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Study of Ground-observed, Satellite-derived and Global Solar Radiation in Enugu and Owerri, Nigeria

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Abstract The present study was designed to locally calibrate Angstrom-Prescott and Hargreaves-Samani computing models employing hybrid parameter-based models to obtain the adjusted Angstrom-Prescott and Hargreaves-Samani coefficients for Enugu and Owerri in the Federal republic of Nigeria. To achieve this purpose, meteorological parameters such as sunshine hours, maximum sunshine duration, minimum and maximum temperatures were employed as input parameters to compute the original Angstrom-Prescott and Hargreaves-Samani models as well as calibrate the original Angstrom-Prescott and Hargreaves-Samani models. The monthly adjusted coefficients of Angstrom-Prescott and Hargreaves-Samani models were obtained by multiplying the monthly ratio of the observed global solar radiation (H), to that calculated from original Angstrom-Prescott and Hargreaves-Samani models with their original coefficients, H and the average value was obtained per station. These adjusted coefficient values were considered as the target values for the development of hybrid parameter-based models (HP) for calibrating original Angstrom-Prescott and Hargreaves-Samani models for Enugu and Owerri. On the whole, the result from the statistical indicators confirmed that the locally calibrated Angstrom-Prescott and Hargreaves-Samani models performed better than the original Angstrom-Prescott and Hargreaves-Samani models for the two stations investigated. Therefore, the calibrated Angstrom-Prescott and Hargreaves-Samani models obtained in this investigation could be highly recommended for estimating global solar radiation in Enugu and Owerri when only sunshine hours and temperature data are available.

Keywords Angstrom-Prescott model, Hargreaves-Samani model, hybrid parameter-based model, global solar radiation, ground measured radiation, satellite derived radiation

1. Introduction

Solar radiation is the principal renewable energy source supporting the biosphere and stimulating the biological, chemical and physical processes on the surface of the earth. The amount of solar energy received by the Earth-atmosphere system is vital to the energy balance. Therefore, accurate knowledge of solar radiation reaching the Earth's surface is a primary factor since it influences systems such as hydrology, ecology and agriculture.

It should be noted that understanding local solar radiation is important for several applications in photovoltaic cells, solar thermoelectric powers, solar lamps, solar architecture, solar heating, solar thermal energy, radiation and energy budget, heating and natural lighting in plant, this is necessary for the supply of energy for natural processes like photosynthesis, agriculture and forestry, molten salt power, water treatment and climate: meteorology, climatology, air conditioning, etc [1-6].

In spite of efforts by governments, scientists, researchers as well as investors to exploit solar energy via various technologies, solar radiation potential remains largely unexploited, yet [6]. For example, the amount of energy emitted by the sun is so enormous that in converting only, say, 0.1% of the solar energy reaching the earth surface to electricity with the efficiency of 10%, the output power would be 17,300GW, which is 7 times higher than the global average momentary electricity consumption in 2012 [7-9].
It is known that Nigeria is a high insolation country with an average of about 2,800 hours/year of sunshine [6]. This form of renewable energy is required to maintain ecology and environment as they are eco-friendly in that they do not contribute to global warming and production of greenhouse gases. This is supposed to plays a significant role in emerging new energy technologies and policies. It is important for us to determine the level of solar radiation, yet its routine measurement is not as widespread as other meteorological parameters such as temperature, precipitation, relative humidity, etc. This is so because of cost implication, maintenance and calibration of the pyranometer used in ground measurement, especially, in rural areas and developing countries. Many estimation models have been proposed for accurate estimation of solar radiation from most available meteorological parameters such as cloud cover, sunshine hours, temperature and precipitation, etc. [10-15] are in use, only limited studies have been conducted in parts of Nigeria in comparison to similar studies conducted in developed countries of the world. The objective of this investigation is therefore to estimate global solar radiation in Enugu and Owerri in the Federal Republic of Nigeria using the calibrated Angstrom-Prescott and Hargreaves-Samani models. To this effect, hybrid parameter-based models (HP) were used to estimate the Angstrom-Prescott Coefficients (APCs) and Angstrom-Hargreaves Coefficients (AHCs).

2. Models

Kimball [16] was the first researcher to conduct studies on the relationship between solar radiation and sunshine duration. Shortly after, Angstrom [10] extended the study by proposing that this relationship is linear.

2.1. Sunshine-based models

Sunshine-based models are the most commonly used models for estimating global solar radiation in Nigeria. This is so because of the fact that sunshine duration fraction has the highest influence on the accuracy of estimation. The next is ambient temperature which is available as well as reliable measured sunshine duration data in most meteorological stations within Nigeria and across the globe [6]. This model, which was pioneered by Kimball [16] and Angstrom [10] and modified by Prescott [11], Page [12] and other researchers, has been applied by many solar radiation researchers for estimating the monthly mean daily global solar radiation on the horizontal surface for several stations within Nigeria and across the globe by determining the empirical constants *a* and *b* of equation (1) employing meteorological parameters of the site of interest:

$$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) \quad (1)$$

where H is the global solar radiation, which is the radiation that reaches the earth surface, H_o is the solar radiation on top of the atmosphere that does not reach the earth surface, S is the sunshine hour; it is the time taken for solar radiation to reach the earth surface, S_o is the extraterrestrial sunshine hour above the earth surface, a and b are regression constants, with values 0.25 and 0.5, respectively, as recommended by FAO-56 [17] in any location across the globe. The ratio, $H/_{H_o}$, is referred to as the clearness index. Equation (1) is the Angstrom-Prescott model.
Apart from the Angstrom-Prescott-Page type model, those fitted by Rietveld [18] seem to be universally applicable also. Akpabio *et al*. [19-20] and Falayi and Rabiu [21] employed empirical model for estimating monthly mean daily global solar radiation on the horizontal surface with fraction of sunshine duration for several locations in Nigeria. The result showed better performance and high accuracy in the fitted sites as compared to reported models in literature that seem to be universally applicable. Several empirical models based on the Angstrom-Prescott-Page type model and other modified models such as exponential form, logarithmic form, second order, third order, power form, etc. models have been applied across the globe for estimating global solar radiation [6].

The temperature-based computing models are especially interesting because the needed input data, air temperature, can be easily measured globally.

2.2. Temperature-based model

Hargreaves and Samani [13] were the first to develop a temperature-based model for estimating global solar radiation using maximum and minimum temperature $\left(\Delta T = T_{max} - T_{min}\right)$, and extraterrestrial solar radiation(H_O) as an input parameter as shown in equation (2); and they obtained an empirical coefficient of 0.17:

$$\frac{H}{H_O} = AHC\left(T_{max} - T_{min}\right)^{0.5} \quad (2)$$

where $T_{max.}$is the maximum temperature, and T_{min}. is the minimum temperature.

Since then, equation (2) has been recognized as one of the famous, simplest and accurate temperature models for estimating global solar radiation and can be employed for short-term forecasting of global solar radiation.

The Hargreaves-Samani (HS) modelis often employed to provide H estimation for weekly or longer periods. However, after Hargreaves [13] calibrated HS model using data from North America and Europe, he observed that Angstrom-Hargreaves Coefficient (AHC) varied in different areas depending on climatic conditions, and a local calibration of theHS model was recommended after obtaining a simplified coefficient, *a*, of 0.16 for interior regions and 0.19 for coastal regions.

Bayat and Mirlaifi [22] applied HS model and reported *a* coefficient of 0.16 for Shiaz, Iran. For Nigeria, it was estimated the coefficient as 0.16 in Uturu; Adaramola [23] obtained a coefficient of 0.1945 for Akure while Ohunakin *et al.* [24] recorded a coefficient of 0.1141 in Osogbo.

In spite of the efforts made by several researchers on calibration of HS computing model in the past decades for different climates and geographical locations across the globe [6, 13, 22, 25], these calibrations were site-specific and cannot be extrapolated to other sites where weather conditions are different and some calibrated HS models are more complicated compared to the original HS model.

2.3. About Enugu and Owerri

Enugu and Owerri are located in South-East geo-political zone in the Federal Republic of Nigeria with Latitude 6.4426^o, Longitude 7.5022^o and Latitude 5.4833^o, Longitude 7.0304^o coordinates for Enugu and Owerri, respectively. The calculated flying distance from Enugu to Owerri is 74 miles (119 km) whilethe driving distance between the two towns is 144.28 km under an average speed of 112 kilometers/hour (70 miles/h) with corresponding travel time of 01 hours 17 minutes (Figure 2) [26].

