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Research paper

A single hybrid parameter-based model for calibrating hargreaves-samani coefficient in Nigeria

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Abstract

The present research was designed to locally calibrate Hargreaves-Samani computing model (HS) in twenty-one (21) locations with their corresponding coastal and interior regions in Nigeria employing a single hybrid parameter-based model to obtain the adjusted Hargreaves-Samani coefficient (AHC) for Nigerian environment. To achieve this purpose, meteorological parameters such as extraterrestrial solar radiation, maximum sunshine duration, minimum and maximum temperatures were employed as input parameters to compute the original HS model and equally calibrate the original HS model. The monthly AHCs were obtained by multiplying the 0.17 by the monthly ratio of the observed global solar radiation (H) to H calculated from original HS model. The average value was obtained per station. These observed AHC values were considered as the target values for the development of hybrid parameter-based models (HP) for every station used for calibrating original HS model. On the whole, the result from the statistical indicators confirmed that the locally calibrated HS model performed better than the original HS model in all stations (including coastal and interior regions) investigated. Both the original and calibrated HS models underestimated H at annual timescale, but the calibrated HS model provided closer average values with H, which could confirm the good performances of the calibrated HS model. Therefore, the calibrated HS model obtained in this research could be highly recommended for estimating H in Nigeria when only temperature data are available.

Keywords: *Hargreaves-Samani Model; Calibration; Hybrid Parameter-Based Model; Global Solar Radiation; Coastal Region; Interior Region*.

1. Introduction

Solar radiation is the principal renewable-energy source supporting the biosphere and stimulating the biological, chemical and physical processes in the surface of the earth. The amount of solar energy received by the Earth-atmosphere systems is also vital to the energy balance. Therefore, accurate knowledge of solar radiation reaching the Earth's surface is a primary factor since it influences the social systems such as hydrology, ecology and agriculture. However, understanding the local solar radiation is significant for other several applications, including energy planners, engineers, architectural design and solar-energy systems Manzano et al. [1]; meteorological and agricultural experts, architect's designers and engineers in the design and selection of solar-energy conversion systems, architectural design, green house structures, heating and cooling system Boukelia et al. [2]; industrial and applications areas such as exciting electrons in a photovoltaic cell, solar heating, solar thermal energy, solar architecture, molten salt power, plants and supplying energy to natural processes like photosynthesis thermal system and photovoltaic Nwokolo and Ogbulezie [3]; meteorology, climatology, radiation and energy budgets, water treatment processes, heating and natural lighting, agriculture and forestry and the use of renewable-energy Souza et al. [4]; air-conditioning engineers and energy-conscious designers of building [5].

In spite of the efforts of governments, scientists, researchers as well as investors so far to exploit solar energy via various technologies, solar radiation potential is fundamentally unexploited yet Nwokolo [6]. For example, the amount of energy emitted by sun is so enormous that in case of converting only 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].

Nigeria is a high insolation country with about an average of 2800 hours/year of of sunshine. Therefore, qualification of this renewable-energy capacity that has the energy 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, plays a significant role in emerging new energy technologies. However, irrespective of the significance of determining solar radiation, its routine measurement is not as widespread as other meteorological parameters such as temperature, precipitation and relative humidity, etc as a result of cost implication, maintenance and calibration of the pyranometer involved in ground measurement, especially in rural area and developing countries, numerous 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].

Kimball [16] was the first researcher that studied on the relationship between solar radiation and sunshine duration then Angstrom [10] proposed that this relationship was linear. Prescott [11] first put the Angstrom equation in terms of extraterrestrial solar radiation. Later, for the same reason, another modification proposed by Page [12] who considered variation of open day solar radiation with the extraterrestrial solar radiation. Since last decades, several solar-energy researchers have employed Angstrom-Prescott-Page model globally as a baseline further developing empirical models for estimating global solar radiation using the same parameter, other meteorological parameters, geographical parameters, geometrical parameters and astronomical parameters that will best fit the local climate of their interest Nwokolo [6].

Sunshine-based models are the most commonly used model for estimating global solar radiation in Nigeria owing to the fact that after investigating a large number of studies, the authors observed that sunshine duration fraction has the highest influence on the accuracy, followed by ambient temperature besides its availability and reliable measured sunshine duration data in most meteorological stations in Nigeria and across the globe [3, 6]. This radiometric model pioneered by Kimball [16] and Angstrom [10] and modified by Prescott [11] and Page [12] and other researchers have been applied by countless number of 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, b) of equation (2) employing meteorological parameters of the site of interest. Apart from an Angstrom-Prescott-Page type model, those fitted by Rietveld [17] seems to be universally applicable. However, Akpabio et al. [18] and Falayi and Rabiu [19] employed empirical model for estimating monthly mean daily global solar radiation on the horizontal surface with a 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 seems to be universally applicable. Countless empirical models based on the Angstrom-Prescott-Page type model and other modified such as exponential form, logarithm form, second order, third order and power form etc models have been applied across the globe for estimating global solar radiation in literature. Thus, this fundamental relation is given as:

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

Where a and b are the empirical constants, H/H_o is the clearness index, S is the measure of sunshine duration and S_o is the daily maximum possible sunshine duration.

The temperature-based computing models are especially interesting due to its needed input data, air temperature, can be easily measured globally. Hargreaves and Samani [20] firstly developed a temperature-based model for estimating global solar radiation using maximum and minimum temperature, and extraterrestrial solar radiation as an input parameter and obtained an empirical coefficient of 0.17 as shown in equation (2). Since then, it has been recognized as one of the famous, simplest and accurate temperature model for estimate global solar radiation and can be employed for short-term forecasting of global solar radiation. Bayat and Mirlaifi [21] applied Hargreaves and Samani (HS) model and reported a coefficient of 0.16 for Shiaz, Iran. Ohunakin et al. [22] recorded a coefficient of 0.1141 in Osogbo; Adaramola [23] obtained a coefficient of 0.1945 at Akure.

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

Where T_{max} is the maximum temperature, T_{min} is the minimum temperature with the values of AHC, 0.17, for arid and semi-arid regions.

However, Hargreaves [24] calibrated the Hargreave-Samani (HS) model empirical coefficient (a) using data from North America and Europe and observed that (a) varied in different area where climate conditions were totally different, and a local calibration of the HS model was recommended after obtaining a simplified coefficient of 0.16 for interior regions and 0.19 for coastal region. Applying the HS model, Allen [25] suggested employing a self-calibrated model to estimate mean monthly global solar radiation.

In spite of the efforts of several researchers on calibration of HS computing model in the last decades for different climate and geographical location across the global [21, 24-25], but these calibrations were site-specific and cannot be extrapolated to other sites where weather conditions are different (Nigeria), and some calibrated HS models are more complicated compared to the original HS model. However, routine calibration of this computing model should be carried out because of the historical data to calibrate HS model directly ignores the ever-changing climate over the time, which may culminate into good performances of calibrated HS model in the calibrated years, but when data set extends, instability of the calibrated HS model may appear.

Therefore, the aim of this present study was to locally calibrate HS computing model in the twenty- one stations in Nigeria using a single parameter-based model to calibrate the HS empirical coefficient so as to improve the applicability of HS computing model for accurate global solar radiation estimation in Nigeria's environment.

