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Variation of the Earth's Irradiance over Some Selected Towns in Nigeria

F. O. Aweda[1]*, J. A. Oyewole[1], J. B. Fashae[1], T. K. Samson[2]

[1] *Physics and Solar Energy Programme, College of Agriculture, Engineering and Science, Bowen University, Iwo, Osun State, Nigeria*
[2] *Statistics Programme, College of Agriculture, Engineering and Science, Bowen University, Iwo, Osun State, Nigeria*

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ABSTRACT

The extraterrestrial radiation is the solar radiation received at the top of the earth's atmosphere on horizontal surface. This quantity over selected stations in the tropics was investigated. Daily data of the extraterrestrial radiation on the earth horizontal surface for the year 2018 for stations: Iwo, Abuja, Enugu, Port-Harcourt, Sokoto and Maiduguri obtained from the archive of HelioClim website were analyzed using MATLAB and Statistical Packages for Social Science (SPSS Version 20.0) to estimate the extraterrestrial radiation of the station considered. The results of the MATLAB revealed that the value of the coincidence is $-2\times10^4\ Wm^{-2}$ across all stations. In January, the values between 15 - 20 peaks were observed in the year with the Irradiation ($-4\times10^4\ Wm^{-2}$) and the maximum ($2\times10^4\ Wm^{-2}$). The results revealed the Root Mean Square Error RMSE for Sokoto (139.99), Abuja (162.72), Iwo (177.07), Maiduguri (171.34), Enugu (191.07), Port-Harcourt (212.27). The results also revealed that quadratic trend equation which accounted in the range 95.9% - 41.9%. The results then concluded that Sokoto and Maiduguri have the highest solar Irradiance as revealed by the result.

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INTRODUCTION

Surface energy balance is the combination of the net radiation to or from the surface, the sensible (i.e direct) and the latent (i,e indirect) heat flux to or from the atmosphere, and the heat fluxes into or out of the sub-medium. Anthropogenic activities taking place on the surface of the earth has contributed significantly to the energy balance of the atmosphere. This solar radiation leads to the transportation and exchange of matters at the interface between the earth surface and the atmosphere which contribute to the climate change [1]. The more the solar radiation, the more the evaporation of water molecules [2]. However, this climate change brings about morbidity to the living and non-living things on the surface of the earth. The extraterrestrial radiation, which is the solar radiation received at the top of the earth's atmosphere on a horizontal surface can be singled out to see it variation latitudinally and temporally [3]. Extraterrestrial radiation is known to be affected by the change in the sun-earth distances and as such, the values of this parameter changing with time, latitude and season [4]. The general equation that models extraterrestrial radiation is employed in this research to investigate how well it simulates the actual extraterrestrial radiation in the tropics. Several works have been done on the estimation of the earth's albedo globally but special attention is given to extraterrestrial radiation component of global radiation in this work. Mohandes, et al. [5]; Trajekovic, et al. [6]; Reddy and Ranjan [7] have used Artificial Neural Network (IA) Technique to estimate the solar radiation. As reported by Aweda et al. [8], seasonal effect on evaporation rate occurs as a result of the dry or wet temperature of the environment. The technical modelling approaches along with up performance of the fabricated solar systems for photovoltaic solar power generation and visible solar irradiation were extensively discussed in literature [9–12]. Babar and Bostrom [13] state that, owing to constraints all over the world, solar radiation equipment is not installed at any weather stations, but for the betterment of research, an internet data or satellite data can perform the same function with the installed equipment data.

The stations considered in this research are Iwo, Ilorin, Abuja, Enugu, Port-Harcourt, Sokoto and Maiduguri (all in Nigeria). The objectives of this research are: (1) comparative analysis of the modeled extraterrestrial and the actual values in prediction of the extraterrestrial radiation (2) significance of the coincidence of the estimated and the observed extraterrestrial radiation.

