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# Estimation of global solar radiation in Nigeria using a modified Angstrom model and the trend analysis of the allied meteorological components

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The trend of some common and related atmospheric variables were investigated in the light of climate change on annual time scale and a suitable scheme was further developed for the simulation of annual global solar radiation in Nigeria. In this connection, annual trends of global solar radiation, air temperature, precipitation, relative humidity and sunshine hours was carried out, covering about 13 tropical stations during 1975-2006 in Nigeria using F-test as the significance test technique. It was found that nine stations exhibited an upward trend in global solar radiation series, of which 6 passed F-test at 1% significant level. At 11 stations, precipitation had shown an increasing trends but none passed F-test at 2.5% and hence, not significant. About 98.8% of the stations displayed an upward trend in sunshine hours of which 16% passed F-test at 1% significant level. On trend analysis for relative humidity series, eight stations exhibited a positive trend and only one station passed F-test at 1% significant level. The trend of temperature series in Nigeria under the period under investigation was found to be increasing at 12 stations and eight stations passed the F-test at 1% significant level. The other objective of this study was to determine a more suitable empirical equation by modifying Angstrom model for the estimation of global solar radiation using all data for all 14 stations pooled together to predict global solar radiation using linear and multiple linear regression. This was done to improve the low performance of the Angstrom model used for the annual estimation of global solar radiation. The model parameters ‘a’ and ‘b’ of Angstrom model were parameterized in terms of the geographical locations (latitude, longitude and elevation) and the meteorological variables (sunshine hour, precipitation, relative humidity and temperature), respectively. This scheme gave better simulation of the global solar radiation compared with other schemes and the original Angstrom models. In addition, the preferential consideration of relative humidity to precipitation as potent contributing factor in the estimation of global solar radiation was also established.

**Keywords:** Global solar radiation, Climate change, Precipitation, Sunshine hours, Relative humidity, Temperature, Angstrom model

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## 1 Introduction

Global solar radiation can be considered as the set of short waves irradiance emitted from the sky and Sun, which is radiating heat at a temperature of about 5800K. It is the source of energy for driving all the observed earth-atmospheric processes and also the main source of renewable energy classified as solar energy, wind energy, water energy, biomass energy and tidal energy of the sea tide[1,2]. The knowledge of solar radiation at any given place is relevant for several applications including architectural designs, solar radiation and irrigation system crop growth models and evapotranspiration estimates[3-5]. The occurrence and effects of trend detection in global solar radiation have been observed and reported by Rensheng *et al.*[4] Many cases of downward trends were equally reported and the affected parts in the globe include Germany[6,7], United States[7,8], Finland[9], former Soviet Union[10], and Nigeria[5,11] among others. The observed dimming in solar radiation is closely related to the increasing rate of emission by both industrial and anthropogenic aerosol and pollutants that have altered the optical properties of the atmosphere and consequently attenuated the receipt of solar radiation at the earth surface. According to Rensheng *et al.*[4], the significant consequential impact of this observation on agricultural production including climate change study and systems that directly depend on solar radiation for operation cannot be over emphasized.

Several measurement campaigns have been launched on the estimation of global solar radiation[12-14]. Direct measurements of solar radiation through the use of sophisticated and expensive equipment are rarely carried out, particularly in the developing countries and this had been responsible for the dearth of data on global solar radiation in most countries of the world[15]. Hence, the indirect measurement techniques are used for the study through the development of empirical equations based on the atmospheric weather conditions of the location. The most popular empirical and widely used empirical equation is the Angstrom[16], which estimates global solar radiation from sunshine hours duration. Several empirical equations based on the relationships between global solar radiation and weather parameters have been equally developed[17-22]. Most of these studies and others[23-26] were used to estimate global solar radiation on different time scales (hourly, daily and monthly). These studies seek to apply some of the empirical equations to simulate annual global solar radiation, which is in view of the climatic variability in the light of the escalating global warming. In this connection, the present study investigated the relationship and the variability of the annual global solar radiation, precipitation, relative humidity, sunshine hours and temperature for some tropical stations in Nigeria.

## 2 Data acquisition

Monthly data on solar radiation including other weather variables [air temperature (Ta), relative humidity (Rh), global radiation (Rs), sunshine hours (SS), and precipitation (P)] for three decades (1975-2006) were collected from the archives of the Nigerian Meteorology Agency positioned at over forty stations across Nigeria. The sites coverage for this study is comparatively large, fourteen stations were involved in this study in view of the dearth of data spanning from the coastal stations to the arid region in Nigeria

## 3 Method and Site description

The monthly data were averaged into annual time scale for the purpose of this study. The data collected were subjected to quality control check so as to ensure that all spurious data including omissions were diligently resolved before applying them for data analysis. The trend analysis for each variable was investigated using linear regression techniques. The significance of the each observed trend was evaluated using F-Test[4,8].

The basic empirical equation used in this study was based on the fundamental Angstrom model[27] defined as the linear relationship between the ratios of average daily global solar radiation and maximum possible sunshine duration to the corresponding value on a completely clear day and ratio of average daily sunshine duration to the maximum possible sunshine duration. Prescott[28] put the equation in a more suitable form by replacing the average global radiation on a clear day with the extraterrestrial solar radiation. This is mathematically expressed as:

$$\frac{Rg}{Rs} = \mathrm{a} + \mathrm{b}\frac{Sd}{Sod} \qquad \dots (1a)$$

where, *R*g, is monthly sum of the total solar radiation received on the horizontal surface; *R*s, the monthly sum of the solar radiation on the upper atmosphere (extraterrestrial radiation); *S*d, the daily sunshine duration; and *Sod* represents the maximum possible monthly hours of sunshine (day length) while the ratio on the left hand side of Eq. (1a) is termed clearness index. The model parameters 'a' and 'b' in Angstrom-Prescott Eq. (1a) above are significantly important in describing the atmospheric condition of a given place. According to Tahas ***et al.***[29], 'a' is a measure of the overall atmospheric transmission for totally cloudy condition and it is a function of the type and thickness of the cloud cover, while 'b' is the regression constant which expresses the rate of increase $\frac{Rg}{Rs}$ with $\frac{Sd}{Sod}$. The sum (a+b) signifies the overall atmospheric transmission under clear sky conditions.