2. Material and method

2.1. Study area

Nigeria is located in the tropics between latitude 4 to 14 ^oN and Longitude 3 to 15 ^oE as shown in Fig. 1. It is bordered by the Gulf of Guinea to the South, Benin to the East. She is blessed with 36 states and its Federal Capital Territory, Abuja, situated at the centre of the country. Nigeria always referred as the giant of Africa has a total land area of 923, 768 sqkm including 13, 000 sqkm of water, a border length of 4.047 km and a coastline of 853 km. The highest point in the country is Chappal Waddi at 2, 419 m (7, 936 ft) and the lowest is the Atlantic Ocean (0 m). River Niger and River Benue are the major rivers in Nigeria, which converge in Lokoja (Kogi State) often known as Conference Town and empty into the Niger Delta, the location of a large area of Central African Mangroves. The climate and vegetation of Nigeria are equatorial in the South, tropical in the Centre, and arid in the North. Rainy and dry seasons are the two distinct seasons in the country. Dry season is attributed to the influence of Inter Tropical Convergence Zone (ITCZ) producing Tropical Continental (TC) associated with dry and dusty North-East winds, which blows from the Sahara desert and finally prevailed over Nigeria; thus, producing the dry-season conditions. The implication is that there is a prolonged dry season in the far North, while the far south undergoes a short dry period annually. However, with the movement of the ITCZ into the Northern hemisphere, the rain-bearing South-West prevails as far inland as possible to bring rainfall during the rainy season. This culminates into prolonged rainy season in the far south, while the far north experiences short rainy periods annually. The dry season begins in April and ends in October. The rainy is characterized by overcast and heavy rain clouds. This result to relatively low global solar radiation, direct normal irradiance, global photosynthetically active radiation, clearness index, sunshine duration, reference evapotranspiration and temperature; high humidity, diffused solar radiation, diffuse photosynthetically active radiation, wind speed and precipitation, etc. as observed between the month of May to October compared to dry season months, November-March. Nigeria is indeed a unique tropical country that cuts across all tropical ecological zones. From the Atlantic Ocean down to the edge of the Sahara desert, all tropical ecological zones are represented. These zones comprise the southern zone of mangrove swamp situated between latitude 4 to 6^o30^1N, the tropical rainforest found around latitude 6^o30^1 to 7^o45^1 N stretching from the South-West to the South-East, the Guinea Savanna belt between latitude 7^045^1 to 10 N, the Sudan Savannah belt around 10 to 12^0 N and Sahel Savannah in areas above latitude 12 ^oN. She is endowed with annual average daily reference evapotranspiration of 6 mm/day ranging from 2.5 mm/day at the coastal region and 9.5 mm/day at the far northern boundary. Similarly, it has an annual average daily global solar radiation of about 4.21 kWh/m^2/day at the coastal region and 6.24 kWh/m^2/day at the Northern boundary. The minimum and maximum temperatures are 16.90 to 37.90 ^oC with an average daily sunshine of 6. 25 hours ranging between 3.5 hours at the coastal region and 9.9 hours at the far northern boundary respectively. Moreover, it has an annual average daily relative humidity of about 62 % spanning between about 82 % at the coastal region and 42 % at the northern boundary; while the annual average daily precipitation of about 92 mm, ranging between 1445 mm in the coastal region and 40 mm at the northern boundary.

2.2. Acquisition of data

The long term monthly mean daily global solar radiation on the horizontal surface (H), minimum and maximum temperature at 2 m height for the period of 1983-2005 for the selected state capitals and stations whose region, station code, coordinates and elevations are listed in Table 1 and Fig. 1 were obtained from the National Aeronautics, and Space Administration (NASA) atmospheric science data centre.

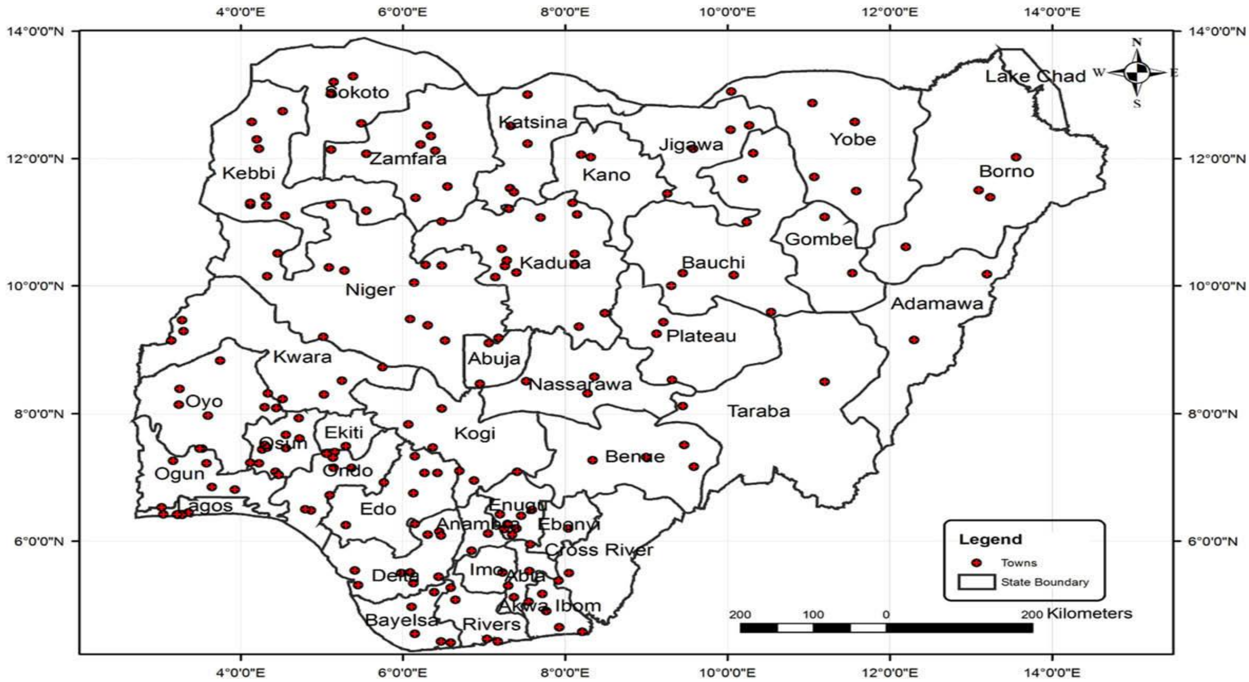

Fig. 1: Map of Nigeria Showing the Geographical Stations of the Cities Used in this Study.

Table 1: Meteorological Stations and Meteorological Variables of Nigeria

Station	State	Station Code	Region	Longitude (ºE)	Latitude (ºN)	Altitude (m)
Calabar	Cross River	1	Coastal	8.317	4.950	42
Port Harcourt	Rivers	2	Coastal	6.998	4.789	52
Uyo	Akwa Ibom	3	Interior	7.933	5.050	45
Yenogoa	Bayelsa	4	Coastal	6.264	4.925	19
Warri	Delta	5	Coastal	5.750	5.517	48
Asaba	Delta	6	Interior	6.750	6.183	46
Benin City	Edo	7	Interior	5.633	6.333	86
Ikeja	Lagos	8	Coastal	3.510	6.563	73
Enugu	Enugu	9	Interior	7.483	6.433	183
Akure	Ondo	10	Interior	5.195	7.250	233
Ilorin	Kwara	11	Interior	4.550	8.500	274
Ibadan	Oyo	12	Interior	3.896	7.388	255
Lokoja	Kogi	13	Interior	6.733	7.800	216
Jos	Plateau	14	Interior	8.900	9.917	587
Bauchi	Bauchi	15	Interior	9.844	10.31	599
Gusau	Zamfara	16	Interior	6.638	12.07	415
Yola	Adamawa	17	Interior	12.46	9.013	430
Kano	Kano	18	Interior	8.500	11.99	457
Kaduna	Kaduna	19	Interior	7.440	10.52	575
Maiduguri	Borno	20	Interior	13.15	11.85	324
Sokoto	Sokoto	21	Interior	5.231	13.05	293
Coastal		22				
Interior		23				
Nigeria		24				

