–31. https://doi.org/10.1016/S0168-1923(99)00055-6.
[41] Miskolczi F, Aro M, Pinker RT. Surface radiation fluxes in sub Sahel Africa. Journal of Applied Meteorology. 1997; 36:521-530. https://doi.org/10.1175/1520-0450(1997)036<0521:SRFISS>2.0.CO;2.
[42] Babatunde EB, Aro TO. Characteristics Variation of total solar radiation at llorin, Nigeria. Nig. J. Sol. Energy 2001; 9: 157 - 173.
[43] Babatunde EB. Solar radiation modeling for a tropical station, llorin, Nigeria. Ph.D thesis pp. 2001; 32-34.
[44] Papaioannou G, Nikolidakis G, Asimakopoulos D, Retalis D. Photosynthetically active radiation in Athens. Agric for Meteorol 1996; 81:287–298. https://doi.org/10.1016/0168-1923(95)02290-2.
[45] Zhang X, Zhang Y, Zhao Y. Measuring and modeling photosynthetically active radiation in Tibetan Plateau during April–October. Agric For. Meteorol. 2000; 102:207–212. https://doi.org/10.1016/S0168-1923(00)00093-9.
[46] Alados I, Arboledas LA. Validation of an empirical model for photosynthetically active radiation. Int J Climatol 1999; 19:1145–1152 https://doi.org/10.1002/(SICI)1097-0088(199908)19:10<1145::AID-JOC428>3.0.CO;2-3.
[47] Willmott CJ. On the validation of models. Phys. Geogr., 1981; 2: 184-194.
[48] Adukunle AO, Emmanuel CO. Correlation of global solar irradiance with some meteorological parameters and validation of some existing solar radiation models with measured data over selected climatic zones in Nigeria. International Journal for Innovation Education and Research. 2014; 2: 1-7.
[49] Ituen EE., Esen NU., Nwokolo SC, Udo EG. Prediction of global solar radiation using relative humidity, maximum temperature and sunshine hours in Uyo, in the Niger Delta Region, Nigeria. Advances in Applied Science Research, 2012; 3(4): 1923-1937.
[50] Etuk ES, Nwokolo SC, Okechukwu AE, John-Jaja SA. Analysis of Photosynthetically active radiation over six tropical ecological zones in Nigeria. Journal of Geography, Environment and Earth Science International. 2016; 7: 1 – 15. https://doi.org/10.9734/JGEESI/2016/27945.
[51] Etuk ES, Okechukwu AE,Nwokolo SC. Modelling and estimating Photosynthetically active radiation from global solar radiation at Calabar, Nigeria. Physical Science International Journal. 2016; 12: 1-12.
[52] Akpabio LE, Etuk SE. Relationship between solar radiation and sunshine duration for Onne Nigeria., Turkish J. Phys. 2002; 27: 161 - 167.
[53] Halouani M, Nguyen CT, VoNgoc D. Calculation of monthly average global solar radiation on horizontal surfaces using Daily Hours of Bright Sunshine, Solar energy 1993; 50: 247-255. https://doi.org/10.1016/0038-092X(93)90018-J.
[54] Che HZ, Shi GY, Zhang XY, Zhao JQ, Li Y. Analysis of sky condition using 40 years records of solar radiation data in China. Theoretical and applied climatology 2007; 89: 83 - 94. https://doi.org/10.1007/s00704-006-0258-0.
[55] Almorox J, Benito M, Hontoria C. Estimating of Monthly Angstrom – Prescott equation coefficients from measured daily data in Toledo, Spain. Renewable Energy J., 2005; 30: 931 – 936. https://doi.org/10.1016/j.renene.2004.08.002.