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Estimation of the Global Solar Radiation Received on the Soil in Nalohou and Natitingou (Northern Benin)

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1 Abstract

The design of solar energy systems requires knowledge of the global solar radiation received by solar panels on the ground. However, for many developing countries such as the Benin Republic, there is a serious lack of radiometric stations everywhere in the country. The unavailability of these data, therefore, limits knowledge regarding the optimal functioning of solar installations. To cope with these difficulties, a method for estimating the global irradiation is developed at Nalohou AMMA CATCH station and Natitingou synoptic station, two sites in North-West Benin. This model depends on meteorological and astronomical parameters. Meteorological data such as sunshine duration, relative humidity, and air temperature have been collected on the synoptic station of Natitingou, and observed data of irradiation are collected from Nalohou. They are used to validate the model. The results show that the estimation of the mean square deviation value is around 10^{-2} . Overall solar radiation is significant in this region and its annual average value varies between 9.80 kWh/m² and 10.50 kWh/m². This model can, therefore, be used by solar system operators to optimize energy production in the region.

2 Introduction

Access to energy is essential for the social and economic well-being of populations worldwide. In most African developing countries, energy accessibility is difficult despite the high potential of renewable sources of energy. Among these sources of renewable energy, solar energy is considered as the most efficient, the best alternative resource [1] adapted for providing heat, electricity, and water in rural and urban areas. However, accurate knowledge of the incoming solar radiation resource at a site is required for the design and the efficiency in the estimation of any solar energy system [2]. Let's remember that solar plants functioning depends mainly on the climatic conditions of the specific location [3]. In Benin Republic (West Africa), few stations consistently measure global daily solar radiation. But, the lack of reliable data on global solar radiation can lead to erroneous evaluation of the solar plants efficiency. Therefore, the availability of certain climatic parameters such as relative humidity, air temperature, and astronomical parameters are necessary for the construction of an empirical model [4,5]. In the literature, several empirical formulations have been developed to predict global solar radiation using several meteorological variables such as sunshine duration, cloud cover, relative humidity, maximum temperature, water vapor pressure, etc. [4-9]. Quansah et al. [10] proposed an empirical model for estimating Global Solar Radiation (GSR) as a function of the sunshine relative duration over the Ashanti region in Ghana. The model can predict very well the pattern of the measured monthly daily mean GSR for the entire period of study with the smallest values of errors. Trabea and Shaltout [7] established a model in which input depends on the mean daily

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maximum temperature, the mean daily relative humidity, the mean daily sea level pressure, the mean daily vapor pressure, and hours of sunshine in Egypt. The Results show values of correlation coefficients varying from 89% to 99% and the errors of estimation are between 0.01 and 0.04. The Angstrom-type model also allows estimating the global solar irradiance by simple linear regression. It has been used by several authors [10-12]. Falayi et al [4, 12,13] correlated global solar radiation and meteorological parameters using monthly mean daily global solar radiation, sunshine duration, temperature, and relative humidity data from Nigeria. Several other authors such as Karoro et al [14], Coulibaly and Ouedoraogo [15], Onyango and Ongoma [16], Yisehak [17], Afungchui and Neba [18], Adeola et al [19], Safari and Gasore [2], Hassan et al. [20], Dankassoua [21], Ajayi et al. [22], Olomiyesan et al. [23] have established models for determining GSR. These authors have estimated global solar radiation in several areas of Africa. The diversity of methods for estimating global solar radiation to improve the design and optimization of solar energy systems clearly shows the interest given by authors on this topic. However, the reliability of these models depends largely on the strong correlation between estimated and measured variables, and many models (from cited above) have shown their limitations to reproduce GSR at other sites. Very few studies have experimented with the estimation of global solar radiation in Benin. One can cite Amoussa [24] who is the first to provide information on the characteristics of solar radiation in Benin using a linear model from Frère and Rietveld's to determine correlation constants of dimensionless parameters for many stations located in Benin. Unfortunately, the linear model is not reliable everywhere to reproduce global solar radiation measurements in the country. To overcome this lack in the current study, we develop and validate a global solar radiation model, capable of better estimation of solar radiation at the ground Surface in Nalohou, a typical and nearest village of Natitingou synoptic station where observed data are available. The reason behind the choice of the location is that solar radiation's data are available for some period in the location. So that we can easily calibrate the model with data recorded at the Nalohou station and regenerate those of Natitingou. This model was then used to generate global solar radiation at this meteorological site with the same meteorological parameters, geographical and topographical characteristics as Nalohou. The remaining parts of the paper are organized as follows: in section 3, study sites, the dataset, and methods are described. Analysis of results and their interpretations are made in section 4. Finally, we conclude the paper with a summary and outlook for further research in section 5.