The extraterrestrial radiation (***Rs***) and monthly maximum possible sunshine duration (***nod***) are expressed according to Allen ***et al.***[30] and stated as:

$$R_s = \frac{24(60)}{\pi} G_{SC} d_r [\omega_s \sin(\theta)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega)] \qquad \dots (1b)$$

$$nod = \frac{24x\omega_s}{\pi} \qquad \dots (1c)$$

where, $G_{sc,}$ is the solar constant numerically stated as 0.0820 (MJ $m^{-2}$ $min^{-1}$); $d_r$, the inverse relative distance Earth-Sun; $\omega_s$, the sunset hour angle expressed in radians, is measured at sunset when the sun's center reaches the horizon; $\theta$, the latitude of the site (radian); and $\delta$, the solar declination in radians.

$$d_r = 1+0.033 \times \cos(2\pi J/365) \qquad \dots (1d)$$

$$\delta = 0.409 \times \sin[(2\pi J/365) - 1.39] \qquad \dots (1e)$$

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \qquad \dots (1f)$$

A set of empirical equations for the estimation of total global radiation were obtained using both linear and multiple regression; the input variables were extended beyond the sunshine hour data utilized for A-P models. In this study, the list of independent variables in Angstrom-Prescott model is enlarged to include temperature, precipitation and relative humidity. Using multiple linear regressions, empirical equations were developed in the form:

$$\frac{Rg}{Rs} = aP + bT + c.\frac{Sd}{Sod} + d \quad \dots (2)$$

$$\frac{Rg}{Rs} = aRh + bT + c.\frac{Sd}{Sod} + d \quad \dots (3)$$

Equation (2) above was used by Rensheng *et al.*[4] to estimate global radiation for China but the contention with the performance of the above scheme is that rain event is not an all-monthly occurring event, though on annual average, this may be found to be available but relative humidity which is a measure of water vapour in the atmosphere would have been found more suitable. Hence, Eq. (2) above was modified to replace precipitation with relative humidity and this modification is expressed by Eq. (3). In a further modification of the A-P model, in this study, the constant 'a' and 'b' were parameterized, respectively in term of location (latitude, longitude, elevation) and other atmospheric variables (precipitation or relative humidity, sunshine hours and temperature). This is expressed as:

$$\frac{Rg}{Rs} = a(\theta, \varphi, z, \text{etc.}) + b(\theta, \varphi, z, \text{etc.}).\frac{nd}{nod} \quad \dots (4)$$

where, $\theta$, $\varphi$ and z, are respectively the latitude, longitude and elevation of each of the stations under consideration.

The procedure for the parameterization was done in two stages. The first stage involved the determination of 'a' and 'b' for each station using Angstrom-Prescott model and these were further combined, in the second stage, with the geographical and the climatological variables for the full parameterization defined by Eq. (4).

In order to validate the predictions by the developed models, some statistical indicators were used including Nash-Sutcliffe efficiency (NSE) scheme to test the efficiency of the models. The efficiency E proposed by Nash & Sutcliffe[31] is defined according to Krause *et al.*[32] as one minus the sum of the absolute squared differences between the predicted and observed values normalised by the variance of the observed values during the period under investigation. According to Willmott[33], NSE shows how well the plot of observed versus simulated data fits the 1:1 line. NSE can be determined using the equation:

$$E = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{o})^2} \quad \dots (5)$$

where, $O_i$, is the i*th* observation for the integral part being evaluated; and $P_i$, stands for the corresponding value of the integral part being evaluated too, while $\bar{o}$ is the mean value of the observed data for the constituent part being estimated and n, being the total number of observations. NSE ranges $-\infty$ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. The values between 0.0 and 1.0 are, generally, considered as acceptable levels of performance and values $\leq 0.0$ indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. The performance of the developed model was carried out using some statistical indicators such as the correlation coefficient, standard deviation and standard error estimate (SEE) and the result of linear regression (slope and intercept) between estimated and the observed global solar radiation.

Table 1 lists the stations which have been used in this study. The latitudinal location ranges from 4.88 (Port Harcourt) in the coastal area to 13.02 (Sokoto) in the Sahel Savannah. All the stations are drawn from different climatic conditions (coastal,

Table 1 — Geographical location of the stations

| Stations | Latitude, °N | Longitude, °E | Elevation, m | Climatic zones |
|---|---|---|---|---|
| Port Harcourt | 4.85 | 7.02 | 19.55 | Coastal |
| Benin | 6.32 | 5.6 | 77.52 | Coastal |
| Lagos | 6.58 | 3.33 | 39.35 | Coastal |
| Akure | 7.23 | 5.22 | 385 | Coastal |
| Ibadan | 7.43 | 3.9 | 227.23 | Guinea Savannah |
| Osogbo | 7.73 | 4.48 | 304.7 | Guinea Savannah |
| Lokoja | 7.8 | 6.73 | 61.4 | Midland |
| Yola | 9.23 | 12.47 | 186.05 | Midland |
| Minna | 9.62 | 6.53 | 258.64 | Midland |
| Jos | 9.87 | 4.97 | 1285.58 | Midland |
| Maiduguri | 11.85 | 13.08 | 353.8 | Sahel Savannah |
| Kano | 12.05 | 8.53 | 472.14 | Sahel Savannah |
| Sokoto | 13.02 | 5.25 | 350.75 | Sahel Savannah |

midland, Guinea Savannah and Sahel Savannah) in Nigeria. The highest elevation is Jos found in the midland region.

## 4 Results and Discussion

### 4.1 Trend analysis of the allied parameters

The method of Mann-Kendal tau_b was used to determine the trend analysis of the global solar radiation and all allied parameters (sunshine hours, relative humidity, air temperature and precipitation) on annual time scale (1975-2006) for all the stations except Akure, where time scale (1975-2002) was considered; while the significance of both the downward and upward trend was determined by using F-test and both results were presented in Table 2. For solar global radiation, 29% of all the stations exhibited decreasing trend, out of which two stations passed the F-test at 1% significant level while the upward trend at the rest two stations failed the F-test and hence, not significant. The trend of the solar global radiation at the rest 71% showed increasing trend. For the increasing trend, five stations passed the F-test at 1% significant level while the upward trend in four stations was not significant as the observed trend failed F-test. The most significant upward trend is observed both for Benin and Jos.