Enugu is the capital of Enugu State. The city had a population of 722,664 people according to the 2006 Nigerian census. The name *Enugu* is derived from the two Igbo words *Énú Ụ́gwụ́* meaning "hill top" denoting the city's hilly topography. The city was named after Enugwu Ngwo, where coal was found. Enugu is located in a tropical rain forest zone with a derived savannah and so has atropical savannah climate. Its climate is humid and this humidity is highest between March and November. For the whole of Enugu State, the mean daily temperature is 26.7 °C. As in the rest of West Africa, the rainy season and dry season are the only weather periods that occur in Enugu. The average annual rainfall in Enugu is about 2,000 mm (79 in), which arrives intermittently and becomes very heavy during the rainy season. Other weather conditions affecting the city include harmattan, a dusty trade wind that lasts for a few weeks in December and January. Like the rest of Nigeria, Enugu is hot all year round [27].

Owerri, the capital of Imo State, is set in the heart of Igbo-land. It is also the State's largest city, followed by Orlu and Okigwe as second and third, respectively. It consists of three Local Government Areas, namely, Owerri Municipal, Owerri North and Owerri West. It has an estimated population of about 401,873 people going by the 2006 census and is approximately 100 square kilometres (40 sq mi) in area. Owerri is bordered by the OtamiriRiver to the east and the Nworie River to the south. Owerri city has a tropical wet climate according to the Köppen-Geiger system. Rain falls for most months of the year with a brief dry season. The harmattan affects the city in the early periods of the dry season and it is noticeably less pronounced than in other cities in Nigeria. The average temperature is 26.4 °C [28].

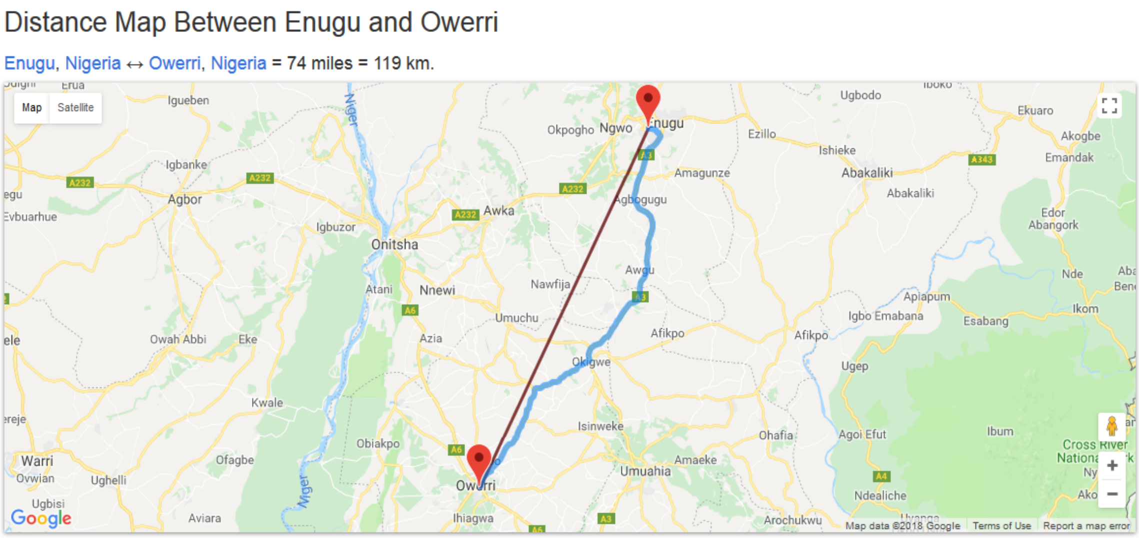

Figure 1: Distance map between Enugu and Owerri [26]

3. Data acquisition and analysis

3.1 Dada acquisition

The monthly mean daily ground measured global solar radiation, monthly mean temperature and sunshine hour data used for this study were obtained from the archives of the Nigeria Meteorological Agency, Oshodi, Lagos [29]. The data covered a period of fifteen years (2000-2014) for Enugu and Owerri. The long term monthly mean daily satellite observation global solar radiation data on the horizontal surface (H) employed for comparing with the ground measured data were obtained from the Atmospheric Science Data Centre of National Aeronautics and Space Administration [31] for the period of 1983-2005 for Enugu and Owerri i.e. 22 years.

3.2 Data analysis

Monthly APCs were obtained by multiplying original coefficients (*a* and *b* differently) obtained by Allen *et al*. [17] from each station by the monthly ratio of ground (NIMET) observed global solar radiation (*H*) to *H* obtained from original Allen *et al*. [17] models. The mean APPC values were obtained for Enugu and Owerri. These "observed" APC data were considered as the target values for the development of HP model for the two stations. The HP was used to evaluate new input combination employing the following variables as potential input parameters: maximum sunshine duration (hours), monthly mean sunshine duration, minimum and maximum temperature data (^oC). The parameter-based models (HP) employed is expressed as:

$$AHC = a + b\left(\frac{S}{S_o}\right) + c\left(\frac{S}{S_o}\right)^2 + d\left(\frac{T_{min}}{T_{max}}\right) + e\left(\frac{T_{min}}{T_{max}}\right)^2 \quad (3)$$

The maximum possible sunshine duration is expressed mathematically as:

$$S_0 = \frac{2}{15}\cos^{-1}(-\tan\delta\tan\phi); \quad (4)$$

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

and ϕ is the latitude, δ is the solar declination and *n* the number of days of the year starting from first January. The daily extraterrestrial solar radiation (H_O) is the solar radiation intercepted by horizontal surface during a day, without the atmosphere, expressed theoretically as:

$$H_o = \frac{24}{\pi} I_{SC} \left(1 + 0.033 \cos \frac{360n}{365}\right) \times \left(\cos\phi \cos\delta \sin\omega_s + \frac{2\pi\omega_s}{360} \sin\phi \sin\delta\right) \quad (6)$$

where the mean sunrise hour angle (ω_s) can be evaluated as:

$$\omega_s = \cos^{-1}\left[\tan\delta \tan\phi\right] \quad (7)$$

I_{SC} is the solar constant and other symbols retain their usual meaning.

For Enugu:

$$AAP_{(a)} = -8.895 + 0.028\left(\frac{S}{S_o}\right) - 0.127\left(\frac{S}{S_o}\right)^2 + 27.938\left(\frac{T\min}{T\max}\right) - 21.285\left(\frac{T\min}{T\max}\right)^2 \quad (8)$$

$$AAP_{(b)} = -17.789 + 0.056\left(\frac{S}{S_o}\right) - 0.255\left(\frac{S}{S_o}\right)^2 + 55.876\left(\frac{T\min}{T\max}\right) - 42.569\left(\frac{T\min}{T\max}\right)^2 \quad (9)$$

For Owerri:

$$AAP_{(a)} = -7.974 - 0.344\left(\frac{S}{S_o}\right) + 0.139\left(\frac{S}{S_o}\right)^2 + 25.461\left(\frac{T\min}{T\max}\right) - 10.375\left(\frac{T\min}{T\max}\right)^2 \quad (10)$$

$$AAP_{(b)} = -15.948 - 0.687\left(\frac{S}{S_o}\right) + 0.279\left(\frac{S}{S_o}\right)^2 + 50.923\left(\frac{T\min}{T\max}\right) - 38.751\left(\frac{T\min}{T\max}\right)^2 \quad (11)$$

For Enugu:

$$AHC = -5.122 + 0.099\left(\frac{S}{S_o}\right) - 0.065\left(\frac{S}{S_o}\right)^2 + 15.952\left(\frac{T\min}{T\max}\right) - 12.120\left(\frac{T\min}{T\max}\right)^2 \quad (12)$$

For Owerri:

$$AHC = -3.910 - 0.044\left(\frac{S}{S_o}\right) + 0.039\left(\frac{S}{S_o}\right)^2 + 12.405\left(\frac{T\min}{T\max}\right) - 9.434\left(\frac{T\min}{T\max}\right)^2 \quad (13)$$

Monthly AHCs were obtained by multiplying 0.17 by the monthly ratio of ground (NIMET) observed H to H obtained from original HS model. The mean AHC value was obtained for Owerri and Enugu. These "observed" AHC data were considered as the target values for the development of HP models for the two stations. The HP was used to evaluate new input combination employing the following variables as potential input parameters: maximum sunshine duration (S_o), monthly mean sunshine duration (S), minimum temperature (*Tmin.*) and maximum temperature (*Tmax.*) data (^{o}C). The HP models are given in equations 12 and 13 for Enugu and Owerri, respectively.