2.3. Hargreaves and samani model

Hargreaves and Samani firstly presented daily air temperature range $\left(\Delta T = T_{\max} - T_{\min}\right)$ and extraterrestrial solar radiation (Ho) to estimate global solar radiation Hargreaves and Samani [20] as given in equation 2. The HS model is often employed to provide H estimation for weekly or longer periods. However, after Hargreaves [24] calibrated HS model using data from North America and Europe, He observed that AHC varied in different areas where climate conditions were totally different and a local calibration of the HS model was recommended after obtaining a simplified coefficient of 0.16 for interior regions and 0.19 for coastal region. In this study, hybrid parameter-based models (HP) were employed to estimate the AHC. Monthly AHCs were obtained by multiplying 0.17 by the monthly ratio of observed H to H obtained from original HS model. The mean AHC value was obtained per station. These “observed” AHC data were considered as the target values for the development of hybrid parameter-based models (HP) for all the stations. The HP was used to evaluate new input combination employing the following variables as potential input parameters: maximum sunshine duration (hours), extraterrestrial solar radiation (kWh/m^2/day), minimum and maximum temperature data (°C). The parameter-based models (HP) employed is expressed as:

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

Where the maximum possible sunshine duration expressed mathematically as:

$$S_o = \frac{2}{15}\cos^{-1}\left(-\tan\delta\tan\varphi\right) \quad (4)$$

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

Where 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) in kWh/m^2/day is the solar radiation intercepted by horizontal surface during a day without the atmosphere expressed theoretically as:

$$H_o = \frac{1}{3.6}\left[\frac{24}{\pi}I_{SC}\begin{pmatrix}1 \\ +0.033\cos\dfrac{360n}{365}\end{pmatrix} \times \begin{pmatrix}\cos\varphi\cos\delta\sin\omega_S \\ +\dfrac{2\pi\omega_S}{360}\sin\varphi\sin\delta\end{pmatrix}\right] \quad (6)$$

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

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

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

2.4. 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 as well as original and calibrated HS models as expressed in equation 8-12.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right) \quad (8)$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{O_i - P_i}{O_i}\right) \times 100 \quad (9)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right)^2} \quad (10)$$

$$NS = 1 - \left[\frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - O_{ave}\right)^2}\right] \quad (11)$$

$$PE = \sum_{i=1}^{n}\left(\frac{O_i - P_i}{P_i}\right) \times 100 \quad (12)$$

Where O_i and P_i are the observed and predicted AHC as well as original and calibrated HS models values of the i-th step obtained by H, AHC, and HS models, respectively. n is the number of observation. O_{ave} is the average value of the observed H and AHC 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 kWh/m^2/day while MPE is measured in %.

Table 2: Meteorological Stations and Input Variables

Station	Ho (kWh/m^2/day)			Tmin (°C)			Tmax (°C)			Δ T (°C)			So (hours)		
	Min	Max	mean	min	Max	mean	min	max	mean	min	Max	Mean	min	max	Mean
Calabar	9.38	10.40	9.97	22.50	24.30	23.42	24.70	27.20	26.01	2.00	3.60	2.59	11.80	12.40	12.08
Port Harcourt	9.38	10.40	9.97	23.30	25.00	24.18	25.50	27.90	26.90	2.10	3.70	2.72	11.80	12.40	12.06
Uyo	9.25	10.40	9.96	21.40	23.30	22.26	26.40	29.90	28.0	4.30	8.30	5.76	11.80	12.40	12.08
Yenogoa	9.38	10.30	9.99	23.30	25.00	24.20	25.50	27.90	26.90	2.10	3.70	2.72	11.80	12.40	12.08
Warri	9.25	10.40	9.96	22.90	24.60	23.78	26.10	29.00	27.67	2.90	5.30	3.89	11.80	12.40	12.13
Asaba	9.11	10.40	9.94	21.30	23.40	22.37	26.70	30.90	28.59	4.60	8.90	6.23	11.70	12.40	12.08
Benin City	9.11	10.40	9.94	21.60	23.50	22.53	26.50	30.40	28.40	4.30	8.30	5.88	11.70	12.40	12.08
Ikeja	9.11	10.40	9.94	23.20	25.20	24.28	25.60	28.50	27.26	2.20	4.30	2.98	11.70	12.50	12.08
Enugu	9.11	10.40	9.94	21.10	23.30	22.24	26.80	31.00	28.62	4.80	9.40	6.38	11.70	12.50	12.08
Akure	8.99	10.40	9.91	20.90	23.00	21.95	26.30	31.20	28.51	4.70	9.60	6.56	11.70	12.50	12.08
Ilorin	8.85	10.50	9.90	20.90	22.90	21.80	26.50	31.90	29.10	5.00	10.60	7.30	11.60	12.60	12.08
Ibadan	8.99	10.40	9.91	21.30	23.30	22.23	26.30	30.70	28.37	4.40	9.10	6.13	11.70	12.50	12.08
Lokoja	8.99	10.40	9.91	21.20	23.30	22.18	26.70	31.90	29.01	4.90	9.90	6.83	11.60	12.50	12.06
Jos	8.72	10.52	9.87	18.60	22.00	20.42	25.10	31.70	28.37	4.40	12.00	7.95	11.50	12.60	12.60
Bauchi	8.58	10.50	9.84	17.40	23.30	20.73	26.40	33.70	29.98	5.10	13.00	9.25	11.50	12.70	12.08
Gusau	8.30	10.50	9.76	16.90	24.20	21.08	27.30	35.30	31.42	5.10	14.20	10.34	11.40	12.80	12.09
Yola	8.72	10.50	9.87	19.10	24.10	21.72	26.90	34.20	30.64	5.20	13.10	8.93	11.60	12.60	12.09
Kano	8.44	10.50	9.82	16.70	23.40	20.68	26.60	34.10	30.23	5.00	13.20	9.56	11.40	12.80	12.08
Kaduna	8.58	10.50	9.84	18.60	22.40	22.66	25.30	32.10	28.85	4.30	12.10	8.19	11.50	12.70	12.09
Maidu-guri	8.44	10.50	9.82	17.30	25.90	22.13	28.20	36.00	32.12	5.50	13.20	9.98	11.40	12.80	1210
Sokoto	8.15	10.60	9.74	17.00	25.60	21.73	28.90	37.90	32.90	6.00	14.50	11.18	11.30	12.80	12.09
Coastal	8.99	10.40	9.93	20.90	25.00	22.65	25.50	31.20	28.15	2.10	9.60	5.51	11.70	12.50	12.08
Interior	8.15	10.00	9.89	16.90	25.90	22.21	25.10	37.90	29.24	2.10	14.50	7.03	11.30	12.80	12.08
Nigeria	8.15	10.60	9.89	16.70	25.90	22.22	24.70	37.90	28.95	2.00	14.50	6.73	11.30	12.80	12.08

3. Results and discussion

3.1. Calibration of hargreaves-samani model

The results of the new single hybrid parameter-based expression (HP) for calibrating Hargreaves-Samani coefficient (AHC) based on linear regression are presented in Table 3-4. The results were used to develop 24 HP models for estimating the monthly mean daily H on the horizontal surface employing extraterrestrial solar radiation, minimum and maximum temperature, and maximum sunshine duration for the 21 stations investigated in the research and their corresponding coastal region, interior region and average of all the stations (Nigerian environment).