*Corresponding Author E-mail: francisaweda4@gmail.com (F. O. Aweda)

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METHODOLOGY

Data collection

The daily data of the extraterrestrial radiation (H_o) of the earth horizontal surface for the year 2018 for six stations (Iwo, Abuja, Enugu, Port-Harcourt, Sokoto and Maiduguri), located in Nigeria were collected from the archive of HelioClim website of soda (http://www.soda-pro.com) of MERRA-2 meteorological re-analysis. The data of twelve months (12) spanning from January to December 2018 were obtained as monthly average in Comma Separated Value (CSV) data format. Environmental running of MATLAB and statistical packages was done on the data for data plotting, curve fittings and other statistical analysis. These stations are spread over Nigeria. The assessment of the data was done on the 27th May, 2019 at about 8:51pm local time of Nigeria [9].

Extraterrestrial radiation modelling

The solar energy conservation requires radiation incident, short wave balancing at the edge of the atmosphere as reported by Audu and Isikwue [3].

$$\frac{H_v}{H_o} + \frac{H_u}{H_o} + \frac{H_k}{H_o} = 1 \quad (1)$$

where H_u is the global solar radiation and $\frac{H_v}{H_o}$ is called clearness index, which is also the ratio of the global to the extraterrestrial radiation transmitted through the atmosphere to the ground surface. Barka et al. [14] H_u is the absorbed solar radiation and $\frac{H_u}{H_o}$ is the fraction absorbed radiation, called the absorption coefficient or absorbance. H_k is the extraterrestrial radiation towards the space. H_o is the extraterrestrial radiation incident on the surface of the earth at the edge of the Earth's atmosphere. According to Babatunde et al. [15], H_u has found very small compared to others ratios. Therefore, the equation becomes

$$\frac{H_v}{H_o} + \frac{H_k}{H_o} \cong 1 \quad (2)$$

However, the reflectivity or albedo can be estimated using

$$\frac{H_k}{H_o} = 1 - \frac{H_v}{H_o} \quad (3)$$

But for this research, the extraterrestrial radiation employed was gotten from the Iqbal [16] which is:

$$H_0 = \frac{24}{\pi} I_{sc} E_0 \left(\frac{\pi}{180} W_s sin\emptyset sin\delta + cos\emptyset cos\delta cos W_s\right) \quad (4)$$

where

$$W_s = \cos^{-1}(-tan\emptyset tan\delta) \quad (5)$$

$\emptyset$ *and* δ are the latitude and declination angle respectively, while the solar constant I_{sc} is 1367 Wm^{-2}, W_s sunset hour angle [rad].

$$\delta = (0.006918 - 0.399912\cos\Gamma + 0.070257\sin\Gamma - 0.006758\cos 2\Gamma + 0.000907\sin 2\Gamma - 0.002697\cos 3\Gamma + 0.00148\sin 3\Gamma)\left(\frac{180}{\pi}\right) \quad (6)$$

However, this equation estimates δ with a maximum error of 0.0006 rad (< 3) or, if the final two terms are omitted, with a maximum error of 0.0035 rad Iqbal [15]. This expression gives the approximate values of solar declination with varying degrees of accuracy which was developed by Spencer [17]

$$E_0 = \left(\frac{r_0}{r}\right)^2 = 1.000110 + 0.034221\cos\Gamma + 0.00128\sin\Gamma + 0.00719\cos 2\Gamma + 0.000077\sin 2\Gamma \quad (7)$$

Γ is called the day angle (radians), where r is the sun-earth distance and r_0 is called one astronomical unit: $1\text{AU} = 1.496 \times 10^8$ km.

$$\Gamma = 2\pi(d_n - 1)/365 \quad (8)$$

d_n is the day number of the year, ranging from 1 on January to 365 on December. February is always assumed to have 28 days; because of the leap year cycles. However, it is more desirable to have the distance expressed in a simple mathematical form as shown in those equation above. For this reason, a number of mathematical expressions of varying complexities are available for the solution of Earth's albedo Iqbal [16]. Traditionally, the distance r is expressed in terms of a Fourier Series Expansion with a number of coefficients. This have a maximum error of 0.0001, but Spencer [17] developed the reciprocal of the square of the radius vector of the earth as shown in Equation (7) which is called the Eccentricity Correction Factor of the Earth's Orbit Iqbal [16].