3 Materials and Methods

3.1 Materials

3.1.1 Study sites

Benin is located between latitudes 6°30'-12°30' N and longitudes 1°-4° E. It is bordered in the North by the Niger River, in the North-West by Burkina Faso, in the West by Togo, in the East by Nigeria and in the South by the Atlantic Ocean. Two (02) study sites (Nalohou and Natitingou) are chosen in this study. Nalohou AMMA CATCH station is located in the Donga watershed in northern Benin, where the global solar radiation model is developed and used to estimate this parameter at Natitingou, the nearest synoptic meteorological station (~70km). The climate in these two locations is Sudanian and characterized by a single dry season from October or November to February or March and a single rainy season from April to October. Figure 1 and Table 1 show the location and the geographical characteristics of these two sites. The rainy seasons transport humid air from the Atlantic Ocean into the continent when the Intertropical Front (ITF) advances toward the North. The dry seasons release a mixture of dusty and dry air

from the Sahara toward the Atlantic Ocean when the ITF is fastly returning to the south. Natitingou is the Rainiest región of the country (1300 mm/year).

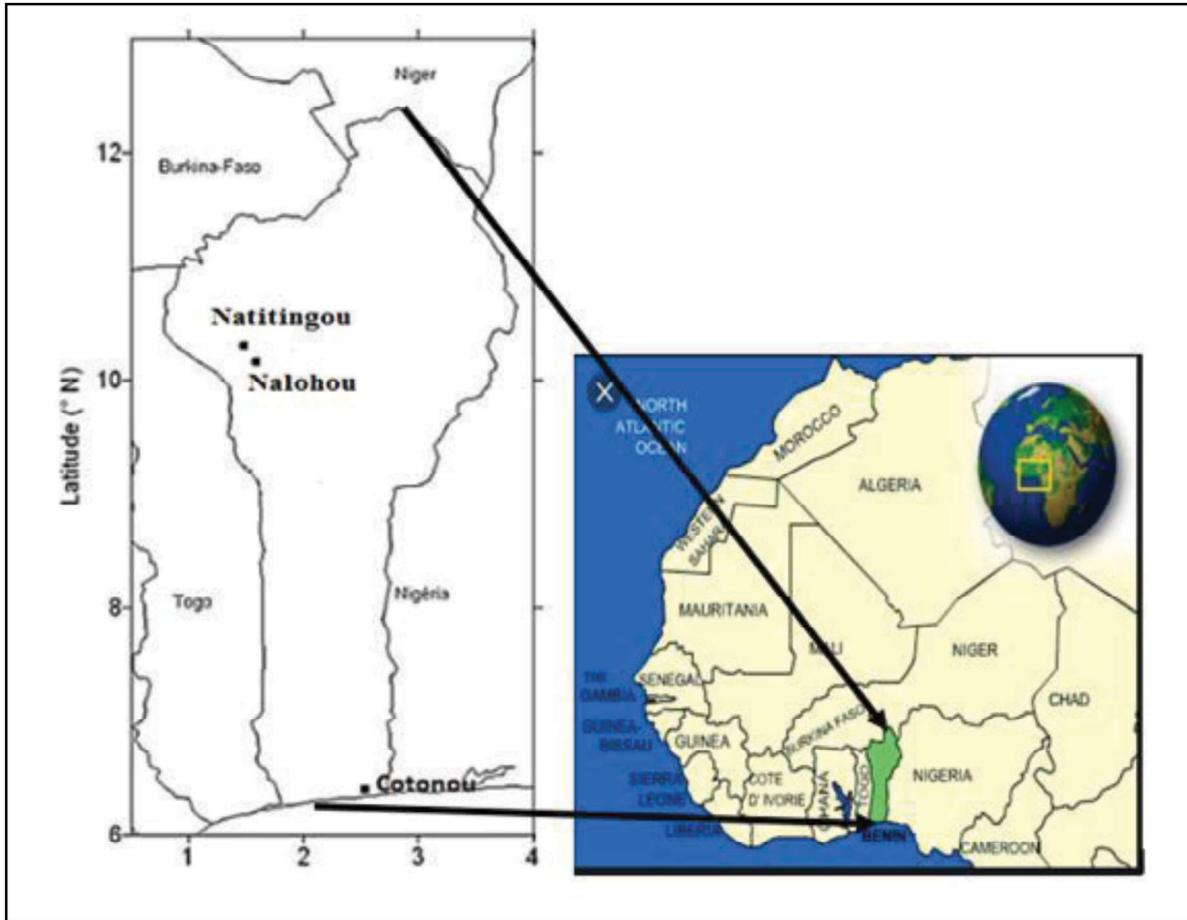


Figure 1: Geographical location of the study sites

Table 1: Geographical characteristics of study sites

Site	Latitude	Longitude	Altitude (m)
Natitingou	10° 19' N	1°23'E	426
Nalohou	9°744N	1°60E	449

3.1.2. Data used

At the Nalohou site, global solar radiation data and meteorological parameters such as ambient air temperature and air relative humidity are measured during the AMMA CATCH project at 2m above ground level every 15 min in the period from July 10, 2007, to July 10, 2010 [25]. As insolation data was not measured at Nalohou, the data recorded at Natitingou was used during the same period. Data were split into two parts: (i) one part covers the period from July 10, 2007, to July 09, 2009 and used to develop the new model; (ii) the second part covers the period from 10 July 2009 to 10 July 2010 which were used to validate the proposed model. Figure 2 gives us an overview of the Nalohou experiment site showing the installed solar radiation sensor.



Figure 2 : Nalohou experimental site (Mamadou [25])

Natitingou site is a synoptic meteorological station of the National Meteorological Agency (ANM). Insolation duration, ambient air temperature, air relative humidity was used as input parameters in the developed model to estimate the global solar radiation at this site. These meteorological parameters were measured hourly over the period from 1st January 2016 to 31 December 2016.