The empirical constants of the proposed model, varying MBE, MPE, RMSE and NS 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 (ΔT) and associated atmospheric moisture with the movement of the Hadley cell circulation system along the equatorial line in the atmosphere which differs from one local climate and geographical region to another. Table 3 shows that the proposed model predicted the observed AHC (target) with high precision except Ilorin that yielded poor performances of statistical indicators, indicating that the station requires other meteorological/atmospheric parameters to calibrate HS model in the site.

The values of AHC for each station are presented in Table 4. The values of the AHC ranged from 0.17-0.31 for the 21 stations with the corresponding mean value of 0.21; 0.17-0.29 for the coastal region (Port Harcourt, Calabar, Warri, Yenogoa and Ikeja) with a corresponding mean value of 0.22; 0.17-0.26 for the interior region (remaining stations excluding coastal region stations) with a corresponding average value of 0.20. The values obtained in this research are higher than the result 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. Hargreaves [24] 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.

The higher AHC (0.17-0.29) reported for coastal region is as a result of increase in cloud cover and humidity which returns additional long-wave radiation to the ground, reducing the influence of air temperature range (Tmax-Tmin) on global solar radiation (H), which may cause larger AHC in the region. This indicates that the smaller the air temperature range primarily attributed to the influence of open water bodies on the atmosphere, the larger the AHC, which may cause larger error when estimating global solar radiation (H) by the original HS model as shown in Table 2 and Table 4. Conversely, the smaller the AHC obtained for the interior region is as a result of decrease in humidity and cloud cover which reduces long-wave radiation to the ground, thereby enhancing the effect of air temperature range on H, which may cause smaller AHC in the region. This indicates that the higher the air temperature range principally caused by decreased in humidity, cloud cover and diffuse solar radiation etc on the atmosphere, the smaller the AHC, which could enhance global solar radiation estimation by the original HS model.

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.

Table 3: Meteorological Stations with Proposed AHS Regression Constants and Associated Statistical Parameters

Station	Station Code	a	b	c	d	e	MBE (kWh/m^2/day)	MPE (%)	RMSE (kWh/m^2/day)	NS
Calabar	1	9.07	-19.64	11.86	0.0001	-0.83	0.000133	0.0516	0.000462	0.765
Port Harcourt	2	5.43	-10.99	6.50	0.0001	-0.67	0.003	1.333	0.012	0.857
Uyo	3	4.76	-14.50	8.68	3.880	-2.53	-0.000067	0.0002	0.0023	0.857
Yenogoa	4	5.68	-11.51	6.84	0.0001	-0.73	0.00001	0.000001	0.0000001	0.901
Warri	5	7.03	-15.97	9.68	0.0001	-0.30	0.0000379	0.01644	0.00013	0.709
Asaba	6	0.68	-7.34	4.32	6.86	-4.46	0.0000	0.0000	0.0000	0.501
Benin City	7	-7.14	5.31	-3.24	13.30	-8.54	0.0000	0.0000	0.0000	0.553
Ikeja	8	6.29	-14.59	8.94	0.0001	-0.082	-0.00004	-0.01341	0.000129	0.456
Enugu	9	2.34	-10.62	6.36	6.014	-3.95	0.00017	0.0822	0.00057	0.556
Akure	10	-0.046	-7.009	4.13	8.50	-5.60	0.00006	0.03235	0.0022	0.500
Ilorin	11	2.07	-9.33	5.63	5.32	-3.55	0.00037	0.18529	0.00128	0.371
Ibadan	12	-1.13	-5.68	3.36	9.69	-6.27	-0.00011	-0.05433	0.00038	0.471
Lokoja	13	1.38	-9.41	5.54	7.41	-4.85	0.0000318	0.01592	0.00011	0.466
Jos	14	3.12	-7.13	4.38	-0.16	0.90	-0.000004	-0.00172	0.00001	0.574
Bauchi	15	-0.99	2.54	-1.73	0.59	-0.26	0.000006	0.00031	0.00002	0.963
Gusau	16	-1.39	3.99	-2.57	-0.18	0.33	0.00008	0.03946	0.00027	0.9550
Yola	17	0.69	-1.55	0.91	0.29	-0.07	-0.00002	-0.0109	0.0008	0.8990
Kano	18	-0.003	0.79	-0.48	-0.61	0.60	0.00083	0.4166	0.00289	0.9530
Kaduna	19	-0.232	-0.85	0.29	2.38	-1.48	0.00013	0.06325	0.00046	0.8240
Maiduguri	20	-0.68	2.59	-1.62	-0.63	0.58	-0.00001	-0.00901	0.00006	0.9390
Sokoto	21	-0.89	3.51	-2.23	-1.11	1.08	0.0002	0.0113	0.0006	0.9610
Coastal	22	8.38	-21.16	12.79	1.132	-0.52	0.0001	0.0174	0.0001	0.5280
Interior	23	-0.097	-0.050	-0.047	0.908	-0.548	-0.0068	-3.3937	0.0235	0.4920
Nigeria	24	0.69	-0.73	0.41	-0.68	0.60	0.0001	0.0251	0.0002	0.697

Table 4: Meteorological Stations with Observed, Original and Calibrated HS Equation and Observed and Predicted AHC

Station	H (kWh/m^2/day)			HS (kWh/m^2/day)			AHS (kWh/m^2/day)			Observed AHC			Predicted AHC		
	min	max	mean	Min	Max	mean	Min	max	mean	min	Max	mean	min	max	Mean
Calabar	3.11	5.70	4.28	2.41	3.21	2.71	3.31	5.81	4.27	0.21	0.31	0.27	0.23	0.31	0.26
Port Harcourt	3.24	5.24	4.21	2.46	3.30	2.84	3.16	4.17	3.53	0.21	0.29	0.25	0.25	0.31	0.27
Uyo	3.77	5.59	4.71	3.48	4.75	4.03	4.04	5.49	4.71	0.17	0.21	0.19	0.19	0.22	0.20
Yenogoa	3.11	5.24	4.13	2.41	3.17	2.77	3.30	5.42	4.12	0.21	0.29	0.25	0.23	0.29	0.25
Warri	3.30	5.33	4.53	2.88	3.80	3.32	3.63	5.48	4.52	0.20	0.26	0.23	0.21	0.26	0.23
Asaba	3.82	5.60	4.81	3.65	4.90	4.18	4.10	5.53	4.82	0.17	0.21	0.20	0.19	0.21	0.20
Benin City	3.57	5.49	4.75	3.53	4.69	4.06	3.82	5.65	4.73	0.17	0.22	0.20	0.18	0.21	0.20
Ikeja	3.95	5.49	4.74	2.52	3.34	2.89	4.00	5.49	4.75	0.25	0.30	0.28	0.27	0.30	0.28
Enugu	3.91	5.74	4.92	3.71	4.98	4.22	4.26	5.71	4.92	0.17	0.21	0.20	0.19	0.21	0.20
Akure	3.78	5.77	4.94	3.72	4.97	4.26	4.11	5.68	4.92	0.16	0.21	0.20	0.19	0.21	0.20
Ilorin	3.95	6.02	5.15	3.84	5.20	4.48	4.27	5.82	5.15	0.17	0.22	0.20	0.19	0.20	0.20
Ibadan	3.79	5.70	4.91	3.60	4.83	4.12	4.08	5.66	4.88	0.17	0.22	0.20	0.19	0.22	0.20
Lokoja	4.13	5.84	5.10	3.76	5.08	4.35	4.43	5.73	5.10	0.17	0.21	0.20	0.19	0.21	0.20
Jos	4.21	6.35	5.47	4.21	6.35	5.47	3.64	5.60	4.60	0.19	0.23	0.20	0.19	0.21	0.20
Bauchi	4.95	6.40	5.77	3.95	5.83	4.97	3.95	5.83	4.97	0.18	0.22	0.20	0.18	0.22	0.20
Gusau	5.25	6.84	6.01	3.99	6.31	5.19	5.17	6.70	5.98	0.17	0.25	0.20	0.17	0.24	0.20
Yola	4.79	6.41	5.70	3.95	5.84	4.89	5.05	6.44	5.70	0.18	0.22	0.20	0.18	0.22	0.20
Kano	5.16	6.69	5.86	3.95	6.08	5.03	5.16	6.35	5.65	0.18	0.24	0.20	0.17	0.32	0.20
Kaduna	4.47	6.32	5.64	3.63	5.55	4.65	4.81	6.26	5.63	0.19	0.24	0.21	0.19	0.23	0.21
Maiduguri	5.14	6.70	5.90	4.15	6.08	5.17	5.37	6.60	5.90	0.18	0.22	0.20	0.18	0.22	0.20
Sokoto	5.25	7.15	6.24	4.37	6.54	5.42	5.18	6.99	6.63	0.17	0.24	0.20	0.17	0.24	0.20
Coastal	3.24	5.77	4.59	2.46	4.97	3.56	3.16	5.68	4.44	0.17	0.29	0.22	0.18	0.25	0.28
Interior	3.30	7.15	5.25	2.88	6.54	4.47	3.63	6.99	5.23	0.17	0.26	0.20	0.25	0.29	0.22
Nigeria	3.11	7.15	5.06	2.41	6.54	4.11	3.16	6.99	5.01	0.17	0.31	0.21	0.18	0.26	0.21