For the country at large, the results indicated an upward trend in solar radiation and this trend passed the F-test at 1% significant level. On the trend analysis for sunshine hours, about 1% of the total stations showed a decreasing trend while the rest 99% exhibited increasing trend. The downward trend passed the F-test at 1% significant level. Two stations with positive trends passed the test at 5% significant level, the rest 10 stations failed F-test and hence, not significant. Port Harcourt exhibited the most significant upward trend of sunshine hours. The observed upward trend may be attributed to the general decrease of atmospheric humidity, which is a signature of clear sky condition.

A downward trend in annual precipitation was observed at only two stations and both were not significant as none of the trend at such stations passed the F-test. The rest of the stations experienced upward trend in precipitation, out of which, two stations passed the F-test at 1% significant level while the rest 10 stations failed the F-test and hence, not significant. Out of the stations that experienced the upward trend, the most significant increasing trend was observed in Port Harcourt (PH). The upward trend observed particularly in Port Harcourt can be credited to several reasons. PH is a coastal tropical station punctuated with a large concentration of refineries. The effluence releases to the atmosphere can result into warming and consequently increases the ambient temperature and hence increase in large water loss through evaporation.

Table 2 — Trends of solar radiation, sunshine hours, relative humidity, precipitation and air temperature at some tropical stations in Nigeria (1975-2007)

| Station | Latiude, °N | Solar radiation | | | Sunshine hour | | | Precipitation | | | Relative humidity | | | Temperature | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Trend | F-value | F-test, % | Trend | F-value | F-test, % | Trend | F-value | F-test, % | Trend | F-value | F-test, % | Trend | F-value | F-test, % |
| All | | ↑ | 37.17 | <1 | ↑ | 7.54 | 1 | ↑ | 8.11 | 1 | ↓ | 2.77 | 11 | ↑ | 1.46 | 24 |
| Port Harcourt | 4.85 | ↑ | 8.38 | 1 | ↑ | 1.29 | >25 | ↑ | 0.01 | >2.5 | ↓ | 3.68 | 6 | ↑ | 6.99 | 1 |
| Benin | 6.32 | ↑ | 0.02 | >2.5 | ↑ | 1.62 | 21 | ↑ | 2.23 | 15 | ↓ | 0.29 | >25 | ↑ | 7.42 | 1 |
| Lagos | 6.58 | ↓ | 66.88 | <1 | ↑ | 12.32 | <1 | ↓ | 0.01 | >2.5 | ↑ | 5.85 | 2 | ↑ | 14.80 | 0 |
| Akure | 7.23 | ↑ | 1.49 | 23 | ↑ | 2.18 | 15 | ↓ | 0.09 | >2.5 | ↓ | 0.03 | >25 | ↓ | 0.02 | >25 |
| Ibadan | 7.43 | ↓ | 0.75 | >2.5 | ↑ | 3.52 | 7 | ↑ | 0.10 | >25 | ↑ | 0.58 | >25 | ↑ | 5.06 | 3 |
| Osogbo | 7.73 | ↑ | 6.74 | 1 | ↑ | 3.26 | 8 | ↑ | 1.71 | 20 | ↓ | 4.18 | 5 | ↑ | 3.92 | 6 |
| Lokoja | 7.8 | ↑ | 140.87 | <1 | ↑ | 2.23 | 15 | ↑ | 7.18 | 1 | ↓ | 0.12 | >25 | ↑ | 7.57 | 1 |
| Abuja | 9.17 | ↑ | 47.61 | <1 | ↑ | 5.22 | 5 | ↑ | 0.00 | >25 | ↑ | 5.28 | 3 | ↑ | 22.94 | 0 |
| Yola | 9.23 | ↑ | 4.18 | 5 | ↑ | 1.31 | >25 | ↑ | 1.25 | >25 | ↑ | 0.11 | >25 | ↑ | 10.05 | 0 |
| Minna | 9.62 | ↓ | 0.16 | >2.5 | ↑ | 1.35 | 25 | ↑ | 0.58 | >25 | ↑ | 1.35 | 25 | ↑ | 14.88 | 0 |
| Jos | 9.87 | ↑ | 0.10 | >2.5 | ↑ | 10.84 | <1 | ↑ | 0.06 | >25 | ↑ | 1.35 | 25 | ↑ | 0.02 | >25 |
| Maiduguri | 11.85 | ↓ | 32.55 | 0 | ↑ | 2.30 | 14 | ↑ | 2.30 | 14 | ↑ | 9.09 | 1 | ↑ | 0.06 | >25 |
| Kano | 12.05 | ↑ | 23.30 | <1 | ↑ | 3.29 | 8 | ↑ | 39.12 | 0 | ↑ | 0.39 | >25 | ↑ | 0.53 | >25 |
| Sokoto | 13.02 | ↑ | 2.72 | 11 | ↓ | 13.72 | <1 | ↑ | 1.15 | >25 | ↑ | 4.90 | 3 | ↑ | 37.76 | 0 |

On the trend analysis for relative humidity, 43% of the stations exhibited downward trend and were all significant while 57% showed positive trend. For the downward trend, one station passed the test at 5% significant level while the rest of the stations did not pass the test and hence, the upward trend of relative humidity at such stations is not significant. The greatest downward significant is noted for Akure in the rainforest region of Nigeria. The downward trend observed particularly in Akure, which lies in the tropical rainforest, is a response to the climatic condition of the rainforest. This is because the rainforest has a humid environment whose atmosphere is often loaded with moisture to the saturated level. The other reason may be attributed to the significant decrease in temperature in major area noted for the decreasing trend.