3.2 Methods

3.2.1 Formulation of the new model

In the work of Chukwujindu [26] who reviewed more than 760 different models for estimating global solar radiation in Africa, we noted that most of the models are based on the Angstrom formulation which is a function of the solar fraction.

Let us thus consider the relation between the components of the global solar irradiation on a horizontal plane and the fraction of insolation given by Angström in Hinrichsen 1994 [27]:

$$\frac{H}{H_0} = a + b\sigma \tag{1}$$

H (W/m^2) is the global solar irradiation on a horizontal plane, a and b are model calibration constants, σ is the fraction of daily sunstroke. It is expressed as:

$$\sigma = \frac{n_j}{N_{oj}} \tag{2}$$

n_j is the insolation duration on the day j , expressed in hours (h) and N_{oj} is the astronomical duration, expressed as follows:

$$N_{oj} = \frac{2}{15} \omega_j \tag{3}$$

ω_j is the daily hourly angle of sunrise on a horizontal plane expressed in radians. It is given by:

$$\omega_j = \text{Arcos}\left(-\tan(\delta_j) \tan(\phi)\right) \quad (4)$$

ϕ is the latitude in degrees and δ_j is the daily solar declination in degrees:

$$\delta_j = 23.45 \sin\left(\frac{360}{365}(N_j + 284)\right) \quad (5)$$

with N_j being the number of the day counted from January 1st. The expression of the daily average H_0 (in W/m^2) of solar irradiation from a horizontal plane outside the atmosphere is given by Tadili and Bargach [28]:

$$H_0 = \frac{24}{\pi} I_o \left(\cos(\delta_j) \cos(\phi) \sin(\omega_j) + \omega_j \sin(\delta_j) \sin(\phi) \right) \quad (6)$$

I_o (W/m^2) is the corrected solar constant which expression is given by equation (7) as follows:

$$I_o = 1367 \left[1 + 0.034 \cos\left(\frac{360}{365}(N_j - 3)\right) \right] \quad (7)$$

By analyzing the models of global solar radiation developed in Africa and reported in the work of Chukwujindu [26], the hybrid models established by several authors have proved to be more reliable than the other formulations encountered. However, no formulation of these Hybrid models exploited in Africa takes into account simultaneously the solar fraction at order greater than 1. The power form of the solar fraction as well as the ambient air temperature and relative humidity is often 1. In this study, we, therefore, preferred to estimate global solar radiation as a function of these meteorological variables.