Statistical analysis model

This study adopted the quadratic trend to estimate the irradiance in six locations (Sokoto, Abuja, Enugu, Iwo, Maiduguri and Port-Harcourt) in Nigeria. The quadratic trend equation is given as:

$$I_t = \beta_0 + \beta_1 t + \beta_2 t^2 + e_t \quad (9)$$

where, I_t is the irradiance at the time t and t is the time, t =1, 2, …., 365, e_t is the error term.

The normal equation for the quadratic trend in Equation (9) is given as:

$$\begin{aligned} \sum_{t=1}^{n} I_t &= n\beta_0 + \beta_1 \sum_{t=1}^{n} t + \beta_2 \sum_{t=1}^{n} t^2 \\ \sum_{t=1}^{n} tI_t &= \beta_0 \sum_{t=1}^{n} t + \beta_1 \sum_{t=1}^{n} t^2 + \beta_2 \sum_{t=1}^{n} t^3 \\ \sum_{t=1}^{n} t^2 I_t &= \beta_0 \sum_{t=1}^{n} t^2 + \beta_1 \sum_{t=1}^{n} t^3 + \beta_2 \sum_{t=1}^{n} t^4 \end{aligned} \quad (10)$$

In matrix form, the systems of equations in Equation (10) can be written as:

$$\begin{bmatrix} \sum_{t=1}^{n} I_t \\ \sum_{t=1}^{n} tI_t \\ \sum_{t=1}^{n} t^2 I_t \end{bmatrix} = \begin{bmatrix} n & \sum_{t=1}^{n} t & \sum_{t=1}^{n} t^2 \\ \sum_{t=1}^{n} t & \sum_{t=1}^{n} t^2 & \sum_{t=1}^{n} t^3 \\ \sum_{t=1}^{n} t^2 & \sum_{t=1}^{n} t^3 & \sum_{t=1}^{n} t^4 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \end{bmatrix} \quad (11)$$

$$\beta = (t^1 t)^{-1} t^1 Y_t, \quad \beta = \begin{pmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \end{pmatrix} \quad (12)$$

The parameters of the quadratic trend equation for irradiance in each of the six locations considered were estimated using the Statistical Package for Social Sciences (SPSS Version 20.0). The F- statistic was used to determine the significance of the quadratic trend equation while the p-values of the t- statistic was used to the significance of each of the term in the trend equation. The extent to which time accounted for the variation in irradiance was determined using the coefficient of determination (R^2) while the forecasting performance of the trend equation was determined using the Root Mean Square Error (RMSE) given by:

$$RMSE = \sqrt{\sum_{t=1}^{n} \frac{(I_{t\,(actual)} - I_{t\,(predicted)})^2}{n}} \quad (13)$$

RESULTS AND DISCUSSION

The radiation of the solar attenuation across the earth surface

The Irradiation for both the estimated and the observed values agreed at the middle of the month i.e. January for all the stations considered except for station Enugu that shift a little to around 20th of January. The results revealed that the value of the coincidence is $-2 \times 10^4 Wm^{-2}$ across all the stations, except that of Enugu which occurred on the 20th day of the month (see Figure 1). This is in line with the fact that extraterrestrial radiation is determined not only by latitude and time of the day but also on the date of the month [18].

Figure 1 revealed that Maiduguri had its peak around the following days (1, 2, 3, 29, 30 and 31) in January 2018. With the minimum between (15–20) in the year considered, with the irradiation ($-4 \times 10^4 Wm^{-2}$) and the maximum is above the $2 \times 10^4 Wm^{-2}$. For the observed value, it was noticed that the low ebb at the beginning of the month (January) rose to its maximum on the 31st of January 2018, with the value 300 Wm^{-2}