4. Performance evaluation

Mean bias error (MBE), mean percentage error (MPE), root mean square error (RMSE), Nash-Sutcliffe coefficient (NS) and percentage error (PE) were applied to evaluate performances of the observed and predicted AHC and APPC as well as original and calibrated HS and APP models. Equations 14-18 were used for performance evaluation of the models.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right), \quad (14)$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{O_i - P_i}{O_i}\right)\times 100, \quad (15)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right)^2}, \quad (16)$$

$$NS = 1 - \left[\frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - O_{ave}\right)^2}\right] \quad (17)$$

$$PE = \sum_{i=1}^{n}\left(\frac{O_i - P_i}{P_i}\right)\times 100 \quad (18)$$

Where O_i and P_i are the observed and predicted AHC and APPC as well as original and calibrated HS models values of the i-th step obtained by H, AHC and APPC, and HS and APP models, respectively; n is the number of observation. O_{ave} is the average value of the observed H and AHC and APPC values. NS is a dimensionless quantity ranging from 1 (perfect fit) to -∞ (the worst fit). PE is also a dimensionless quantity. MBE and RMSE are measured in MJ/m^2/day while MPE is measured in %.

5. Results and Discussions

5.1 Presentation of Results

The ground measured global solar radiation and meteorological datafor Enugu and Owerri are shown in Tables 1-6 together with the statistical indicators. The calibrated APCs models for Enugu are given in equations 8 and 9 (Figures 1-5) while those for Owerri are given in equations 10 and 11 (Figure 6-10). The calibrated HS coefficients for Enugu and Owerri is expressed in equations 12 and 13 (Figures 6-10). Monthly measured ground global solar radiation (H) and Satellite-Derived Data (NASA) from 2000-2005 in MJm^{-2}day^{-1} for Enugu and Owerri are shown in Figure 11 and 12, respectively.

3.1.1 Ground Measured global solar radiation data for Enugu and Owerri

The ground measured global solar radiation data for Enugu and Owerri are presented in Tables 1-6.

Table 1: Ground measured global solar radiation data for Enugu

Month	H (MJm^{-2}day^{-1})	Ho (MJm^{-}day^{-1})	Tmin (^{o}C)	Tmax (^{o}C)	S (hours)	So (hours)	S/So	H/Ho
JAN	16.36	34.09	23.27	33.81	7.82	11.80	0.66	0.48
FEB	17.63	36.11	23.65	34.78	6.46	11.90	0.54	0.49
MAR	16.69	37.55	24.11	34.71	8.35	12.00	0.70	0.44
APR	16.27	37.55	23.89	34.27	8.79	12.20	0.72	0.43
MAY	15.96	36.43	23.54	33.57	9.20	12.30	0.75	0.44
JUN	15.18	35.57	23.25	32.85	6.52	12.40	0.53	0.43
JUL	13.47	35.78	23.03	32.29	5.60	12.40	0.45	0.38
AUG	13.85	36.76	22.80	31.87	4.24	12.30	0.34	0.38
SEP	15.67	37.19	22.48	31.87	7.89	12.10	0.65	0.42
OCT	16.70	36.25	22.23	32.16	6.45	12.00	0.54	0.46
NOV	18.67	34.45	21.79	32.57	8.85	11.80	0.75	0.54
DEC	17.21	33.30	21.53	33.04	8.45	11.80	0.72	0.52
Average	**16.14**	**35.92**	**22.97**	**33.15**	**7.38**	**12.08**	**0.61**	**0.45**

Table 2: Global solar radiation data for Enugu

Months	**H**	**HS**	**AHS**	**AP**	**AAP**	**H (NIMET)**	**H (NASA)**
JAN	16.92	18.58	16.92	18.84	16.92	16.63	20.77
FEB	18.71	20.31	18.71	22.05	18.71	18.14	21.10
MAR	17.30	20.72	17.30	23.95	17.30	17.60	20.41
APR	16.77	20.62	16.77	24.37	16.77	16.74	19.22
MAY	16.67	19.75	16.67	24.39	16.67	16.86	18.18
JUN	15.51	18.90	15.51	22.66	15.51	16.21	16.78
JUL	13.82	18.67	13.82	20.71	13.82	13.34	15.44
AUG	13.51	18.91	13.51	20.31	13.51	13.10	14.58
SEP	16.23	19.35	16.23	22.29	16.23	15.98	15.77
OCT	17.26	19.31	17.26	23.58	17.26	17.26	17.06
NOV	19.03	19.00	19.03	22.03	19.03	18.61	18.79
DEC	17.98	18.93	17.98	19.53	17.98	17.72	19.98
Average	**16.64**	**19.42**	**16.64**	**22.06**	**16.64**	**16.52**	**18.17**

Table 3: Ground measured global solar radiation data for Owerri

Months	**H** ($MJm^{-2}day^{-1}$)	**Ho** ($MJm^{-2}day^{-1}$)	**S_o (hours)**	**Tmax (^oC)**	**Tmin (^oC)**	**S (hours)**	**S/So**	**H/Ho**
JAN	16.92	33.66	4.35	34.47	24.27	7.02	0.62	0.50
FEB	18.71	35.82	6.24	35.55	24.74	8.55	0.73	0.52
MAR	17.30	37.44	7.29	35.21	24.66	9.35	0.78	0.46
APR	16.77	37.66	7.73	34.68	24.21	9.79	0.79	0.45
MAY	16.67	36.68	8.50	33.96	23.93	10.24	0.83	0.45
JUN	15.51	35.89	7.05	32.81	23.45	9.28	0.76	0.43
JUL	13.82	36.11	5.06	31.92	23.03	7.79	0.65	0.38
AUG	13.51	36.94	4.05	31.15	22.70	6.75	0.60	0.37
SEP	16.23	37.15	5.97	30.58	22.29	8.53	0.70	0.44
OCT	17.26	36.04	7.93	31.27	21.97	9.79	0.81	0.48
NOV	19.03	34.06	7.30	31.99	21.38	9.21	0.79	0.56
DEC	17.98	32.83	5.00	32.53	21.08	7.25	0.69	0.55
Average	**16.64**	**35.86**	**0.37**	**33.01**	**23.14**	**8.63**	**0.73**	**0.47**

Table 4: Global solar radiation data for Owerri

Month	**H**	**HS**	**AHS**	**AP**	**APP**	**H (NASA)**	**H(NIMET)**
JAN	16.36	18.82	16.36	19.82	16.36	19.94	16.00
FEB	17.63	20.48	17.63	18.83	17.63	20.09	17.56
MAR	16.69	20.78	16.69	22.45	16.69	16.81	16.86
APR	16.27	20.57	16.27	22.91	16.27	18.00	16.40
MAY	15.96	19.61	15.96	22.73	15.96	16.52	16.09
JUN	15.18	18.73	15.18	18.24	15.18	14.22	15.69
JUL	13.47	18.50	13.47	17.03	13.47	13.00	13.10
AUG	13.85	18.81	13.85	15.52	13.85	14.11	12.94
SEP	15.67	19.37	15.67	21.43	15.67	13.39	15.37
OCT	16.70	19.42	16.70	18.81	16.70	14.76	16.80
NOV	18.67	19.22	18.67	21.53	18.67	16.85	18.27
DEC	17.21	19.20	17.21	20.24	17.21	19.37	17.22
Average	**16.14**	**19.46**	**16.14**	**19.96**	**16.14**	**16.42**	**16.02**

Table 5: The statistical test indicators of calculated and calibrated models for estimating global solar radiation at Enugu

Model	MBE ($MJm^{-2}day^{-1}$)	MPE (%)	RMSE ($MJm^{-2}day^{-1}$)	NS	PE
HS	0.2316	-1.47777	2.8953	0.371	-17.7326
AHS	0	$8.66*10^{-18}$	$7.59*10^{-31}$	0.999	$1.04*10^{-16}$
AP	0.4514	-2.80447	9.84311	0.190	-336537
AAP	$1.23*10^{-17}$	$-9.4*10^{-17}$	$1.29*10^{-30}$	0.909	$-1.1*10^{-15}$
AHC predicted	$-1.3*10^{-5}$	0.00154	$5.62*10^{-6}$	0.945	0.018423
AAP(a) Predicted	$-3*10^{-5}$	0.011469	$6.17*10^{-6}$	0.980	0.137634
AAP(b) Predicted	$1.87*10^{-5}$	-0.00955	$2.46*10^{-5}$	0.980	-0.1146
Satellite-Derived data (NASA)	0.1381	-0.84464	1.295319	0.785	-10.1357

Table 6: The statistical test indicators of calculated and calibrated models for estimating global solar radiation at Owerri

Model	MBE ($MJm^{-2}day^{-1}$)	MPE (%)	RMSE ($MJm^{-2}day^{-1}$)	NS	PE
HS	0.2767	-1.7774	0.95856	0.490	-17.08
AHS	$-7.4*10^{-17}$	$4.78*10^{-16}$	$2.56*10^{-16}$	0.999	$5.7*10^{-15}$
AP	0.3185	-1.99002	1.1033	0.578	-18.58
AAP	$-1.20*10^{-17}$	$6.52*10^{-17}$	$2.99*10^{-16}$	0.999	$7.83*10^{-16}$
AHC predicted	$2.617*10^{-5}$	-0.01833	0.0011	0.899	-0.2199
AAP(a) Predicted	$-3.606*10^{-5}$	0.01795	0.0011	0.965	0.21540
AAP(b) Predicted	$2.41*10^{-5}$	-0.00741	0.0022	0.965	-0.1499
Satellite-Derived data (NASA)	0.03310	-0.10299	0.45474	0.675	-1.23588

5.1.2. Target and predicted values of Hargreaves-Samani and Angstrom Prescott models for Enugu and Owerri

Target and predicted values of Hargreaves-Samani and Angstrom Prescott models for Enugu and Owerri are shown in Tables 7 and 8.