Temperature was found to decrease insignificantly at only one station. This observed trend failed the F-test while the rest 13 stations showed positive trends. At eight stations, air temperature exhibited positive upward trend and found to pass the test at 1% significant level, one station passed F-test at 5% significant level while the observed upward trend in rest four stations was not significant as they could not pass F-test. Akure and Jos exhibited the maximum significant downward trend in temperature compared with other stations under consideration. This shows a marked tendency for warming in these two stations. Generally, the increase in temperature is an index of climate change coupled with the increase in precipitation as revealed in this study. Therefore, increased greenhouse gases through increased vehicular emission may results in an increased ambient temperature.

The average trends of the parameters from 1975 to 2006 were also determined for Nigeria too. Generally, an average upward trend was observed for all parameters (solar global radiation, sunshine hour, temperature and precipitation) except relative humidity that exhibited a non-significant downward trend. The observed upward trend in solar radiation, sunshine hours, and precipitation passed the F-test at 1% excluding temperature that was not significant. The positive trend observed for temperature and precipitation is a good signal for climate change that has become a global household name. This is evident in the recent flood event in some parts of Nigeria.

### 4.2 Estimation of global solar radiation

Table 3 presents the result of the estimated parameters for three different empirical equations [Eqs (1-3)] including the popular global solar radiation model termed the A-P model. The estimated parameters spanned all the fourteen stations pooled from different geographical regions in Nigeria.

In this study, the estimations are based on annual timescales as several estimations have been carried out both on daily and monthly time scale (though the years may not coincide with the annual range under consideration) and the various results of studies[20,26] confirmed a satisfactory performance of Eq. (1) as earlier pointed out. In this study, A-P was modified with the inclusion of thermal factor (temperature) and water moisture (precipitation and temperature) variables, in a similar study[4] on the estimation of

Table 3 — Estimated parameters of both the Angstrom models and the modified version

| Stations | Model 1 | | Model 2 | | | | Model 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | a1 | b1(n/N) | a2 | b2(T) | c2(RH) | d2(n/N) | a3 | b3(T) | c3(P) | d3(n/N) |
| Port Harcourt | 0.453 | 0.0641 | 0.439 | 0.0194 | -0.00689 | 0.119 | -0.158 | 0.0235 | -0.00024 | 0.141 |
| Benin | 0.406 | 0.0724 | 0.728 | -0.00642 | -0.00218 | 0.116 | 0.66 | -0.00754 | -0.00043 | 0.15 |
| Lagos | 0.713 | -0.752 | 2.459 | -0.0881 | 0.00779 | -0.549 | 3.2 | -0.0938 | 9.1E-05 | -0.553 |
| Akure | 0.361 | 0.212 | 0.333 | -0.0000537 | 0.00017 | 0.233 | 0.333 | -5.37E-05 | 0.00017 | 0.233 |
| Ibadan | 0.46 | -0.0778 | 0.291 | 0.0205 | -0.00603 | -0.0029 | -0.279 | 0.027 | -7.9E-05 | -0.0331 |
| Osogbo | 0.195 | 0.423 | 0.743 | 0.0187 | -0.0138 | 0.266 | -0.711 | 0.0342 | -8.1E-05 | 0.466 |
| Lokoja | 0.61 | -0.331 | 2.873 | -0.0908 | 0.00379 | -0.453 | 2.873 | -0.0784 | -0.001 | -0.42 |
| Yola | 0.69 | -0.158 | -0.65 | 0.0459 | -0.000926 | -0.0336 | -0.648 | 0.0464 | -0.00067 | -0.0429 |
| Minna | 0.471 | 0.128 | 0.777 | -0.0104 | -0.000342 | 0.128 | 0.793 | -0.0114 | -7.7E-05 | 0.133 |
| Jos | 0.47 | 0.129 | 0.875 | -0.036 | 0.00684 | 0.214 | 0.923 | -0.0187 | -0.0009 | 0.209 |
| Maiduguri | 1.217 | -0.897 | 2.166 | 0.00294 | -0.032 | -0.819 | 1.951 | -0.0235 | -0.00336 | -0.77 |
| Kano | 7.725 | 0.103 | 2.31E-14 | 5.415E-16 | 11.996 | -4E-14 | 0.27 | 0.0107 | -0.00059 | 0.178 |
| Sokoto | 0.494 | -0.0655 | 0.382 | 0.00602 | -0.00157 | -0.0712 | 0.291 | 0.00656 | 3.6E-05 | -0.0482 |

global solar radiation. They utilized precipitation and since precipitation is not an all season occurring event in most part of Nigeria except in the coastal stations, their modification was further modified by replacing precipitation with relative humidity, which is a measure of the amount of water vapour in the atmosphere. This is reasonable because evaporated water escapes into the atmosphere to form cloud which later drops as rain, and event which occurs at a particular time of the year[34-38]. The significant amount of cloud formed in the atmosphere attenuate the receipt of solar radiation at the earth surface. Further, reason for this modification is because the contribution of water loss into the atmosphere through evapotranspiration can be properly taken care of and hence, Eq. (2) should be studied parallel with Eqs (1 and 3).

The performance of Eqs (1, 2 and 3) were tested for different stations covering different climatic zones using NSE and the results were presented in Table 4. The NSE values are only reasonable for just three (Minna, Jos and Maiduguri) stations out of the fourteen stations involved in the study. The NSE values are generally low and characterized with poor performance for 78.6% of the total number of stations as indicated by the NSE values shown in the table based on the three models in question.