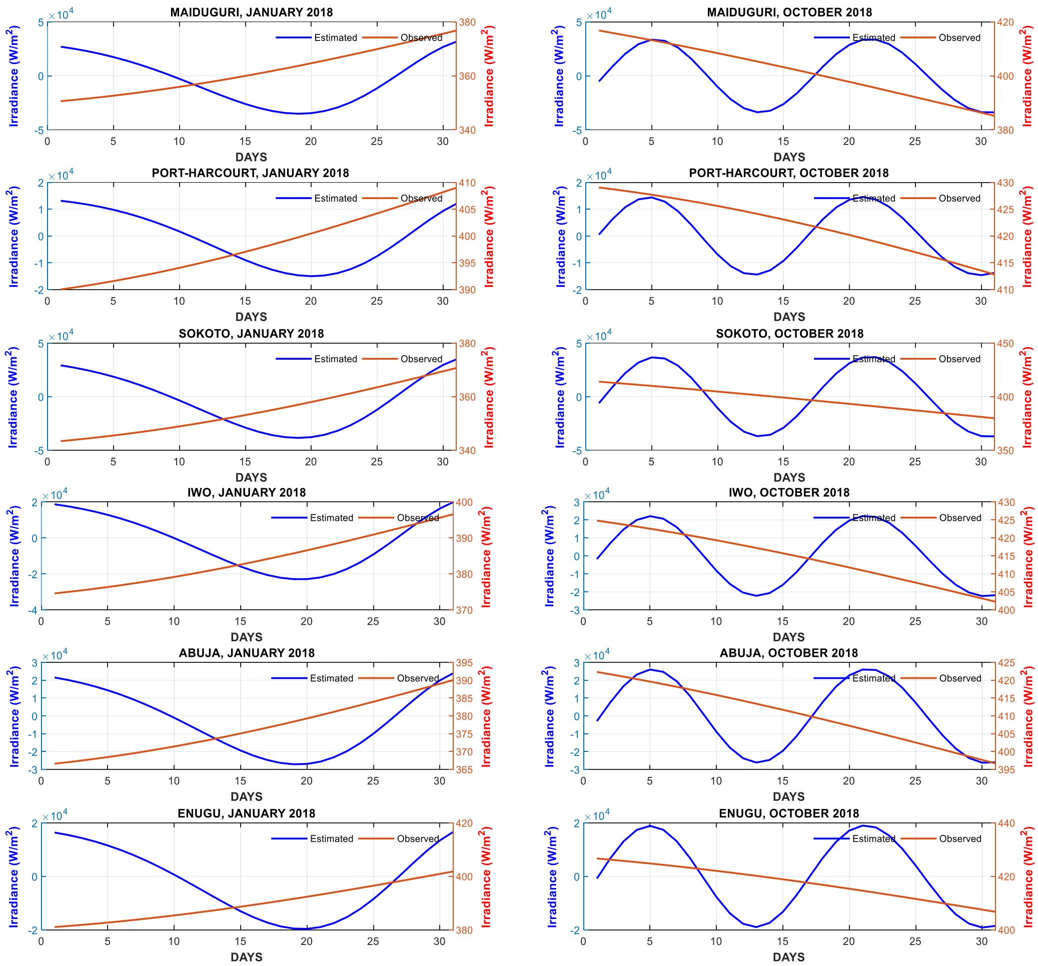


Figure 1. Variation of the coincidence point of the estimate and observed values of extraterrestrial radiation for January and October

(same for Port-Harcourt, Sokoto, Maiduguri and Abuja) except for Iwo that had a little variation of the $375\,Wm^{-2}$. For the estimated, it was observed that the values have the same pattern all through the stations observed with minimum value at the middle of the month range from $-3.5 \times 10^4 Wm^{-2}$ to $2.0 \times 10^4 Wm^{-2}$ for all the stations considered. The minimal value of the estimated ranges between $-4.0 \times 10^4 Wm^{-2}$ to $-2.0 \times 10^4 Wm^{-2}$ for all the stations. However, it was observed that the values reduced drastically across all the stations owing to cloudiness of the sky which lead to low solar radiation getting to the surface of the earth in the month of October (year).