3.2. Performances of Hargreaves-samani model

Comparison of monthly global solar radiation values by observed data, those computed by original and calibrated HS models in each station are presented in Fig. 2-5 and also in Table 4. It could be observed that the original and calibrated HS model underestimated observed global solar radiation (H) for all stations at monthly time-scale; however, the underestimation of calibrated HS model was lower than that of original HS model. Average for all the stations, the original and calibrated HS models underestimated H by 24.99% and 1.1039% at monthly timescale, respectively as shown in Table 5.

Table 5 and Fig. 6-10 also presented the performances of the original and calibrated HS models in each station at annual timescale for the average of all stations, interior region and coastal region. From the overall trend (21 stations) of MBE, MPE, RMSE and NS, the locally calibrated HS model had much better performances than the original HS model at each station. The MBE, MPE, RMSE and NS of the calibrated HS model for each station varied significantly, with MBE ranging -0.00003 to 0.0567 kWh/m^2/day, MPE ranging -0.0061 to 1.3460 %, RMSE ranging 0.0001-0.2136 kWh/m^2/day and NS ranging 0.847-0.973, respectively. Compared with the calibrated HS model, MBE, MPE, RMSE and NS of the original HS model were much more subject to fluctuation, with MBE ranging 0.04917-0.1532 kWh/m^2/day, MPE ranging 1.02110-3.2394 %, RMSE ranging 0.1703-0.53079 kWh/m^2/day and NS of 0.464-0.943, respectively.

The performance of the locally calibrated HS model also yielded better result for the coastal and interior regions of the studies sites (Table 5). The MBE, MPE, RMSE and NS of the calibrated HS model for the coastal and interior regions varied significantly with average MBE of 0.0125 and 0.00167 kWh/m^2/day, MPE of 0.272333 and 0.03175 %, RMSE 0.0433 and 0.00577 kWh/m^2/day and NS 0.843 and 0.949, respectively. Compared with the calibrated HS model, MBE, MPE, RMSE and NS of the original HS model were much more subject to fluctuation, with average MBE of 0.0858 and 0.065 kWh/m^2/day, MPE of 4.04866 and 1.2381 %, RMSE of 0.2974 and 0.2252 kWh/m^2/day, and NS of 0.707 and 0.866 for coastal region and interior region, respectively.

Poor performances of the original HS model were observed in 21 stations in Nigeria, especially in the coastal region (Port Harcourt, Warri, Calabar and Ikeja) where cloud cover and humidity are high. High cloud and humidity attenuate air temperature range which is the most important variable in the original HS model. Increased cloud cover also return additional long-wave radiation to the ground thereby reducing the effect of air temperature range on global solar radiation (H), which may cause larger error obtained in the coastal region employing original HS model. The present study found the calibrated HS model had better performances for monthly global solar radiation estimation, indicating that the calibrated HS model could be recommended to estimate monthly global solar radiation for coastal and interior regions and in Nigeria as a whole.

Table 4 presents the annual variation of the annual observed global solar radiation (H), H computed by original and calibrated HS models in Nigeria. From the general trend of the distribution, H decreased from the far Northern region of Sokoto to the far southern region of Port Harcourt for the observed data, and original and calibrated HS models. Averaged to the whole area, the annual H for observed data, original and calibrated HS models were 5.06 kWh/m^2/day, 4.11kWh/m^2/day 11kWh/m2/day and 5.01 kWh/m^2/day, respectively, and the original and calibrated HS models underestimated H by 24.99 % and 1.039 % at annual timescale. The annual variations of the observed data could be attributed to the combined effect of climatic factors affecting H, while the annual variation in the patterns of the annual original and calibrated HS models may be caused by the spatial distribution of air temperature. Air temperature decreased from the far Northern region of Sokoto to the far southern region of Calabar (Table 2). Same annual patterns of the H for the two models were observed, but the calibrated HS model provided closer H values at annual timescale (Fig. 2).

The present study found both the original and calibrated HS models underestimated H at annual scale in Nigeria, in accordance with the findings of [24, 25] in other parts of the world. However, the original HS model overestimated at monthly timescale in the month of August for Uyo, Asaba, Akure, Ibadan, Enugu, Ilorin and Osogbo. The month of occurrence, August, is well expected because it is characterized by heavy rainfall, high humidity and cloud cover in the climax of the growing season. The HS model was developed to estimate global solar radiation for the growing season and is theoretically not valid for estimating global solar radiation (H) for non-growing season, but overestimation was observed during the growing season of main crops in this research, although the values were not disclosed in the paper. Also, the calibrated HS model overestimated H for all stations in several months at monthly timescale, except Port Harcourt station. Average for all the stations, the original and calibrated HS models overestimated H by 0.15-4.41% and 0.05-155.03 % at monthly time scale, respectively.

This study calibrated HS model based on single hybrid parameter-based models for 21 stations and in coastal and interior regions of

Nigeria using extraterrestrial solar radiation, minimum temperature, maximum temperature, and maximum sunshine duration, updating the AHC of the model and finally improving the performances of the model. However, it is a mathematical approach, hence; the calibration of the HS model is just based on mathematical theory, and no physical basis of global solar radiation processes is taken into consideration. As a result of higher cloudiness in coastal region, lower global solar radiation values were found compared with interior regions in Nigeria. This may cause larger underestimation of the HS model, as observed for coastal region stations with the highest cloudiness where the original HS model totally underestimated global solar radiation (Port Harcourt) at monthly timescale, thus further study should focus on applying recent measured solar radiation data for the calibration. Thus, adjusted Hargreaves-Samani coefficient (AHC) in Table 4 could be employed to estimate global solar radiation in Nigerian environment employing the proposed functional form reported in equation 3.