Table 7: Target and predicted values of Hargreaves-Samani and Angstrom-Prescott models for Enugu

Months	AHC Target	AHC Predicted	$AAP_{(a)}$ Target	$AAP_{(a)}$ Predicted	$AAP_{(b)}$ Target	$AAP_{(b)}$ Predicted
JAN	0.154812	0.152215	0.224540	0.219472	0.449080	0.440035
FEB	0.156564	0.158663	0.212106	0.213160	0.424212	0.427249
MAR	0.141888	0.148423	0.180503	0.186042	0.361007	0.372959
APR	0.138269	0.146033	0.172108	0.179234	0.344216	0.359324
MAY	0.143544	0.141662	0.170908	0.165308	0.341817	0.331419
JUN	0.139561	0.134470	0.171183	0.163339	0.342366	0.327598
JUL	0.125803	0.126651	0.166827	0.168148	0.333654	0.337386
AUG	0.121448	0.122963	0.166251	0.169141	0.332502	0.339434
SEP	0.142577	0.137163	0.182051	0.178609	0.364102	0.358226
OCT	0.151987	0.151212	0.183029	0.186391	0.366059	0.373607
NOV	0.170208	0.163026	0.215904	0.211286	0.431809	0.423389
DEC	0.161406	0.163762	0.230153	0.231123	0.460306	0.463195
Average	0.145672	0.145520	0.189630	0.189271	0.379261	0.379485

Table 8: Target and predicted values of Hargreaves-Samani and Angstrom-Prescott models for Owerri

Month	AHC Target	AHC Predicted	$AAP_{(a)}$ Target	$AAP_{(a)}$ Predicted	$AAP_{(b)}$ Target	$APP_{(b)}$ Predicted
JAN	0.147841	0.146915	0.206402	0.204854	0.412804	0.411025
FEB	0.146388	0.150690	0.234117	0.234624	0.468235	0.470304
MAR	0.136533	0.143174	0.185905	0.191372	0.371810	0.384135
APR	0.134500	0.141598	0.177564	0.183896	0.355128	0.369242
MAY	0.138348	0.138696	0.175516	0.173233	0.351032	0.347983
JUN	0.137782	0.131524	0.208020	0.198087	0.416040	0.397184

JUL	0.123701	0.126474	0.197712	0.202167	0.395425	0.405193
AUG	0.125155	0.125621	0.223065	0.222481	0.446130	0.445629
SEP	0.137573	0.134089	0.182884	0.180072	0.365769	0.361429
OCT	0.146156	0.144835	0.221937	0.223392	0.443874	0.447825
NOV	0.165131	0.155546	0.216852	0.208051	0.433703	0.417635
DEC	0.152371	0.156088	0.212558	0.215110	0.425117	0.431675
Average	0.140957	0.141271	0.203544	0.203112	0.407089	0.407438

5.1.3. Global solar radiation, Angstrom-Prescott and Hargreaves-Samani models for Enugu and Owerri.

In Figures 1-5 are presented Global solar radiation, Angstrom-Prescott model and Hargreaves-Samani model for Enugu.

(a) Global solar radiation, Armstrong-Prescott model and Hargreaves-Samani model for Enugu

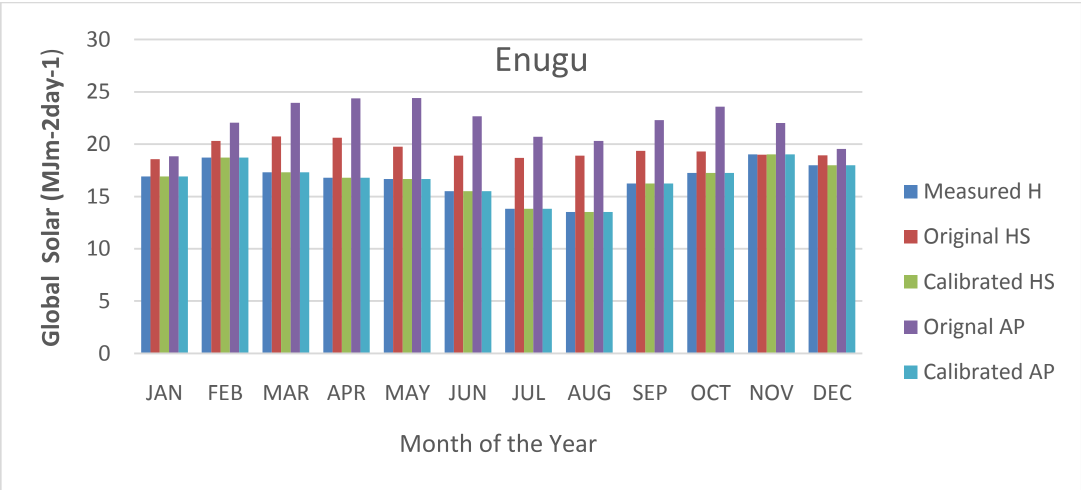

Figure 1: Comparison between measured, calculated and calibrated global solar radiation in Enugu

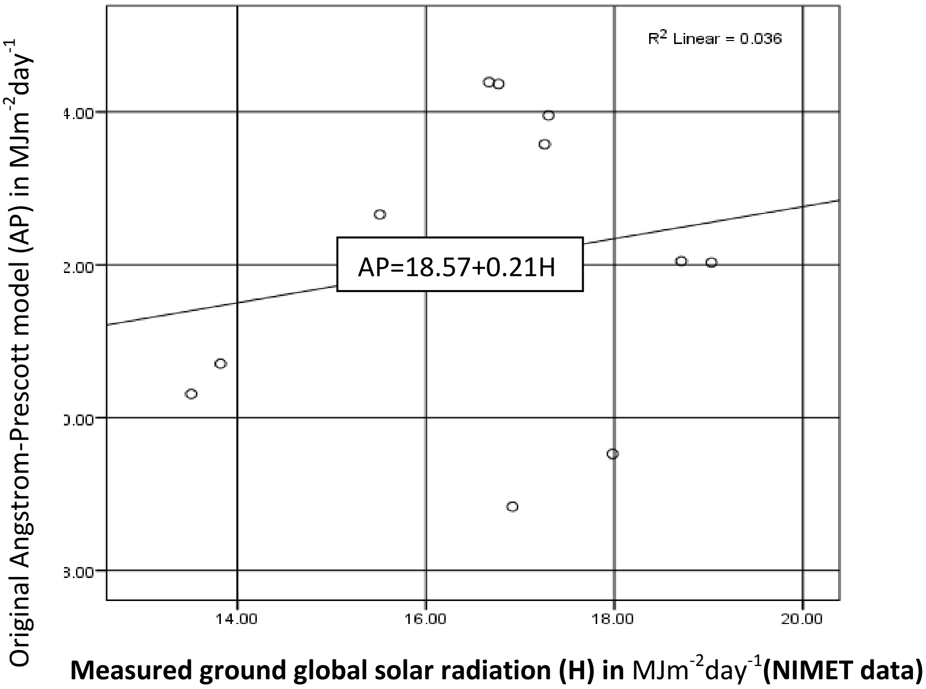

Figure 2: Measured monthly ground global solar radiation (H) and calculated original Angstrom-Prescott model (HS) in $MJm^{-2}day^{-1}$ for Enugu