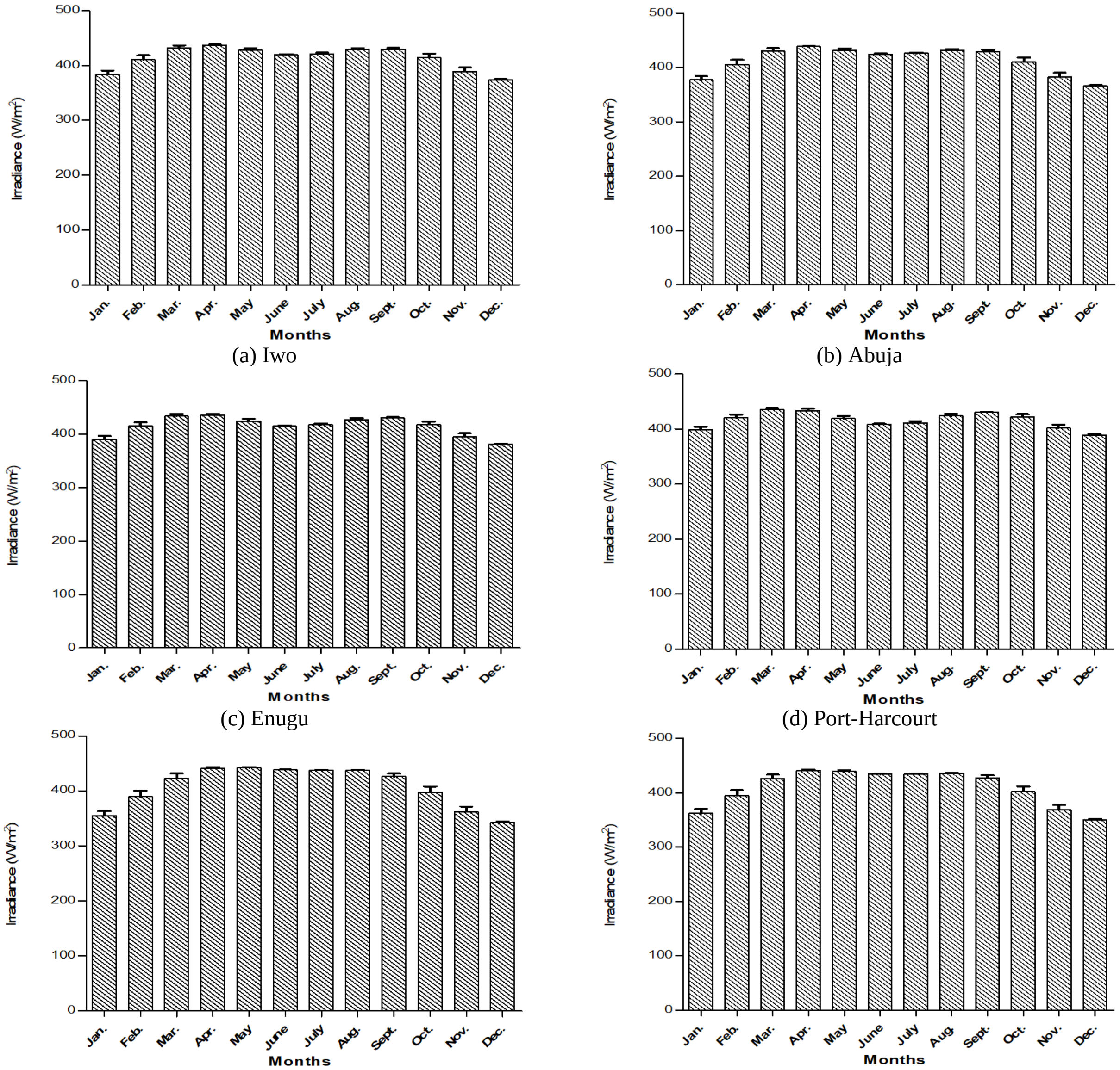
Maiduguri, Port-Harcourt, Sokoto, Iwo and Abuja all have their coincidence around mid of the month of January. However, Enugu station had it coincidence at about 25th of the same month. In spite of the variation in the latitude and time of the day, the season and even the date are serious factors than the latitudinal variation. In October, the point of coincidence between the estimated and observed values occurred more than once. In the stations such as: Sokoto, Abuja, Iwo, Port-Harcourt and Maiduguri they have only one point of coincidence. This might also be owing to season or time of the day. Results in Table 1 show that the quadratic trend equation accounted for 95.9% of the variation in irradiance in Sokoto and 87.8%, 68.1%, 79.6%, 94.6% and 41.9% of the variation in irradiance in Abuja, Enugu, Iwo, Maiduguri and Port-Harcourt respectively. Result of the F- statistic which determines the significance of the quadratic trend equation gave the F- statistic of 4208.06, 1298.72, 386.94, 705.87, 3192.60 and 130.51 for Sokoto, Abuja, Enugu, Iwo, Maiduguri and Port-Harcourt, respectively with p-values of 0.0000 (p<0.05). The p-values obtained for the six locations were all less than 0.05 meaning that the quadratic equations used in estimating irradiance in all the locations were significant. This also implies that time accounted for significant variation in irradiance in the six locations as highlighted in section 3.1. Result also shows that both the coefficient of the linear term and quadratic terms in the trend equations have p-values less than 0.05 which implies that these terms were all significant. The linear terms were positive and significant while the quadratic terms were all negative and significant for all locations which indicate that irradiance increases linearity at the beginning and then with time decreases significantly as the time increases. Result shows Root Mean Square of 139.99 for Sokoto and 162.75, 191.07, 177.34, 143.38, 212.327 for Abuja, Enugu, Iwo, Maiduguri and Port-Harcourt, respectively. Sokoto gave the least Root Mean Square Error (139.99) meaning that the actual and estimated irradiance were closer in Sokoto than the other locations. Port-Harcourt gave the highest Root Mean Error (212.327) which means that based on the quadratic trend equation; the values of the actual and predicted irradiance were far apart in Port-Harcourt compared with that of other locations. This confirmed with the features of the Figure 2(a-f), which shows very little variance in the error bar with the exception Port-Harcourt. The graphs of the actual and estimated irradiance in each of the location are presented below:

The trend equation for each of the location is presented below:
For Sokoto: $I_t = 344.32 + 1.190t - 0.003t^2$
Abuja: $I_t = 374.293 + 0.748t - 0.002t^2$
Enugu: $I_t = 393.062 + 0.455t - 0.001t^2$
Iwo: $I_t = 384.652 + 0.588t - 0.002t^2$
Maiduguri: $I_t = 353.610 + 1.056t - 0.003t^2$
Port-Harcourt: $I_t = 404.766 + 0.267t - 0.001t^2$

TABLE 1. Summary of the results of the trend equation for predicting irradiance in the six selected locations in Nigeria

Location	β_0 (p-value)	β_1 (p-value)	β_2 (p-value)	R^2	F-stat.	P-values	RMSE
Sokoto	344.32** (0.0000)	1.190** (0.0000)	-0.003** (0.0000)	0.959	4208.06	0.0000	139.99
Abuja	374.293** (0.0000)	0.748** (0.0000)	-0.002** (0.000)	0.878	1298.72	0.0000	162.75
Enugu	393.062** (0.0000)	0.4560** (0.0000)	-0.001** (0.0000)	0.681	386.94	0.0000	191.07
Iwo	384.652** (0.0000)	0.5880** (0.0000)	-0.0020** (0.0000)	0.796	705.87	0.0000	177.34
Maiduguri	353.652** (0.0000)	1.0560** (0.0000)	-0.003** (0.0000)	0.946	3192.60	0.0000	143.38
Port-Harcourt	404.766** (0.0000)	0.2670** (0.0000)	-0.0010** (0.0000)	0.419	130.51	0.0000	212.327

**significant at 1 %(p<0.01), values in the parentheses are the probability values



(a) Iwo (b) Abuja

(c) Enugu (d) Port-Harcourt

(e) Sokoto (f) Maiduguri

Figure 2. Monthly error bar variation of irradiance

Figure 3(a-f) shows the plot of the actual and estimated irradiance in the selected six locations based on the quadratic trend equations. The figures revealed some level of agreement between the actual and estimated value of irradiance with the result of the estimated irradiance value closer to the actual in Sokoto than other locations. While less agreement in actual and estimated irradiance were obtained in Port-Harcourt.