Table 4 — Nash-Sutcliffe Efficiency (NSE) values of Angstrom model and its revised form at some tropical stations in Nigeria

| Stations | NSE1 | NSE2 | NSE3 |
|---|---|---|---|
| Port Harcourt | -0.923 | -0.629 | -0.783 |
| Benin | -0.047 | -3.894 | -0.525 |
| Lagos | -17.09 | -3.353 | -3.613 |
| Akure | 0.1483 | 0.4949 | -0.525 |
| Ibadan | -0.189 | -0.411 | -0.561 |
| Osogbo | -1.763 | -2.688 | -0.81 |
| Lokoja | -4.133 | -4.31 | -2.818 |
| Yola | -17.09 | -3.353 | -3.613 |
| Minna | 0.9063 | 0.9177 | 0.909 |
| Jos | 0.9959 | 0.9964 | 0.996 |
| Maiduguri | 0.624 | 0.863 | 0.674 |
| Kano | -2.676 | -2.826 | -1.464 |
| Sokoto | 0.011 | -1.455 | -1.455 |

Table 5 —Statistical comparison between observed and estimated global solar radiation

| Model type | Correlation coefficient (R) | Slope | Intercept | Standard error of estimate (SEE) |
|---|---|---|---|---|
| M1 | 0.54 | -0.25 | 13.75 | 0.016 |
| M2 | 0.77 | 0.72 | 6.26 | 0.097 |
| M3 | 0.77 | 0.36 | 11.87 | 0.157 |

In addition to the above analysis, the annual variation and the regression graphs of the estimated and the observed global solar radiation were also investigated and the results are presented in Figs (1 and 2) and Table 5. Figure 1 represents the comparison between the annual variation and the simulated global solar radiation averaged over all the stations. The patterns of variation are consistently similar except that M1 and M3 strongly over estimated the observed values while M2 appears closer to the observed. The statistical comparison between the observed and the predicted values are shown in Table 5. The above result is based on the regression between the observed and the estimated datasets. From the table, the correlation coefficients of all the models are significantly high but higher with M1 and M2, which shows that all the simulated values are linearly related with the observed values. The slope indicates the magnitude of variation of the observed with the predicted values; the desired value is 1 and from the table the highest slope is 0.72 for M2. The intercept is an indication of error, hence, the lower intercept is better; thus, 0 is the desired value for cases of accuracy. Also, from the table, the least intercept is 6.26 for M2 and finally the standard error of estimate is also a measure of error; and for the lower value, the result is more accurate. The SEE values for M1 and M2 are relatively better than M3. From the foregoing validation result and considering the cumulative analysis of the results, M2, which

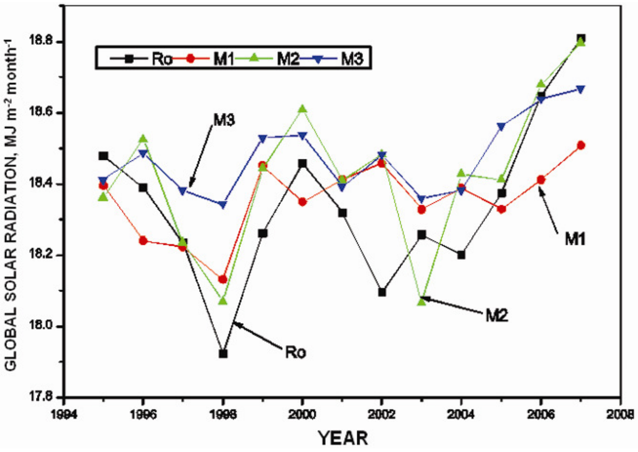

Fig. 1 — Annual variation of global solar radiation in Nigeria

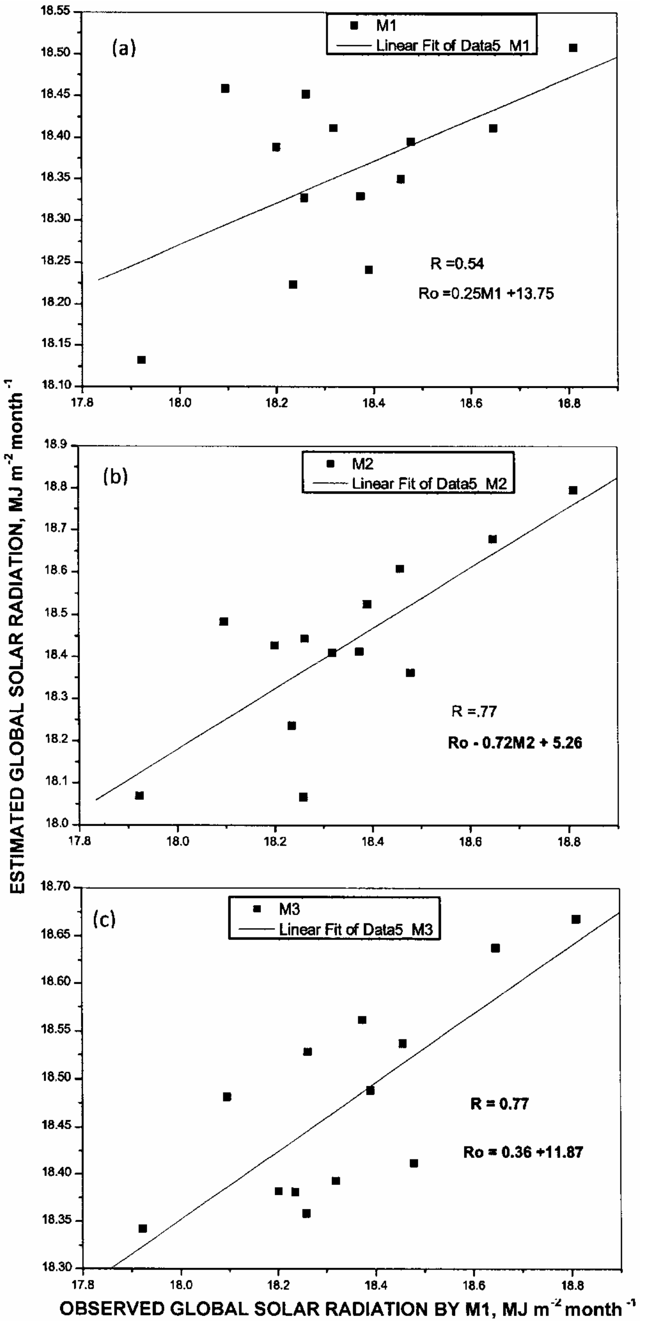

Fig. 2 — Linear regression between observed and estimated values of global solar radiation in Nigeria

expresses global solar radiation as a function of humidity is preferred to M3, which is a function of precipitation and the A-P model.