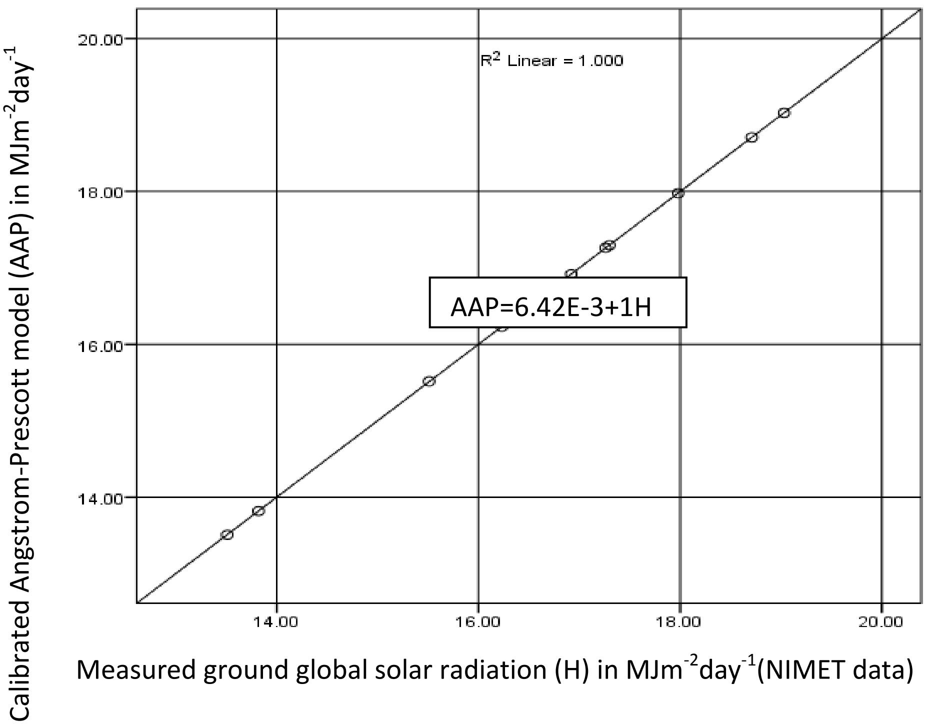

Figure 3: Measured monthly ground global solar radiation (H) and calibrated Angstrom-Prescott model (AAP) in $MJm^{-2}day^{-1}$ for Enugu

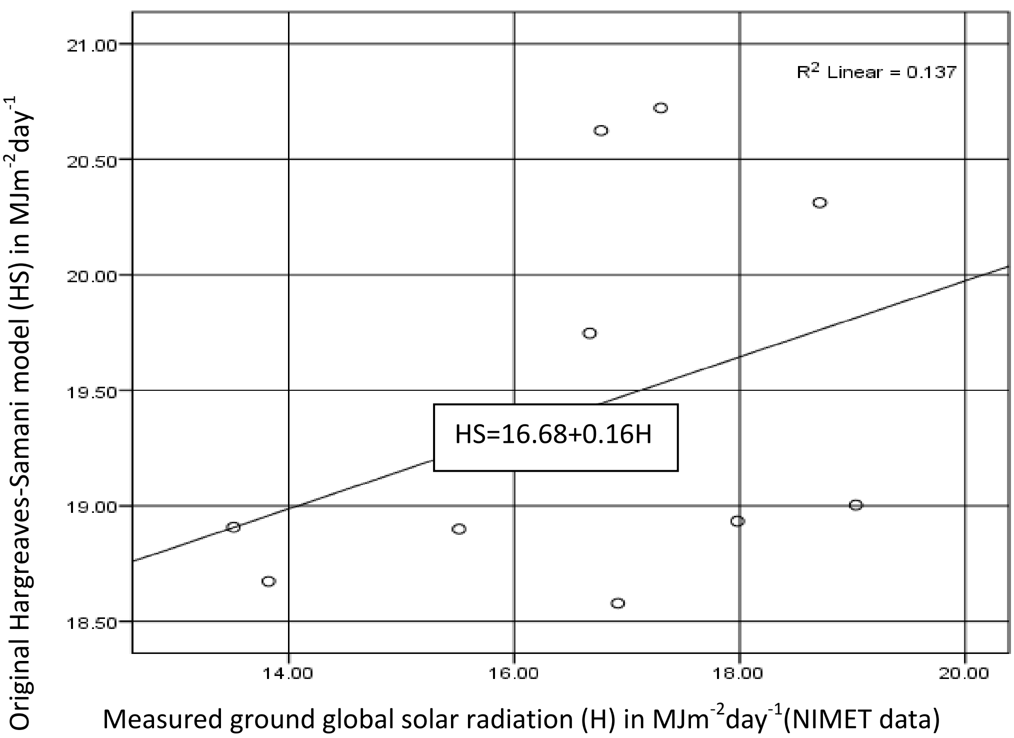

Figure 4: *Comparison of monthly measured ground global solar radiation (H) and Calculated Original Hargreaves-Samani model (HS) in $MJm^{-2}day^{-1}$ for Enugu*

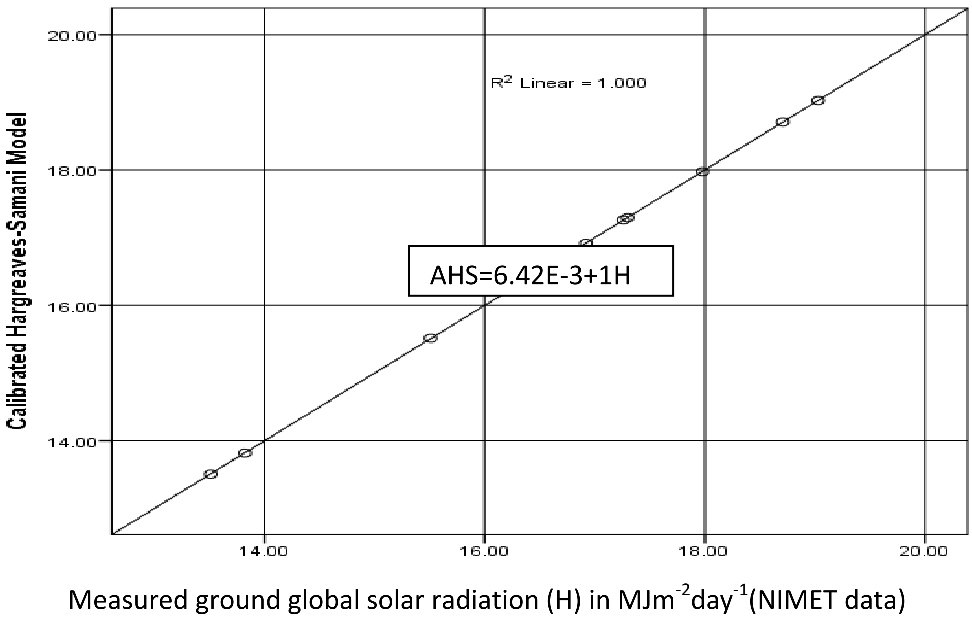

Figure 5: Measured monthly ground global solar radiation (H) and calibrated Hargreaves-Samani model (AHS) in MJm^{-2}day^{-1} for Enugu.

(b) Global solar radiation, Angstrom-Prescott model and Hargreaves-Samani model for Owerri.

Results on global solar radiation, Angstrom-Prescott and Hargreaves-Samani model for Owerri are shown in Figures 6-12.

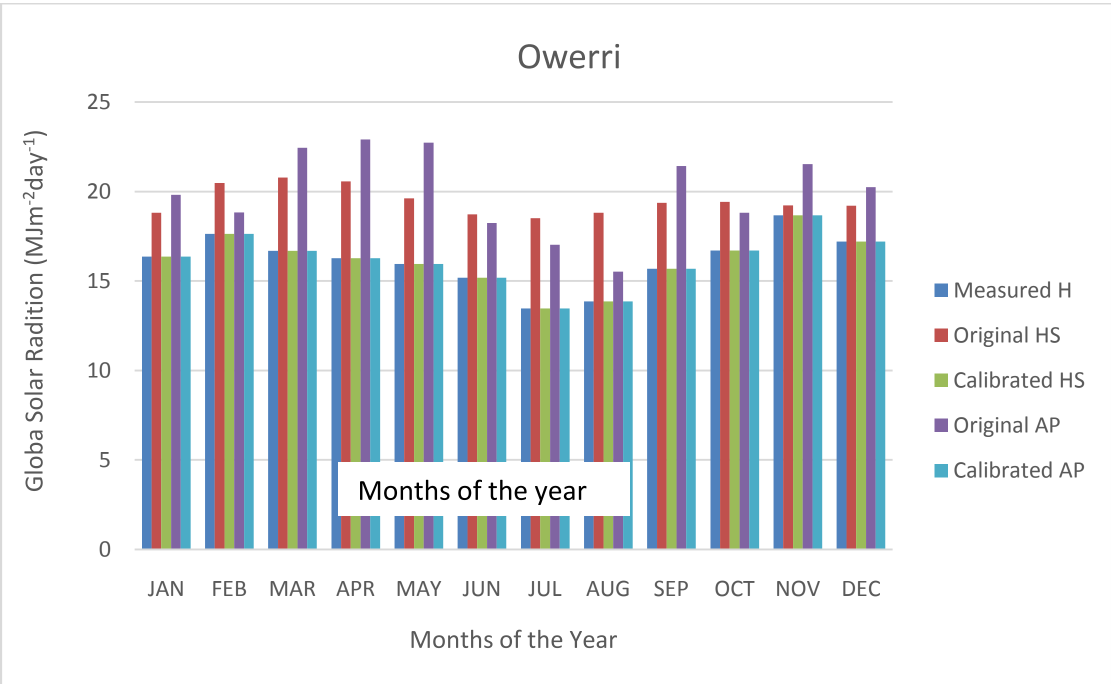

Figure 6: Measured, calculated and calibrated global solar radiation for Owerri (MJm^{-2}day^{-1})