The value of irradiance across all the stations as shown in Figures 2a to 2f revealed that, all the stations follow the same pattern and there was a constant increase in Irradiance as compared to that of January and December until after the month of October when the irradiance decrease even more than that of November. However, months such as June, and July have their values less than $400Wm^{-2}$. Other months such as February, March, April, May, August and September have their values of Irradiance greater than $400Wm^{-2}$. While December have it value of irradiance around $380Wm^{-2}$. The variation of irradiance across all the stations observed showed that the maximum irradiance occurred in the months February ($420Wm^{-2}$) and March ($419Wm^{-2}$), while the minimum irradiance occurred in the month January ($372Wm^{-2}$) December ($370Wm^{-2}$). Therefore, the solar radiation in the months February and March observed tend to be high due to the high increase of the Earth's Irradiation. While the solar radiation in the months January and December observed to be the minimum value due to winter period in Nigeria.

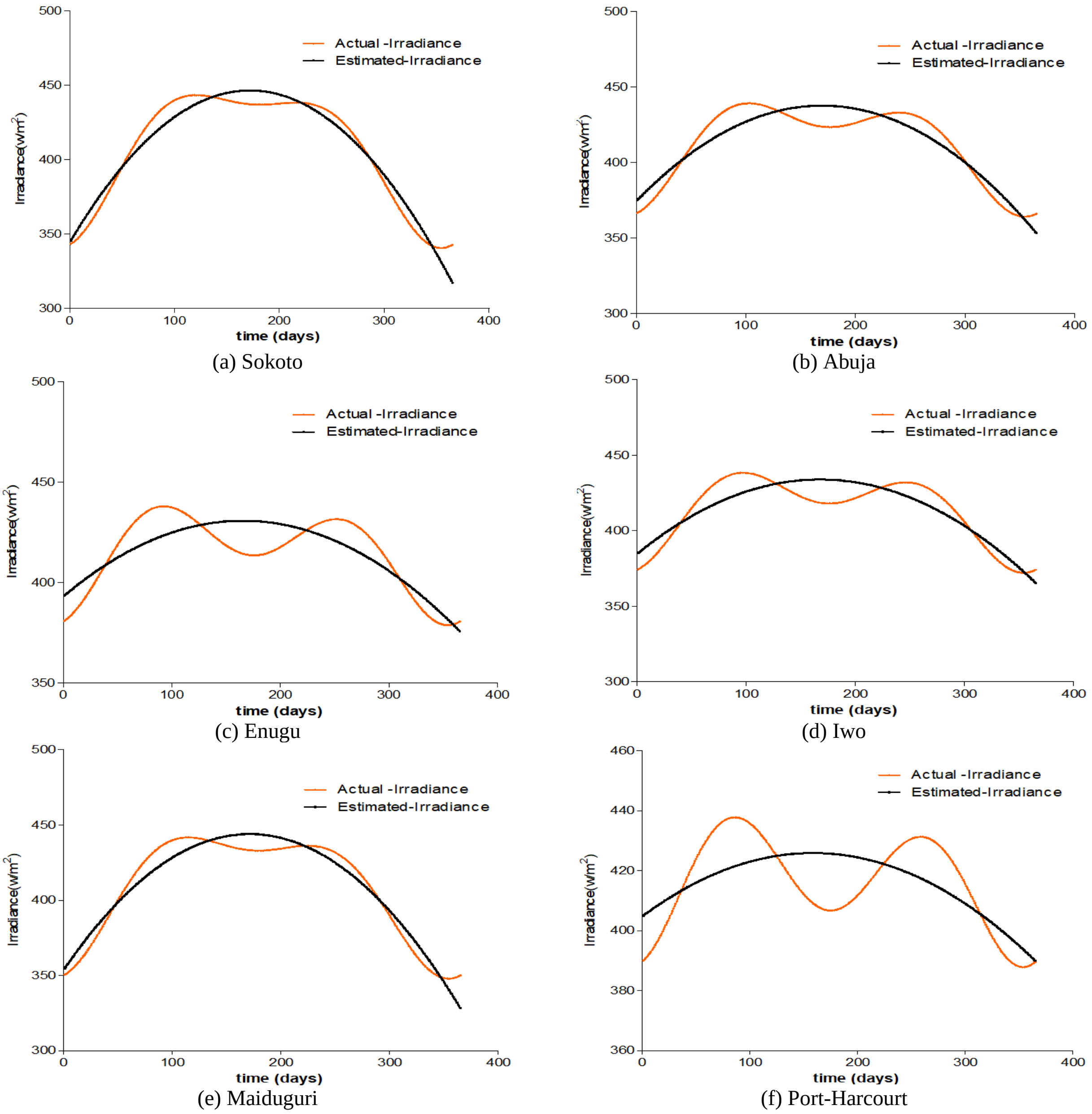


Figure 3. The Actual and Estimated Irradiance of the quadratic trend

CONCLUSION

For this study, we used quadratic trend, error bar and extraterrestrial radiation equation on irradiance of the earth surface parameter. From the satellite data obtained from achieve of HelioClim website of soda, we then deduced the correlation between observed value of irradiance and the estimated value. This shows that there is a drastic difference between the estimated and the observed values as revealed by other authors. For this research, January has a sharp increase while October has sharp decrease. The two months signify high