Table 5: Meteorological Stations with Associated Statistical Indicators

Station	Station Code	Region	MBE HS	AHS	MPE HS	AHS	RMSE HS	AHS	NS HS	AHS	PE HS	AHS
Calabar	1	Coastal	0.1292	-0.0008	3.0321	-0.0196	0.4474	0.0029	0.912	0.927	56.41	0.07
Port Harcourt	2	Coastal	0.1142	0.0567	2.7118	1.3460	0.1963	0.0116	0.931	0.954	43.30	18.42
Uyo	3	Interior	0.0558	-0.0008	1.1879	-0.0177	0.1934	0.0029	0.896	0.928	16.56	-0.16
Yenogoa	4	Coastal	0.1117	-0.0003	2.7104	-0.0061	0.3868	0.0087	0.943	0.973	47.65	0.08
Warri	5	Coastal	0.1001	0.0003	2.2150	0.0077	0.3468	0.0012	0.904	0.920	35.71	0.19
Asaba	6	Interior	0.0525	-0.0017	1.0938	-0.0347	0.1819	0.0058	0.882	0.908	14.94	-0.37
Benin City	7	Interior	0.0492	0.0067	1.0574	-0.1434	0.1703	0.0231	0.811	0.868	16.78	0.25
Ikeja	8	Coastal	0.1532	-0.0016	3.2394	-0.0342	0.5308	0.0056	0.895	0.906	63.76	-0.16
Enugu	9	Interior	0.0575	-0.0083	1.1711	-0.0170	0.1992	0.0029	0.898	0.929	16.49	0.004
Akure	10	Interior	0.0558	0.0008	1.3252	0.01690	0.1934	0.0029	0.874	0.894	15.61	0.39
Ilorin	11	Interior	0.0558	0.0002	1.0841	-0.0046	0.1934	0.0007	0.829	0.858	14.93	-0.08
Ibadan	12	Interior	0.0650	0.0017	1.3265	0.0340	0.2252	0.0058	0.839	0.874	18.89	0.40
Lokoja	13	Interior	0.0617	-0.0008	1.2115	-0.0164	0.2136	0.2136	0.890	0.915	17.18	-0.20
Jos	14	Interior	0.0717	-0.0006	1.3126	-0.0102	0.2483	0.0019	0.904	0.931	19.38	-0.020
Bauchi	15	Interior	0.0658	0.0003	1.1429	-0.0048	0.2281	0.0009	0.871	0.962	17.03	0.042
Gusau	16	Interior	0.0673	0.0020	1.1215	0.0326	0.2331	0.0007	0.464	0.922	17.52	0.49
Yola	17	Interior	0.0665	-0.0008	1.3596	-0.0137	0.2304	0.0027	0.839	0.940	17.36	-0.13
Kano	18	Interior	0.0692	0.0175	1.1803	0.2986	0.2396	0.0606	0.636	0.847	17.85	3.77
Kaduna	19	Interior	0.0825	0.0008	1.4628	0.0148	0.2858	0.0029	0.805	0.892	22.34	0.19
Maiduguri	20	Interior	0.0601	-0.0009	1.0211	-0.0153	0.2083	0.0031	0.733	0.959	14.83	-0.11
Sokoto	21	Interior	0.0907	-0.00003	1.0839	-0.0005	0.2339	0.0001	0.481	0.953	16.34	0.19
Coastal	22		0.0858	0.0125	4.0487	0.2723	0.2974	0.0433	0.707	0.843	30.22	3.888
Interior	23		0.065	0.0017	1.2381	0.0318	0.2252	0.0058	0.866	0.949	17.91	0.2355
Nigeria	24		0.0792	0.0042	1.5646	0.0823	0.2742	0.0144	0.825	0.940	24.99	1.1039

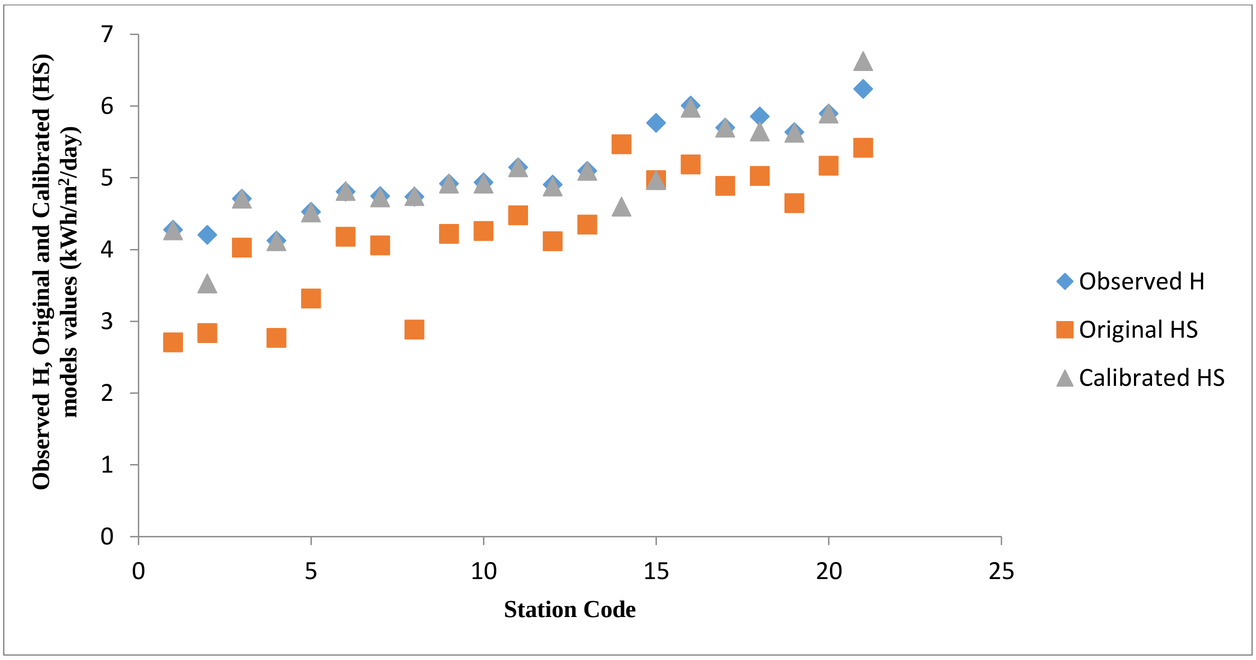

Fig. 2: Comparison of Annual Observed H Values, Original HS and Calibrated HS Models in Each Station of Nigeria.

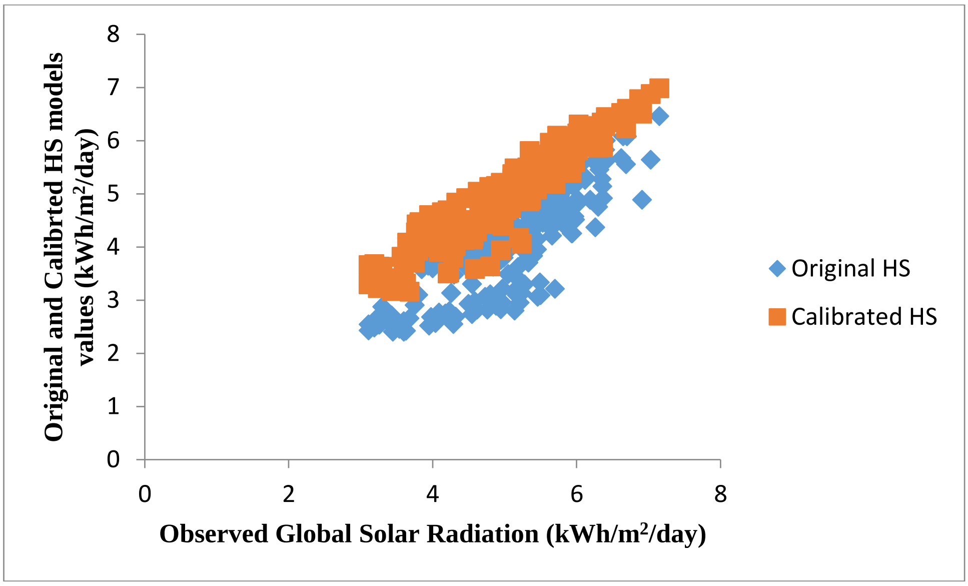

Fig. 3: Comparison of Monthly Observed H Values, Original HS and Calibrated HS Models in Each Station of Nigeria