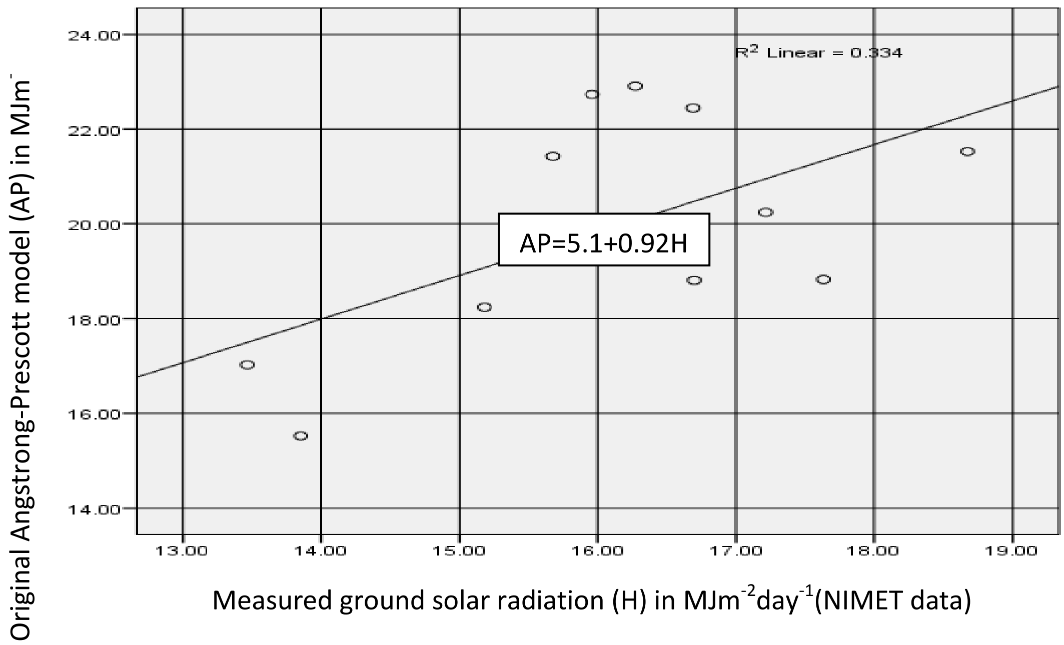

Figure 7: Measured monthly ground global solar radiation (H) and calculated Angstrom-Prescott model (AP) in MJm^{-2}day^{-1} for Owerri.

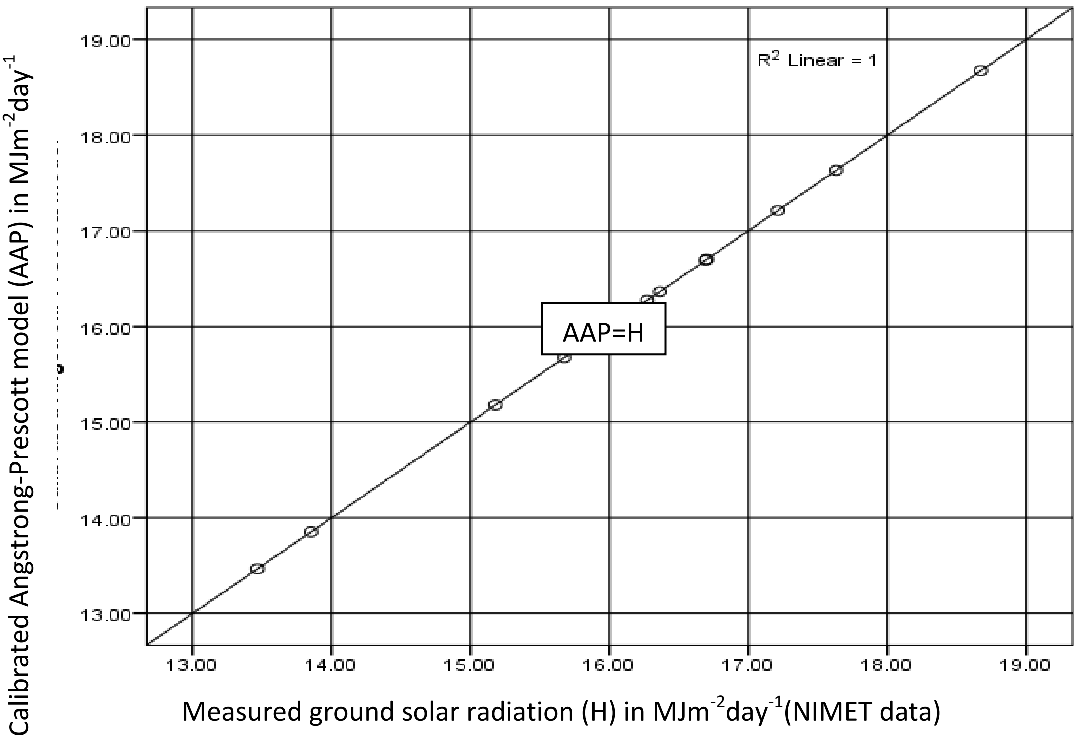

Figure 8: Measured monthly ground global solar radiation (H) and calibrated Angstrom-Prescott model (AAP) in MJm^{-2}day^{-1} for Owerri.

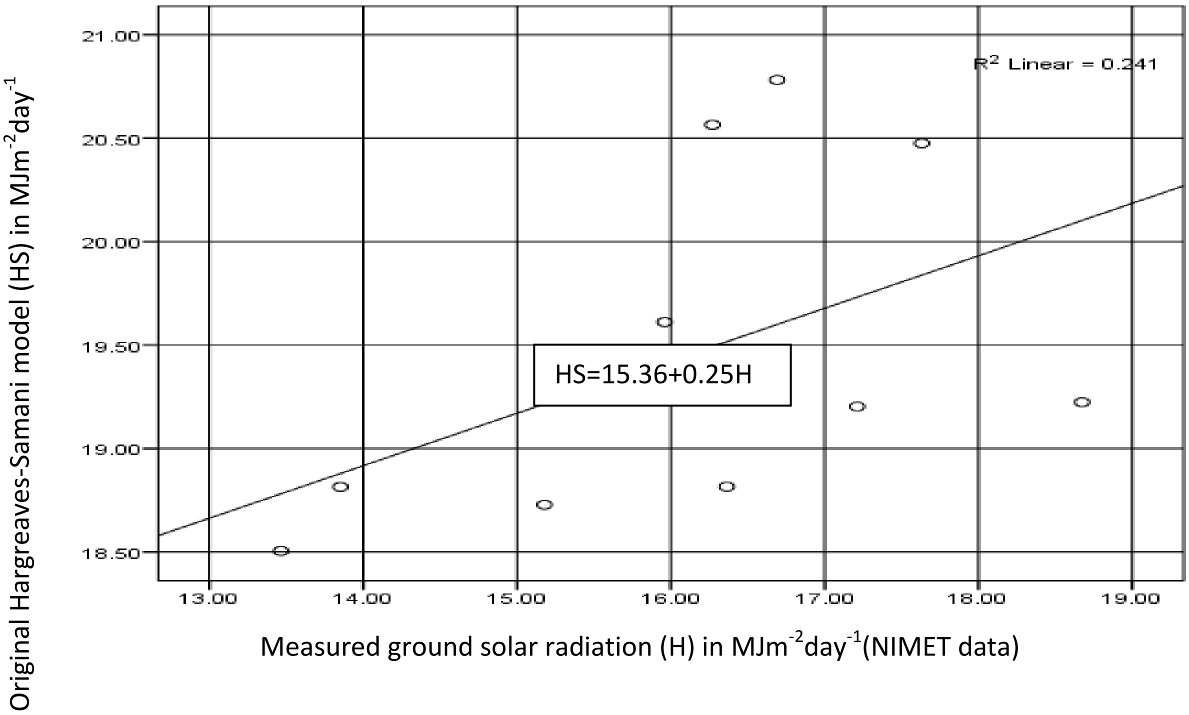

Figure 9: Measured monthly ground global solar radiation (H) and calculated original Hargreaves-Samani model (HS) in MJm^{-2}day^{-1} for Owerri