However; the performance can be improved when modified with the introduction of some atmospheric variables as can be seen from the table. The NSE values were found to improve with the introduction of precipitation but were further improved when the precipitation was replaced with relative humidity. This observation was only peculiar to few stations where NSE values were found to be high. However, this low NSE values observed were attributed to short length of the global solar radiation. Nevertheless, the observed poor NSE values on the timescale can be improved upon by increasing the time series[4] and that this can be achieved by pooling all the annual data for all the stations together (i.e. 14 by 30, which is equivalent to 430) to form a series and which had been used to design another set of equation which is a modified version of Eq. (1). The developed set of equations is presented as follows:

***Angstrom modified models***

$$R/Ro = 0.281 + (0.414\ n/N) \quad \ldots (6)$$

$$R/Ro = (0.363 + 0.375\ n/N - 0.00170\ T - 0.000151\ P) \quad \ldots (7)$$

$$R/Ro = (0.855 - 0.0947\ n/N - 0.00459\ RH - 0.00177\ T) \quad \ldots (8)$$

$$R/Ro = ((-0.0108 + 0.0136\ lat + 0.0622\ long + 0.0000498\ z) + (0.507 - (0.00845\ lat - 0.0650\ long - 0.000103\ z))\ n/N) \quad \ldots (9)$$

$$R/Ro = ((0.544 - 0.0156\ lat + 0.0309\ long + 0.000346\ z) + (-1.154 + 0.111\ lat - 0.0159\ long - 0.000391\ z)\ n/N - 0.00170\ T - 0.000151\ P] \quad \ldots (10)$$

$$R/Ro = ((1.992 - 0.0987\ lat - 0.0298\ long + 0.0000468\ z) - (0.0170 - 0.0137\ lat + 0.00133\ long + 0.000219\ z)\ n/N - 0.00459\ RH - 0.00177\ T) \quad \ldots (11)$$

$$R/Ro = ((1.039 + 0.0000308\ P^2 - 0.00995\ P + 0.00645\ T) + (-0.351 + 0.0125\ P - 0.0000421\ P^2 - 0.0174\ T)\ n/N) \quad \ldots (12)$$

$$R/Ro = ((2.164 - 0.0621\ RH + 0.000484\ RH^2 + 0.00918\ T) + (3.548 + 0.143\ RH - 0.00122\ RH^2 - 0.0142\ T)\ n/N) \quad \ldots (13)$$

$$R/Ro = ((1.006 - 0.00955\ P + 0.0000294\ P^2 - 0.00107\ T + 0.000290\ T^2) + (-0.237 + 0.0111\ P - 0.0000373\ P^2) + 0.00853\ T - 0.00100\ T^2)\ n/N) \quad \ldots (14)$$

$$R/Ro = ((2.066 - 0.0587\ RH + 0.000454\ RH^2 - 0.00274\ T + 0.000450\ T^2) + (-3.382 + 0.137\ RH - 0.00117\ RH^2 + 0.00597\ T - 0.00076\ T^2)\ n/N) \quad \ldots (15)$$

$$R/Ro = ((1.069 - 0.00952\,P + 0.0000293\,P^2 - 0.00218\,T + 0.0000621\,T^2 + 0.00000659\,T^3) + (-2.167 + 0.0102\,P - 0.0000348\,P^2 + 0.0425\,T + 0.00593\,T^2 - 0.000201\,T^3)\,n/N) \quad \ldots (16)$$

$$R/Ro = ((0.922 - 0.0591\,RH + 0.000451\,RH^2 + 0.0168\,T + 0.00454\,T^2 - 0.000118\,T^3) + (-5.460 + 0.136\,RH - 0.00117\,RH^2 + 0.0415\,T + 0.00667\,T^2 - 0.000214\,T^3)\,n/N) \quad \ldots (17)$$

$$R/Ro = ((0.409 - 0.00205\,P + 0.0139\,T) + (0.510 + 0.00164\,P - 0.0277\,T)\,n/N) \quad \ldots (18)$$

$$R/Ro = ((0.607 - 0.00779\,RH + 0.0149\,T) + (0.374 + 0.00591\,RH - 0.0286\,T)\,n/N) \quad \ldots (19)$$

$$R/Ro = ((0.320 + 0.0000111\,P - 0.00216\,T + 0.00720\,lat + 0.0214\,long + 0.0000699\,z) - (0.00816\,n/N) \quad \ldots (20)$$

$$R/Ro = ((0.873 - 0.00487\,RH - 0.00124\,T - 0.0170\,lat + 0.0138\,long + 0.0000492\,z) - (0.0507\,n/N)) \quad \ldots (21)$$

$$R/Ro = ((0.723 + 0.00000705\,P + 0.000656\,T - 0.00137\,T^2 + 0.0000254\,T^3 + 0.0126\,lat + 0.0211\,long - 0.0000323\,z) + (0.00489\,n/N)) \quad \ldots (22)$$

$$R/Ro = ((0.344 - 0.00539\,RH + 0.0101\,T + 0.00188\,T^2 - 0.0000559\,T^3 - 0.0189\,lat + 0.0131\,long + 0.0000488\,z) - (0.0222\,n/N)) \quad \ldots (23)$$

$$R/Ro = ((0.320 + 0.00000443\,P + 0.0000000235\,P^2 - 0.00216\,T + 0.00719\,lat + 0.0214\,long + 0.0000700\,z) - (0.00810\,n/N)) \quad \ldots (24)$$

$$R/Ro = ((0.619 + 0.00238\,RH - 0.0000591\,RH^2 - 0.000954\,T - 0.0127\,lat + 0.0156\,long + 0.0000504\,z) - (0.0745\,n/N)) \quad \ldots (25)$$

$$R/Ro = ((0.726 + 0.000023\,P - 0.0000000583\,P^2 + 0.0000258\,T^3 - 0.00139\,T^2 + 0.000591\,T + 0.0129\,lat + 0.0211\,long) - (0.000032\,z)) \quad \ldots (26)$$

$$R/Ro = ((0.0974 + 0.00108\,RH - 0.0000540\,RH^2 - 0.0000577\,T^3 + 0.00199\,T^2 + 0.00991\,T - 0.0162\,lat + 0.0144\,long + 0.0000598\,z) - (0.0470\,n/N) \quad \ldots (27)$$

$$R/Ro = ((0.268 + 0.00636\,lat + 0.0214\,long + 0.0000827\,z) - 0.0130\,n/N) \quad \ldots (28)$$

$$R/Ro = (1.151 + 0.00000930\,P^2 - 0.00324\,P + 0.0000319\,T^3 - 0.00137\,T^2 - 0.00242\,T) \ldots (29)$$

$$R/Ro = (0.726 - 0.0000000583\,P^2 + 0.0000237\,P + 0.0000258\,T^3 - 0.00139\,T^2 + 0.000591\,T + 0.0129\,lat + 0.0211\,long - 0.0000323\,z) \ldots (30)$$

where, P, is precipitation; T, temperature; RH, relative humidity; lat, latitude; long, longitude; and z, altitude.