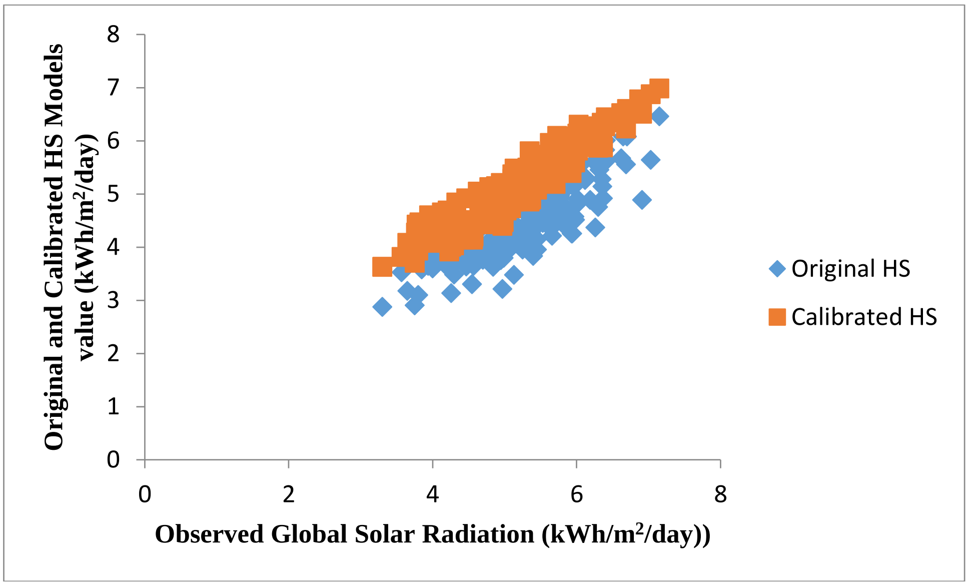

Fig. 4: Comparison of Monthly Observed H Values, Original HS and Calibrated HS Models for Interior Region of Nigeria.

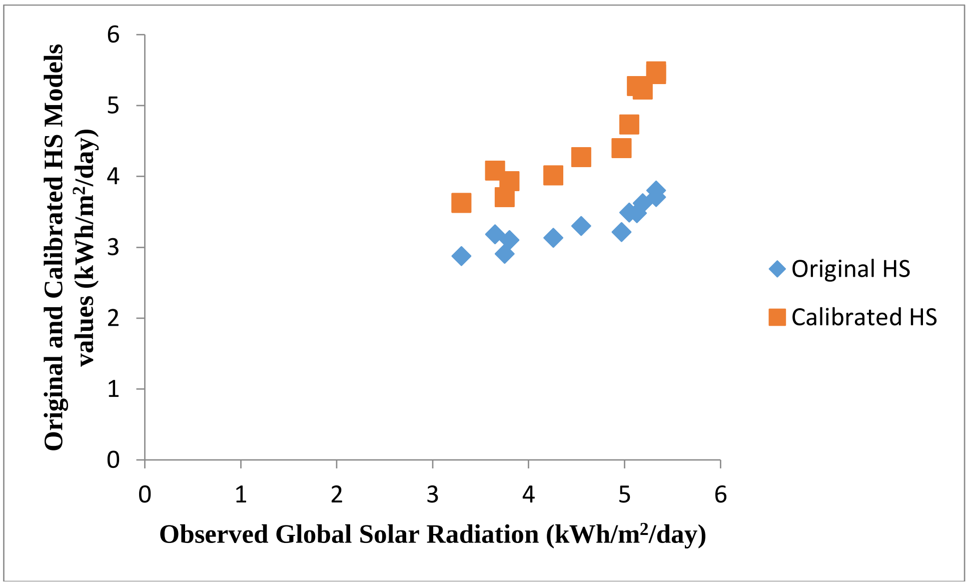

Fig. 5: Comparison of Monthly Observed H Values, Original HS and Calibrated HS Models for Coastal Region of Nigeria.

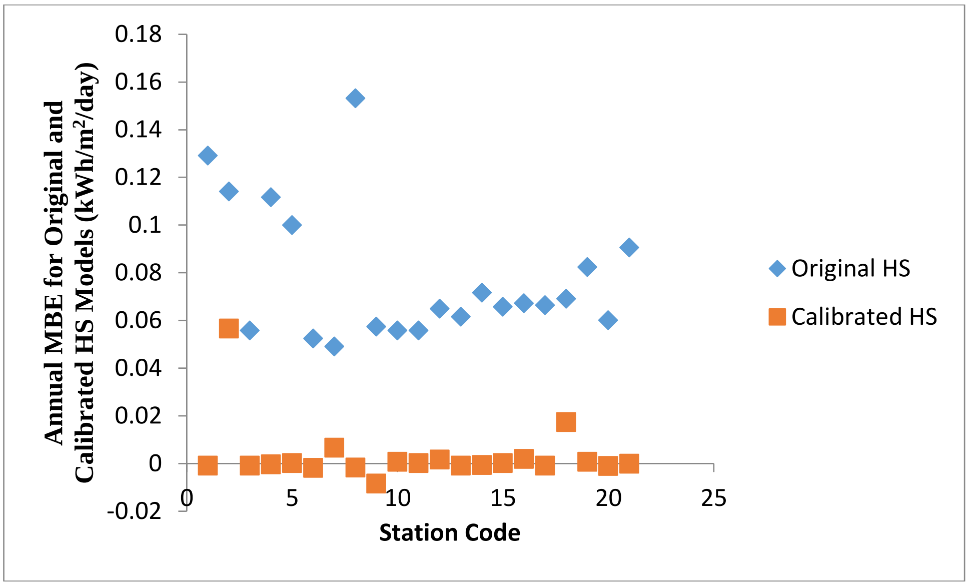

Fig. 6: Comparison of Annual MBE of Original and Calibrated HS Models with Station Code for All Stations.

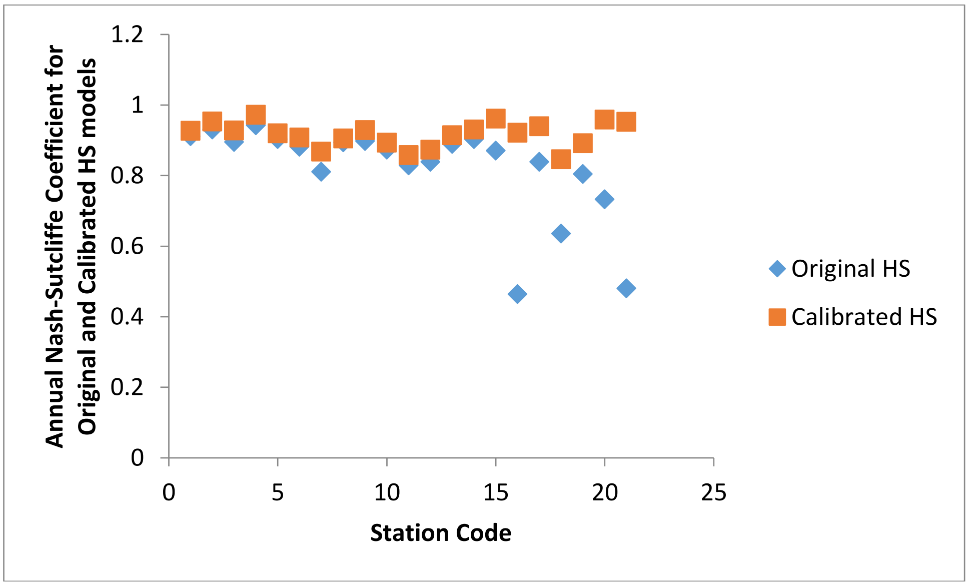

Fig. 7: Comparison of Annual Nash-Sutcliffe Coefficient (NS) of Original and Calibrated HS Models with Station Code for All Stations.