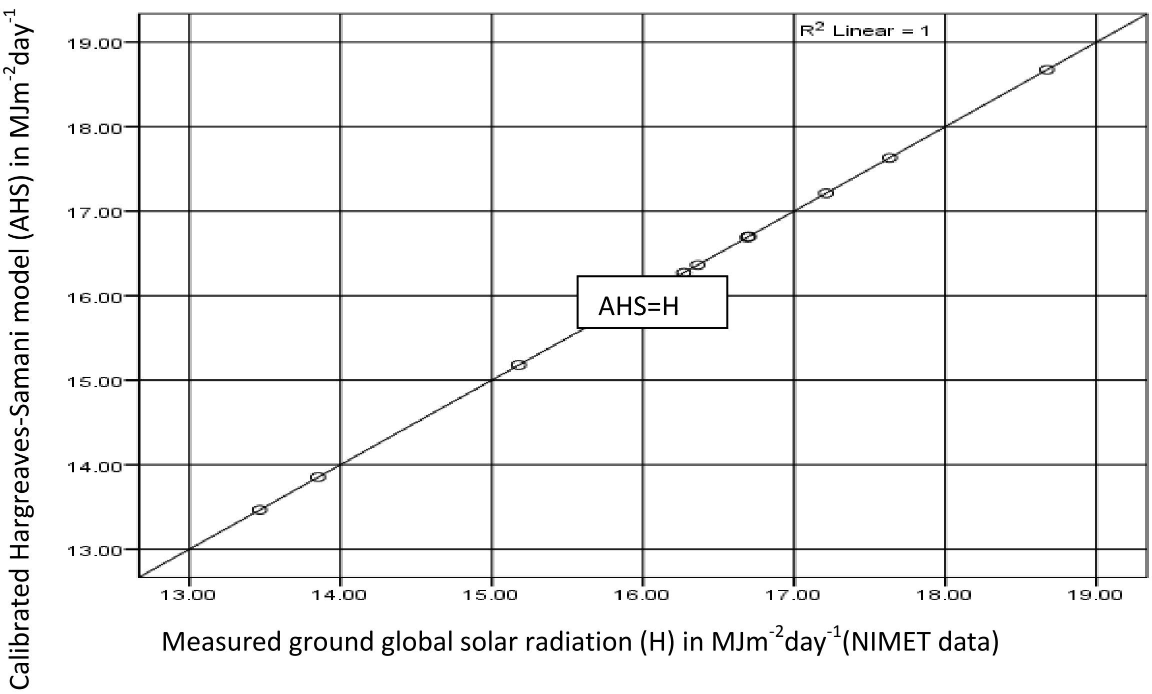

Figure 10: Measured ground global solar radiation (H) and calibrated Hargreaves-Samani model (AHS) in MJm^{-2}day^{-1} for Owerri.

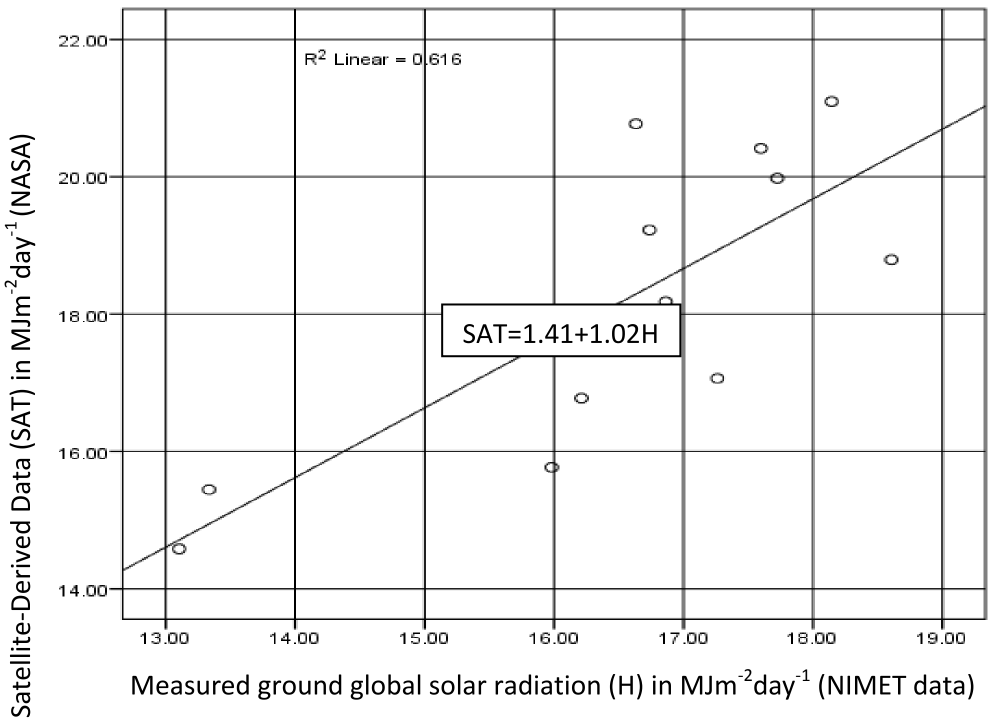

Figure 11: Measured monthly ground global solar radiation (H) and Satellite-Derived Data (NASA) between 2000-2005 in $MJm^{-2}day^{-1}$ for Enugu

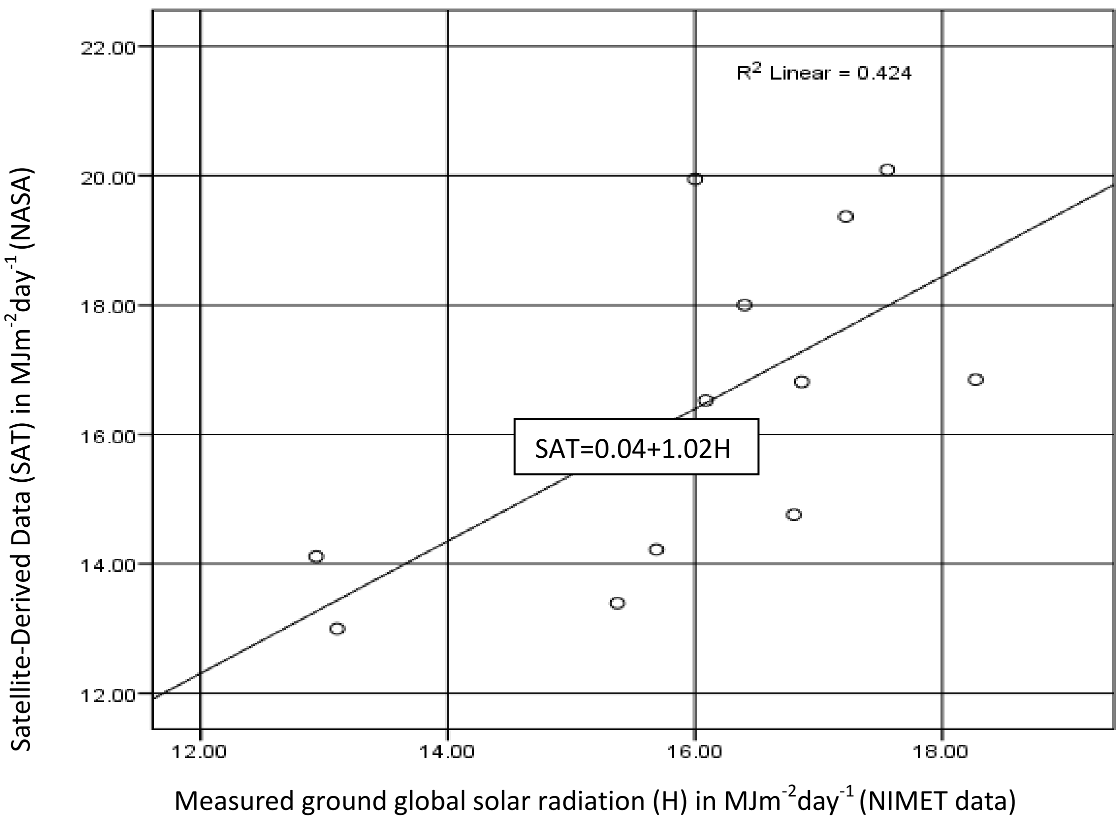

Figure 12: Measured ground global solar radiation (H) and Satellite-Derived Data (NASA) between 2000-2005 in $MJm^{-2}day^{-1}$ for Owerri

5.2. Discussion

5.2.1. Ground measured global solar radiation data for Enugu and Owerri

A close examination of Table 1 shows that the maximum values of the monthly mean daily sunshine hours and the monthly mean daily solar radiation on a horizontal surface for Owerri are 8.85 hours and 18.67 $MJm^{-2}day^{-1}$ and they occur in the month of May and November, respectively. This value is within what is expected of a tropical site [31]. The month of occurrence, May, is not expected for daily sunshine hour because of heavy rainfall, relative humidity and low ambient temperature loading greatly reduces the intensity of daily sunshine hours for the months of November – January. This could be attributed to the effect of climate change on the station. While the month of occurrence, November, is expected value of global solar radiation because the aerosol mass loading during Hamattan season had not commenced thereby increasing the intensity of solar radiation [31-32].