irradiance of the atmosphere across the entire country. Therefore, further studies are encouraged to reveal more details using some climatological parameters (rainfall, temperature, wind speed, pressure etc.) and the rate of sun incident angle and cloud to improve irradiance observation using other months of the year. Analytically, the modelling of solar irradiance using statistical package sometimes is difficult and requires some basic information for the completion of the Solar Irradiance Model Aweda and Samson [19]. However, this research concluded that solar irradiance across Nigeria got to its peak in the months February and March.

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Persian Abstract

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چکیده

تابش فرازمینی، تابش خورشیدی دریافت شده در بالای جو زمین در سطح افقی است. این مقدار بیش از ایستگاه‌های انتخاب شده در مناطق استوایی مورد بررسی قرار گرفت. داده‌های روزانه تابش فرازمینی روی سطح افقی زمین برای سال ۲۰۱۸ برای ایستگاه‌ها: Iwo، Abuja، Enugu، Port-Harcourt، Sokoto و Maiduguri به دست آمده از بایگانی وب سایت HelioClim با استفاده از MATLAB مورد تجزیه و تحلیل قرار گرفت و بسته‌های آماری علوم اجتماعی (SPSS نسخه ۲۰.۰) برای تخمین تابش فرازمینی ایستگاه در نظر گرفته شده است. نتایج MATLAB نشان داد که مقدار همزمانی $2 \times 10^4\ Wm^{-2}$ – در تمام ایستگاه‌ها است. در ژانویه، مقادیر بین ۱۵ تا ۲۰ قله در سال با تابش $4 \times 10^4\ Wm^{-2}$ – و حداکثر $2 \times 10^4\ Wm^{-2}$ مشاهده شد. نتایج نشان داد RMSE خطای میانگین مربعات RMSE برای Sokoto (۱۳۹/۹۹)، Abuja (۱۶۲/۷۲)، Iwo (۱۷۷/۰۷)، Maiduguri (۱۷۱/۳۴)، Enugu (۱۹۱/۰۷)، Port-Harcourt (۲۱۲/۲۷) است. همچنین نتایج نشان داد که معادله روند درجه دوم که در محدوده ۴۱/۹٪ - ۹۵/۹٪ قرار دارد. بر اساس داده‌ها می‌توان به این نتیجه رسید که Sokoto و Maiduguri بالاترین تابش خورشید را دارند.