In equation (1), we therefore optimally introduce the solar fraction with an unknown exponent α , the ambient temperature (T_a) and air relative humidity (R_r) meteorological factors that directly influence global solar radiation. To further reduce the divergence between observation data and estimated ones, we have also introduced calibration constants for the proposed model. The expression of global solar radiation is given by equation (8) as follows:

$$\frac{H}{H_0} = \left(a + b \left(\frac{n_j}{N_{oj}} \right) + c \left(\frac{n_j}{N_{oj}} \right)^\alpha + d T_a + e \text{RH} \right) \quad (8)$$

α , c , d , and e are model calibration constants. All the constants α , a , b , c , d , and e are determined by numerical simulation of the Nelder-Mead simplex algorithm [29]. Indeed, the simplex algorithm, one of the most widely adopted methods for unconstrained nonlinear multidimensional optimization, was used in this study to better calibrate the proposed model. In the Matlab software, the function “*fminsearch*” was used to simulate this algorithm. “Fminsearch” finds the minimum of a scalar function of several variables, starting with an initial estimation. This is generally called unconstrained nonlinear optimization. The method consists of wrapping the minimum in a simplex. A simplex is a set of (N+1) points surrounding the minimum (a line in one dimension, a triangle in 2 dimensions, and a pyramid in 3dimension). Each simplex is characterized for N+1 vectors at the vertices of the simplex. A new point is taken inside or next to the simplex at each calculation step. The value of the function at this point is compared with the values of the functions evaluated at the vertices. One of the vertices is then replaced by the new point generating a new simplex (by reflection, expansion, or contraction). The procedure is repeated as long as the diameter of the simplex is not smaller than a specified tolerance.

3.2.2 Statistical Testing

To evaluate the discrepancies between global solar radiation measurements and model estimates, the square root mean square error (RMSE) and absolute mean error (MAE) estimators were determined:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (p_i - f_i)^2}$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |(p_i - f_i)|$$

Where p_i represents measurements, f_i the predictions and n the number of observations. When these estimators are low and close to zero the estimates are in agreement with the measurements.

4 Resultats and discussion

4.1 Daily variation of solar declination δ_j , the irradiation out of the atmosphere I_0 , the angle of sunrise ω_j and the astronomical length of the days N_{0j}

Figure 3 presents the variations of the astronomical parameters of the sun in the Nalohou AMMA CATCH measurement site.