Equations (6-30) above are the various modifications which have been carried out on Angstrom-Prescott (A-P) model in this study and are classified into seven categories. This is described in the Table 6.

The set of equations were validated at all the stations using the data for 1994 – 2007. The statistical comparison of the performance of the various equations developed above is shown in Table 7. The

Table 6 — Classifications and description of the developed equations

| S No | Classification of developed equations | Description of each category of classification |
|---|---|---|
| 1 | Equation (6) | This is A-P basic model. |
| 2 | Equations (7-8) | Expanded form of Eq (6) above with the inclusion of temperature, precipitation and relative humidity in addition to sunshine hours. |
| 3 | Equation (9) | Parameters ‘a’ and ‘b’ are each parameterized as functions of geographical positions. |
| 4 | Equations (10-11) | Form of Eqs (7-8) but having the model parameters (‘a’ and ‘b’) expressed as a function of geographical parameters. |
| 5 | Equations (12-19) | Here the model parameters ‘a’ and ‘b’ of the form of Eq (6) were expressed as function of climatological parameters. |
| 6 | Equations (20-27) | Here only the model parameter ’a’ was expressed as function of both climatological (temperature, precipitation and relative humidity) and geographical position (longitude, latitude and elevation). |
| 7 | Equation (28) | This is a typical form of Eq (6) but having only model parameter ‘a’ expressed as a function of the geographical location. |
| 8 | Equations (29-30) | Both equations are forms of the basic A-P equation but void of sunshine hour term. Here, Eq. (29) expresses global solar radiation (R) as a function of temperature and precipitation exclusively while Eq. (30) parameterizes R as a function of climatological variables (temperature and precipitation) and geographical location (latitude, longitude and elevation). |

Table 7 — Statistical comparison of the Angstrom modified models

| Model type | NSE | AR | SD | SEE | R | Intercept | Slope |
|---|---|---|---|---|---|---|---|
| M6 | 0.293 | 1.02886 | 0.17933 | 0.00871 | 0.54283 | 12.4613 | 0.30952 |
| M7 | 0.298 | 1.02771 | 0.17878 | 0.00868 | 0.5473 | 12.333 | 0.31576 |
| M8 | 0.40226 | 1.02394 | 0.16289 | 0.00791 | 0.63448 | 10.5842 | 0.41307 |
| M9 | 0.42 | 1.062 | 0.16156 | 0.00785 | 0.68515 | 9.36839 | 0.52038 |
| M10 | 0.0092 | 0.98373 | 0.2052 | 0.00997 | 0.6262 | 3.66597 | 0.77034 |
| M11 | -8.619 | 1.37421 | 0.5789 | 0.02811 | -0.6255 | 45.6145 | -1.2531 |
| M12 | 0.144 | 1.09191 | 0.19613 | 0.00952 | 0.49318 | 14.3894 | 0.26144 |
| M13 | 0.229 | 1.06645 | 2.41509 | 0.11729 | 0.59651 | 11.7628 | 0.41295 |
| M14 | 0.156 | 1.08995 | 0.19426 | 0.00943 | 0.50534 | 13.9034 | 0.28745 |
| M15 | 0.289 | 1.07217 | 0.16671 | 0.0081 | 0.6027 | 11.2171 | 0.42565 |
| M16 | 0.131 | 1.08176 | 0.19959 | 0.00969 | 0.46675 | 13.9071 | 0.27879 |
| M17 | 0.295 | 1.06282 | 0.17051 | 0.00828 | 0.60069 | 10.6025 | 0.45134 |
| M18 | -0.0076 | 1.08737 | 0.21696 | 0.01054 | 0.36837 | 14.8917 | 0.22788 |
| M19 | 0.32812 | 1.07551 | 0.1715 | 0.00833 | 0.63616 | 10.859 | 0.44875 |
| M20 | 0.519 | 1.02123 | 0.15255 | 0.00741 | 0.72085 | 8.39902 | 0.53525 |
| M21 | 0.55544 | 1.01855 | 0.14128 | 0.00686 | 0.7454 | 7.84258 | 0.56525 |
| M22 | 0.53806 | 1.02246 | 0.14854 | 0.00721 | 0.73394 | 8.15692 | 0.55059 |
| M23 | 0.56388 | 1.02556 | 0.14144 | 0.00687 | 0.7522 | 7.75457 | 0.57727 |
| M24 | 0.51917 | 1.02033 | 0.1524 | 0.0074 | 0.72089 | 8.37823 | 0.53555 |
| M25 | 0.5647 | 1.01688 | 0.13997 | 0.0068 | 0.75157 | 7.66194 | 0.57409 |
| M26 | 0.53796 | 1.0135 | 0.14724 | 0.00715 | 0.73408 | 8.00521 | 0.55039 |
| M27 | 0.57316 | 1.01868 | 0.13978 | 0.00679 | 0.75725 | 7.52425 | 0.58378 |
| M28 | 0.51678 | 1.01936 | 0.15295 | 0.00743 | 0.71919 | 8.41055 | 0.53268 |
| M29 | 0.25371 | 1.03189 | 0.18292 | 0.00888 | 0.50498 | 13.175 | 0.27132 |
| M30 | 0.53796 | 1.0135 | 0.14724 | 0.00715 | 0.73408 | 8.00521 | 0.55039 |