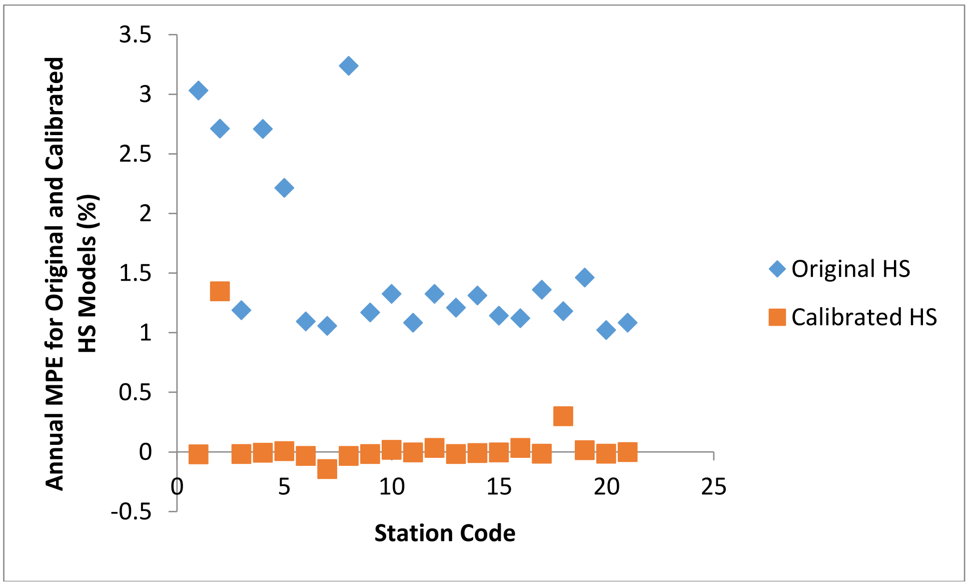

Fig. 8: Comparison of Annual MPE of Original and Calibrated HS Models with Station Code for All Stations.

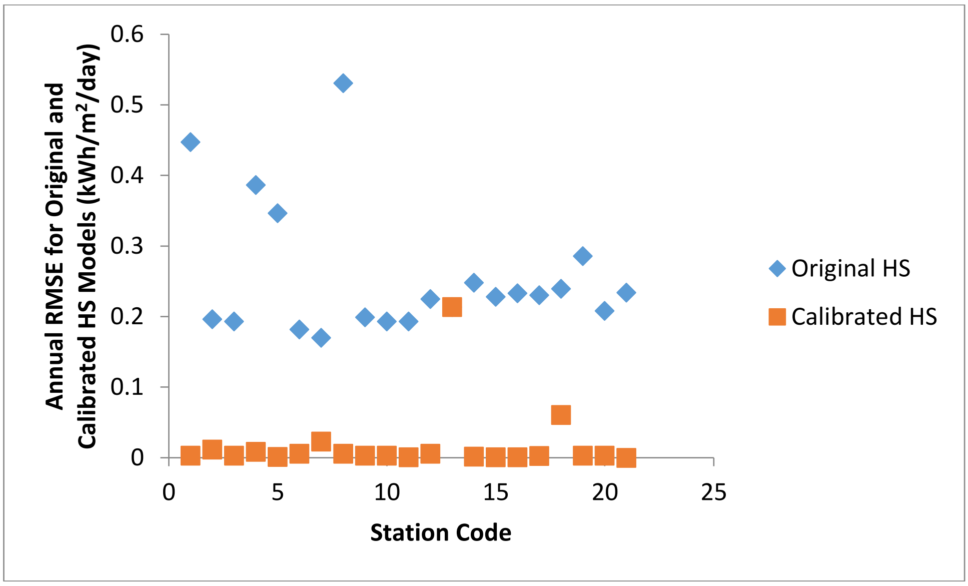

Fig. 9: Comparison of Annual RMSE of Original and Calibrated HS Models with Station Code for All Stations.

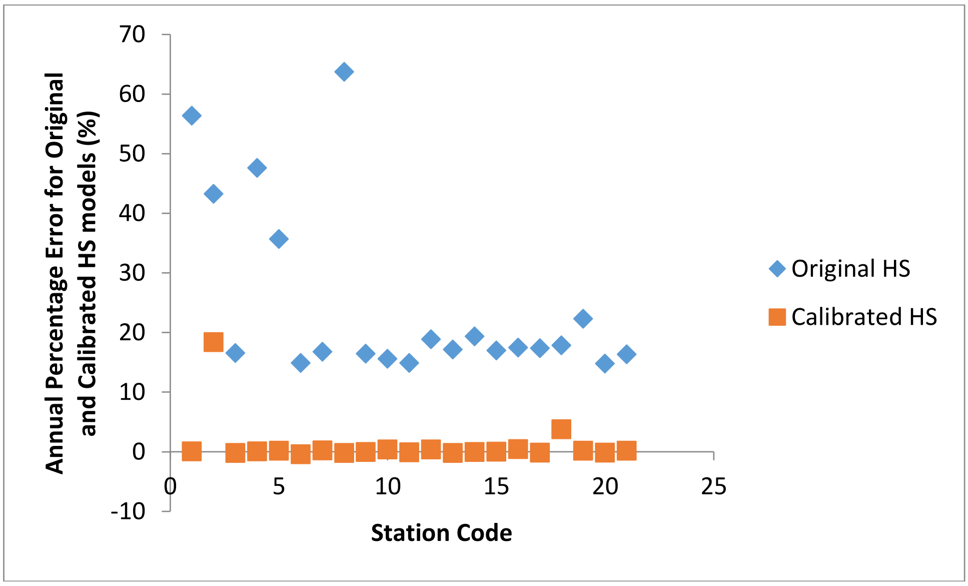

Fig. 10: Comparison of Annual Percentage Error of Original and Calibrated HS Models with Station Code for All Stations.

4. Conclusion

The Hargreaves-Samani model is recommended by Allen et al. [25] as the most simple and practical method for estimating global solar radiation (H). In the present study, the author employed monthly mean meteorological data during 1983 – 2005 to calibrate the HS model based on a single hybrid parameter-based model at 21 locations at both monthly and annual timescale.

The calibrated HS model yielded better performance than the original HS model for each station, with average MBE, MPE, RMSE and NS of 0.004167 KWh/m^2/day, 0.0823%, 0.0144KWh/m^2/day 0144KWh/m2/day and 0.940 for calibrated HS model; 0.0792 KWh/m^2/day, 1.5646%, 0.2742 and 0.825 for original HS model. Similar performances were sound for coastal and interior regions. Both the original and calibrated HS models underestimated H at annual timescale, which might result from high cloudiness in the study area with average underestimation of 24.99% and 1.1039% for the original and calibrated HS models. The present study found the locally calibrated HS model had better performances for global solar radiation at monthly and annual timescale, hence the calibrated models could be highly recommended to predict monthly global solar radiation in Nigeria when only temperature data are available.

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