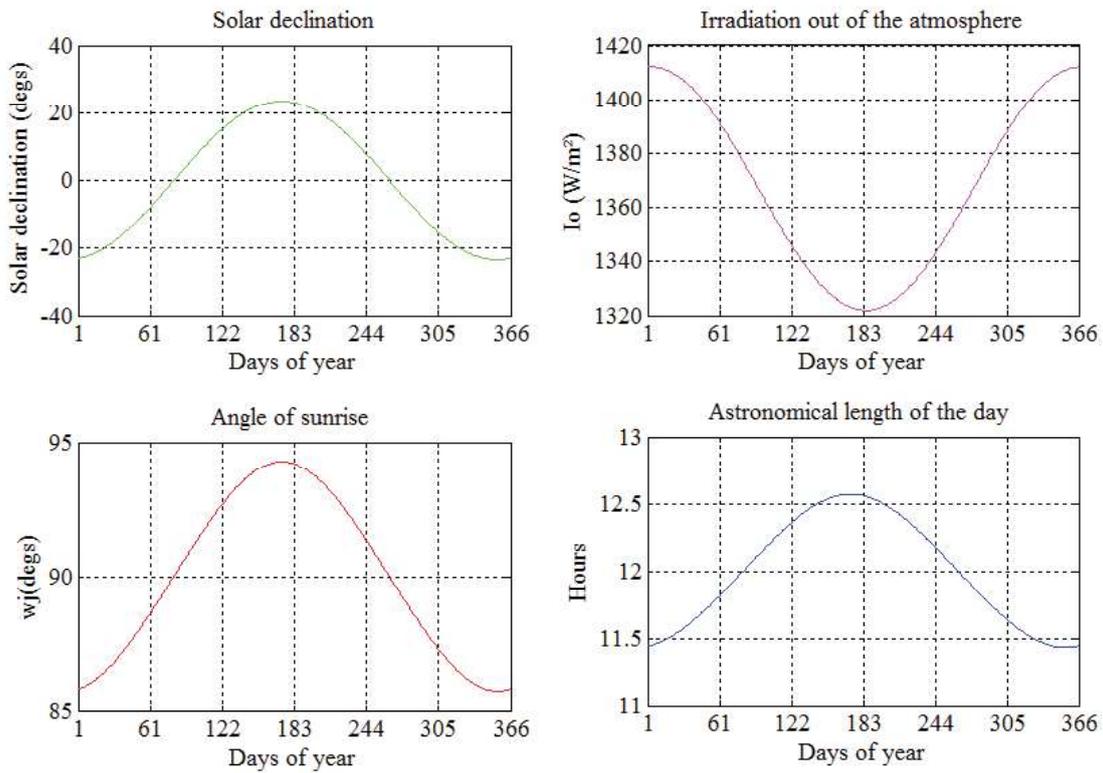


Figure 3: Daily mean variation of δ_j , I_o , ω_j , N_{oj} during the year in Nalohou (2007-2009)

Sun's declination angle during the period from July 2007 to July 2009 varies on average from -19° to 21° . The peak of this angle is observed in early July. The irradiation outside the atmosphere varies between 1320W/m^2 and 1410W/m^2 with the minimum recorded at the beginning of July. The angle of the sunrise is between 86° and 94° during the year and the astronomical length of the day varies from 11.4 h to 12.6 h with a peak always observed around the beginning of July. The lowest values of out of atmosphere irradiation are therefore reached when the sun's declination angle, the sunrise angle, and the astronomical length of the day are at their maximum values.

4.2 Simulation and validation of the proposed model at Nalohou site

Figures 4 and 5 present the results of the simulation from the proposed model using global solar radiation data measured at the Nalohou site. The calibration's constants of the model are also evaluated throughout the year. From figure 4, one can notice a seasonal variation of the solar irradiation. So, figure 5 is drawn to compare the seasonally observed data to those generated by the model.

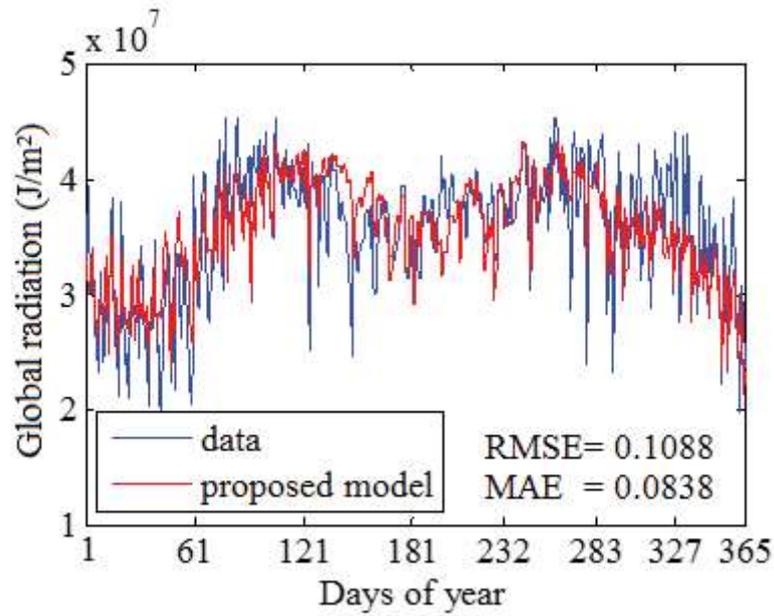


Figure 4: Correlation between the proposed model and the global solar radiation observed data for 2016