The minimum values of the monthly mean daily sunshine hours and the monthly mean daily global solar radiation on the horizontal surface are 4.25 hours and 13.47 $MJm^{-2}day^{-1}$, respectively and they occur in the month of July and August, respectively. Again, this value is within what is expected of a tropical site [32]. The month they occurred is also well expected because is characterized by heavy rainfall and low values of minimum and maximum temperature as shown in Table 1.

Also from Table 2, it is shown that the maximum values of the monthly mean daily sunshine hours and the monthly mean daily solar radiation on a horizontal surface for Enugu are 10.24 hours and 19.03 $MJm^{-2}day^{-1}$ and they occur in the month of May and November respectively. This value is within what is expected of a tropical site [32]. The month of occurrence, May, of daily sunshine hour is not expected for because of heavy rainfall, relative humidity and cloud cover loading greatly reduces the intensity of daily sunshine hours due to climate change. While the month of occurrence of global solar radiation, November, is expected value because of high intensity of solar radiation without the interference of harmattan season when aerosol mass loading greatly reduces its intensity [31-32].

The minimum values of the monthly mean daily sunshine hours and the monthly mean daily global solar radiation on the horizontal surface for Enugu are 7.02 hours and 13.51 $MJm^{-2}day^{-1}$ respectively, and they occur in the months of August and December. Again, this value is within what is expected of a tropical site [32]. The month they occur in is also well expected because is characterized by heavy rainfall for global solar radiation and the interference of Harmattan season when aerosol mass loading greatly reduces its intensity for sunshine hours.

From NASA and NIMET datasets reported in Tables 3 and 4 and Figures 2 and 3 for Enugu and Owerri, it could be observed that the NASA data were higher in numerical values compared to NIMET values. This could be attributed to crude instrument and lackof professional personnel capable of calibrating and setting measuring instrument so as to capture maximum global solar radiation in Nigeria by NIMET.

5.2.2. Target and predicted values of Hargreave-Samani and Armstrong Prescott models for Enugu and Owerri

The results of the new single hybrid parameter-based expression (HP) for calibrating Hargreaves-Samani coefficient (AHC) and Angstrom-Prescott (AAP) based on linear regression according to equations 8-13 are presented in Tables 7 and 8. The results were used to develop two (Hargreaves-Samani coefficient and Angstrom-Prescott) HP models for estimating the monthly mean daily H on the horizontal surface employing sunshine hour, maximum sunshine duration, minimum and maximum temperature for the Enugu and Owerri stations.

The empirical constants of the proposed model, varying MBE, MPE, RMSE NS and PE could be attributed to seasonal variations of the global solar radiation (H) caused apparently by the atmospheric dust, presence of water vapour and ozone, cloudiness, difference in temperature range and associated atmospheric moisture with the movement of the Hadley cell circulation system along the equatorial line in the atmosphere which differs from Enugu local climate and regional geography to Oweeri environs. Tables 5 and 6 show that the proposed model predicted the observed AHC (target) with high precision.

The values of Hargreaves-Samani coefficient (AHC) for Enugu and Owerri stations are presented in Tables 7 and 8. The values of the AHC ranged from 0.121-0.170 with the corresponding mean value of 0.145 for Enugu station; and 0.124-0.165with the corresponding mean value of 0.141 for Owerri station. The values obtained for the two stations studied are similar due to proximity in local climate and regional geography. However, the report for the two studied stations are equally similar to the report for Enugu and other South-Eastern part of the country (0.20) and Nigeria at large (0.21) using extraterrestrial solar radiation, maximum sunshine hour, and minimum and maximum temperature by Nwokolo and Ogbulezie [6]. Similarly, the value obtained in this study compares favourably with the reported by other researchers across the globe. Allen [25] employed ratio of atmospheric pressure at the site (Ps, kPa) and the sea level (Po, 101.3kPa) to estimate empirical coefficient of HS model. The researcher (Allen) reported values of 0.17 for interior regions and 0.20 for coastal regions.

5.2.3. Global solar radiation, Angstrom-Prescott model and Hargreave-Samani model for Enugu and Owerri

Hargreaves [13] calibrated HS model and obtained AHC of 0.16 for interior regions and 0.19 for coastal regions. These discrepancies could be attributed to the fact that global solar radiation is solely dependent on local climate and regional geography of the site. In general, an observable trend of the AHC was recorded in this study. All the AHC values were higher than those of the original HS model (0.17) for annual values, coastal and interior regions.

The values of Angstrom-Prescott coefficients *a* and *b* for Enugu and Owerri stations are presented in Tables 7 and 8.

(a) Global solar radiation, Angstrom-Prescott model and Hargreaves-Samani model for Enugu

The values of the $AAP_{(a)}$ ranged from 0.166-0.230 with the corresponding mean value of 0.1896, the values of the $AAP_{(b)}$ ranged from 0.332-0.4603 with the corresponding mean value of 0.3793 for Enugu station.

(b) Global solar radiation, Angstrong-Prescott model and Hargreaves-Samani model for Owerri

The values of the $AAP_{(a)}$ ranged from 0.175-0.234 with the corresponding mean value of 0.203 for Owerri station, the values of the $AAP_{(b)}$ ranged from 0.351-0.468 with the corresponding mean value of 0.4071 for Owerri station.

The values of *a* and *b* obtained for the two stations studied are similar due to proximity in local climate and regional geography. From the result obtained for Enugu and Owerri stations reported in Tables 7 and8 in relation to Allen *et al*. [17] recommendation that AAP coefficients *a* = 0.25 and *b* = 0.50, it could be observed that the values in obtained for the two stations studied yielded slightly lower values compared to Allen *et al*. [17] recommended values. This could be attributed to the fact that global solar radiation depends solely on local climate and regional geography at any location upon the face of the Earth as a result of the movement and rotation of the Earth about its axis. Values of *a* and *b* obtained in this study are within the range of those obtained by other researchers in some parts of the world (Table 9).

Table 9: Some published Angstrom-Prescott constants across the globe

Location	AAP(a)	AAP(b)	Reference
World	0.23	0.48	Black *et al*. [33]
World	0.29 cos (latitude)	0.52	Glover & McCulloch [34]
South-Eastern England	0.18	0.55	Penman [35]
Canberra, Australia	0.25	0.54	Quoted by Penman [35]
Brisbane, Australia	0.23 – 0.35	0.38 – 0.54	Cartledge [36]
Wageningen, Netherlands	0.20	0.56	Spitters [37]

Comparison of monthly global solar radiation values by observed data, those computed by original and calibrated Hargreaves-Samani (HS) and Angstrom-Prescott (AAP) models in Enugu and Owerri are presented in Tables 5 and 6 and also in Figures 1 and 6, respectively. It could be observed that the original and calibrated HS and AAP model overestimated observed global solar radiation (H) for two stations at monthly time-scale; whereas, the calibrated HS and APP yielded precise estimate the observed data.

The performances of the original and calibrated HS models for Enugu and Owerri at annual timescale are presented in Tables 5 and 6. From the trend it is seen that the locally calibrated HS and AAP models had much better performances than the original HS and APP models at each station in respect of MBE, MPE, RMSE, NS and PE.

6. Conclusion

The Hargreaves-Samani (HS) model was recommended by Allen *et al*. [17] as the simplest and practical temperature method for estimating global solar radiation (H). Also, the Angstrom-Prescott (AP) sunshine model has been accepted globally for estimating global solar radiation. This is due to the close relationship existing between HS and AP models. In this investigation, the researchers employed monthly mean meteorological data from 2000-2014 to calibrate Angstrom-Prescott and Hargreaves-Samani coefficients based on a single hybrid parameter-based model for Enugu and Owerri at both monthly and annual timescales. From the statistical analysis, calibrated Angstrom-Prescott and Hargreaves-Samani models yielded better performance than the original Angstrom-Prescott and Hargreaves-Samani models for both cities of Enugu and Owerri.

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