results revealed a general improvement of the performance of Eqs (6, 7 and 8) over what was previously obtained in Table 4. In particular, the NSE values obtained for A-P is 0.29 and this is greater than what was obtained for different stations in Table 4 except for those stations already identified with high NSE values. In addition, when A-P model is expanded as seen in Eqs (7 and 8), there was a further improvement in the NSE values including the regression parameters, like slope and the intercept with the standard (but higher distinctively for relative humidity than precipitation). In a further modification of A-P global solar radiation model, Eq. (9) is the only equation in the third category and in this case, the model parameters ‘a’ and ‘b’ were parameterized in terms of the location parameters (i.e. latitude, longitude and elevation). This is because the parameters (a and b) including the atmospheric variables (P, T) vary as the location parameters; and the NSE value was found to be higher than that of A-P (Table 4). This result confirms the relevance of location parameters in the estimation of global solar radiation. Further modification of A-P was intensified [as represented by Eqs (10-11)] with the inclusion of more atmospheric variables in the parameterization of the model parameters in Eq. (1), which is done by populating the independent variables in the basic A-P model. This study is also aimed at considering the comparative potential contribution of precipitation[4] and relative humidity in the estimation of global solar radiation (GSR) over any given location. Hence, for any given form of empirical equation involving precipitation developed in this study, there is also a replica form involving relative humidity. The result is quite impressive as can be seen in Table 4; the NSE values for relative humidity (0.402) are higher than that of precipitation (-8.62). This is because moisture is always resident in the atmosphere and measured by relative humidity. The evolution of GSR is a daily occurring phenomenon while precipitation is a seasonal occurring event in the study area. This disparity in the observed performance between the two sets of GSR models may be responsible for the above performance results. Equations (12-19) represent another form described by category 2, which takes the form of Eqs (7-8) but having the

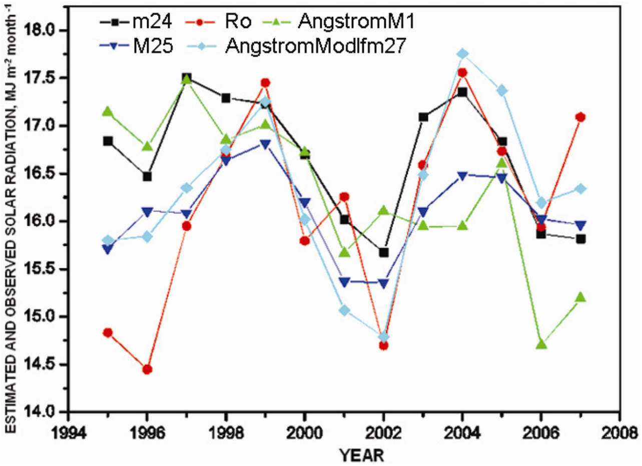

Fig. 3 — Comparison of annual variation of observed and simulated global solar radiation over Nigeria

model parameters (‘a’ and ‘b’) expressed as a function of geographical parameters. The result of the validation for these equations (the highest NSE values is 0.328) is better than that of Eq. (6) (NSE =0.29) but not as good as Eq. (9) (NSE value=0.42). In Eqs (20-27), ‘a’ alone is expressed as a function of climatological variables and geographical position, the NSE values of these equations are greater than those equations that only use the geographical position exclusively. This category of the developed equations is found to perform better than the rest categories in the series. The NSE values and the correlation coefficients are greater than the rest. Finally, Eqs (29 and 30) are peculiar empirical equations, in the sense that they are void of sunshine term. Equation (29), which is absolutely expressed as a function of climatological parameters alone perform poorly when compared with Eq. (30), which is expressed as function of both climatological variables and geographical position.

Figure 3 shows comparative graph of the average annual variations of the simulated [by Eqs (23, 25 and 27) including that of Angstrom-Prescott] and the observed values of global solar radiation. The pattern of the simulated values are quite equivalent to the observed values. However, cases of over and under estimation were observed by the simulated data. Nevertheless, both reported the downward trend in the global solar radiation observed between 2001 and 2002.

## 5 Conclusions

The trend of global solar radiation alongside some allied meteorological variables was investigated in this study. It was found that most of the stations under this study exhibited an upward trend in the annual global solar radiation and about 50% of this passed F-test at 1% significant level. An upward annual trend of sunshine hours was observed at most stations except at one station where a downward trend that passed the F-test at 1% significant level was noted. However, the observed positive trend of sunshine hours failed the F-test at 2.5% significant test. The annual precipitation showed an insignificant upward trend at most stations across Nigeria during the period of study. Furthermore, the annual trend analysis for relative humidity indicated a little less than 50% of the coverage experienced negative trend in RH while the rest, larger per cent, exhibited positive trend but none was significant. Finally, the trend analysis also confirmed that larger part of the country experienced a significant upward trend in temperature, which may be assumed responsible for the upward trend in precipitation observed in most part of the country. The study, further, establishes good relationship between an increasing global solar radiation and increasing temperature. A signature of climate change is detected with both the upward increase in temperature and precipitation.

In this study, Angstrom model of the first order on annual scale was carried out and a weak empirical linear relationship was noted between global solar radiation and sunshine hour at most stations; this was found to be due to the short duration data which were used[4]. However, when the data for all the stations were combined together to generate an annual global radiation with the parameters 'a' and ‘b’ of the Angstrom model adjusted and expressed as functions of the longitude, latitude, and the elevation or/and precipitation, relative humidity and temperature, a tremendous improvement was obtained between *R*s and SS.

In this study, the performance of each set of equations in terms of contributing effect of precipitation and relative humidity was also investigated. It was observed that equations involving relative humidity have better potential GSR prediction than other empirical equations involving precipitation as indicated by their respective NSE values and other statistical indicators. This suggests that both climatological and geographical factors should be considered significant in the development of any scheme for the simulation of global solar radiation. This modification on the Angstrom-Prescott model have brought a significant improvement on the accuracy of the simulated results as can be observed in this study (Table 4 and Fig. 3)

In conclusion, Eq. (27) when compared with other schemes, had been found to have the highest NSE value of 0.573, lowest standard deviation of 0.13978, and highest correlation coefficient of 0.75 and a low SEE of 0.0068. Hence, it is recommended for the simulation of annual global solar radiation in Nigeria.

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