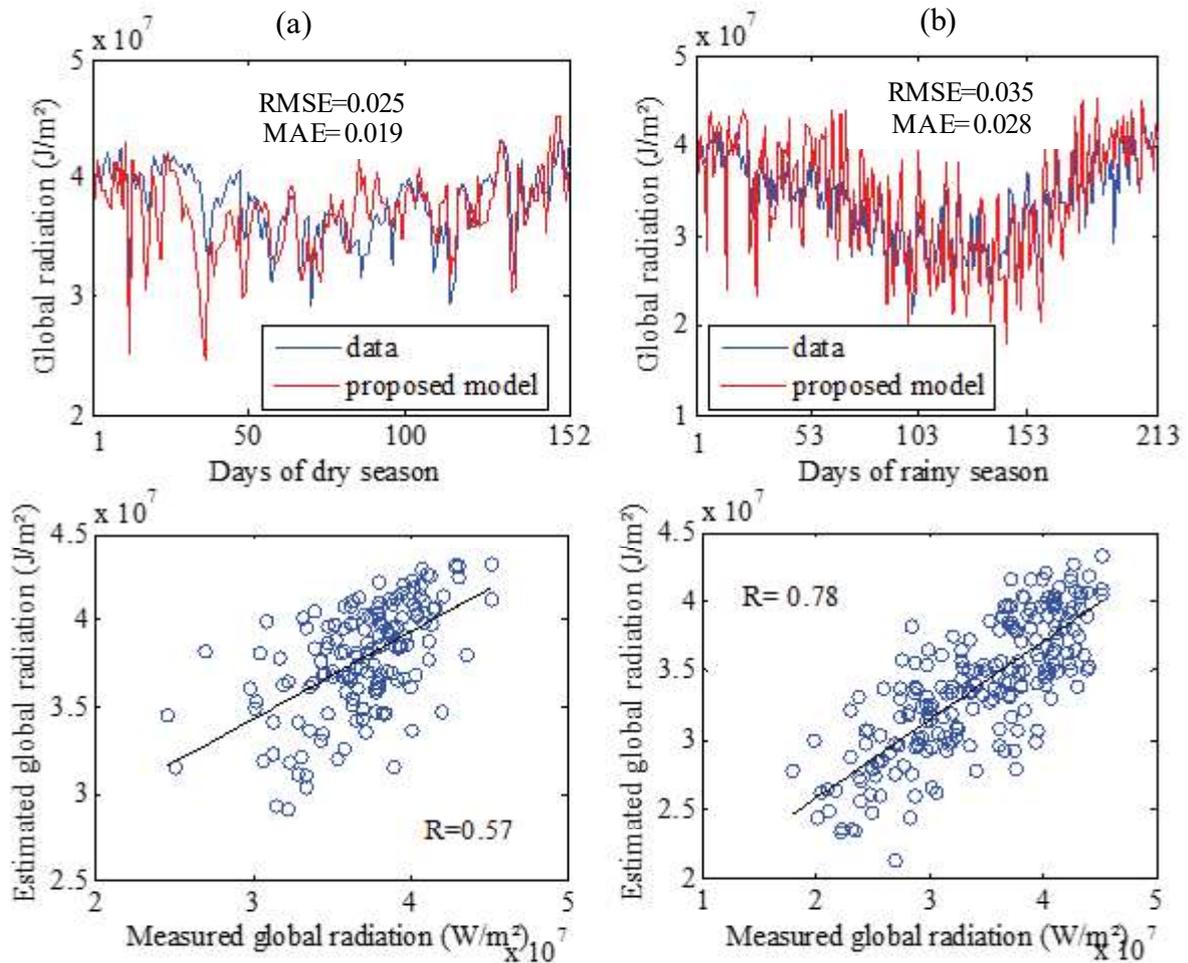


Figure 5: Correlation between proposed model estimates and global solar radiation data in 2016: (a) dry season and (b) rainy season

The model proposed in this study and the measurements of global solar radiation generally show good agreement throughout the year. The error estimators of the square root mean square error (RMSE) and the absolute value of the mean error (MAE) values are 0.1088 and 0.0838, respectively. Similarly, a seasonal analysis of the correlation between estimated values of GSR and observed data shows that during the dry season from November to March, the errors of estimates (RMSE, MAE) values are 0.025 and 0.019 respectively, showing the model's seasonal efficiency. During the rainy season from April to October, these values are 0.035 and 0.028, respectively. One can notice that the seasonal error estimators are lower than those of the entire year 2016 from figure 4. Therefore in the study site, the seasons have a greater influence on global solar radiation. From November to December, there is a divergence between the regenerated GSR values and the measurements. This observation is confirmed by the low value of the correlation coefficient obtained during the dry season (0.57). This gap could be due to the influence of "Harmattan" flux (dry air blowing from Sahara toward the Atlantic Ocean) in the study area at this period of the year. This dry and dusty wind brings suspended particulates matters in the atmosphere which could attenuate the global solar radiation received on the ground. A model integrating the aerosol rate in the atmosphere could therefore better reproduce this radiation sequence at our site during the period. On the other hand, during the rainy season, the measurements and the estimates values of GSR show the same direction of variation, justified by a fairly good value of the correlation coefficient (0.78). However, we note that the model slightly overestimates the measurements throughout the rainy season. This observation could be justified by the presence of frequent clouds events in the sky during the rainy season. The integration of cloud cover parameters in the model could correct this overestimation.

The error obtained in this study were compared to those observed by other authors who used the Angström formulation to estimate GSR in Africa. Adeyemi *et al.* [30] developed global solar radiation estimation models for the nine South African provinces using several meteorological parameters such as insolation, ambient temperature, relative humidity, and wind speed. The accuracy of the models was verified by comparing the estimated values with the measured values, using the following statistical error tests: mean bias error, mean absolute bias error, mean absolute percentage error, root mean square error. His results indicate that these error estimators range from 5.40% to 11.19% at the study sites. Adeniji *et al.* [31] estimated global solar radiation from the distribution of sunshine hours and the brightness index in Enugu (Nigeria). The authors then evaluated the margins of error between models and measurements and the values obtained did not exceed 2.5%. Okundamiya and Nzeako [3] proposed a model based on the monthly mean global solar radiation temperature on horizontal surfaces for selected cities, representing the six geopolitical zones of Nigeria. The results of three statistical indicators: mean bias error (MBA), root mean square error (RMSE) and *t-statistic* test (TS) evaluated indicate that the RMSE and MBA ranged from 0.0023 at the Benin City site, 0.2685 for Katsina site. Quansah *et al.* [10] after estimating global solar radiation by empirical models in the Ashanti region of Ghana obtained error estimators mean percentage error (MPE), mean bias error (MAE) and root mean square error (RMSE) ranging from 0.0102 to 1.7075.

Coulibaly and Ouedraogo [15] correlated the global solar radiation of eight synoptic stations in Burkina Faso based on linear and multiple linear regression methods. The results show that the relative errors obtained range from 3.16% to 3.65% in Dedougou. In the study of Ajayi *et al.* [22], the authors proposed five models for estimating

global solar radiation over 12 sites spread over the six geopolitical zones in Nigeria based on the solar fraction, maximum temperature, relative humidity, the latitude of the site. The estimation errors of these models vary between $3.9 \cdot 10^{-5}$ and 0.36. In the study of Asilevi *et al.* [5], the global solar radiation in Ghana was quantified using the Angström-Preseott sunshine model and sunshine duration data from 22 synoptic stations distributed over the ecological zones of the country. The absolute mean percentage error obtained by the authors range from 3% to 29%. Onyango and Ongoma [16] estimated the global solar radiation potential over the city of Nairobi. Hassan *et al.* [20] have presented new ambient temperature-based models for estimating global solar radiation at several sites in Egypt as alternatives to the widely used sun-based models due to the unavailability of solar radiation's data. Seventeen new temperature-based models are established, validated, and compared to the three other models proposed in the literature to estimate monthly mean daily global solar radiation on a horizontal surface. The estimation errors of these models range from 0.006 to 0.70. Solar irradiation data recorded in three localities (Lomé, Atakpame, and Mangue) representing the climate and geographical areas of Togo were analyzed by Banna and M. Gnininri [32]. The monthly daily global radiation on a horizontal surface for the three cities is deduced from the relative sunshine data using the method developed by Angstrom. Appropriate regional parameters are determined and used to predict the solar irradiation in the three localities with an error of less than 8%.

Because of these various studies, one can see that the performance of solar radiation estimation models vary from one site to another. Some values of the error estimators found in the literature are higher than those observed in the current study, especially at some sites in Egypt, Nairobi, Ghana, Nigeria, and South Africa. Others, on the other hand, are lower than the estimators obtained in Nalohou, particularly in Dedougou sites in Burkina Faso, Enugu in Nigeria, and at other sites in Ghana, Nigeria, and Egypt. However, models with margins of error of 10 to at most 20% have been approved and validated by the various authors. Given these observations, the errors in the estimation of global solar radiation presented at the Nalohou site are tolerable and thus allow us to confirm the performance of the proposed model. The margins of error of the model estimation is tolerable as they are of the order of 10^{-1} to 10^{-2} . However, this model could be improved by integrating meteorological parameters such as aerosol content in the atmosphere and cloud cover data.

In Table 2, the values of the calibration constants of the proposed model are presented

Table 2: Model fitting constant

Proposed model (Nalohou)						
Constant	a	b	c	α	d	e
Along year	0.0571	0.1589	0.3739	0.7216	0.0173	0.0021

Figure 6 presents the validation of the proposed model.

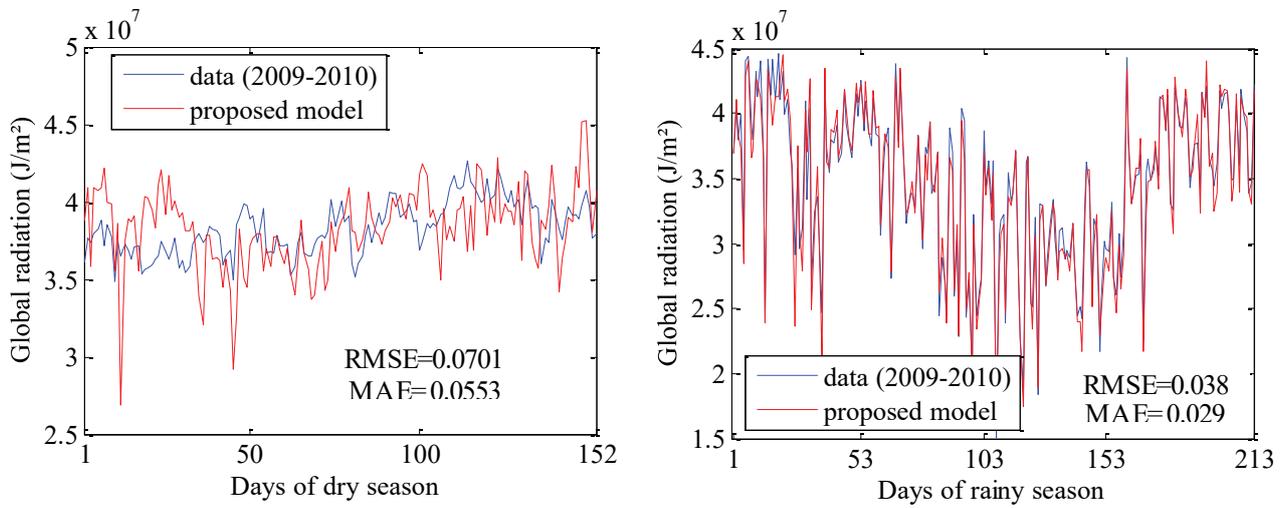


Figure 6: Validation of the proposed model (2009-2010)

The estimation errors (RMSE; MAE) of global solar radiation obtained from the proposed model and the data measured over the period from 10 July 2009 to 10 July 2010 are 0.0701 and 0.0553 for the dry season; they are 0.038 and 0.029 for the rainy season. These small margins of error allow us to validate the proposed model, which can now be used in this region of north-west Benin as a model for estimating global solar radiation.

4.3 Estimation of global solar radiation

Based on the proposed model, the estimated global solar radiation at Natitingou synoptic station is presented in Figure 7 for an entire year (2016).

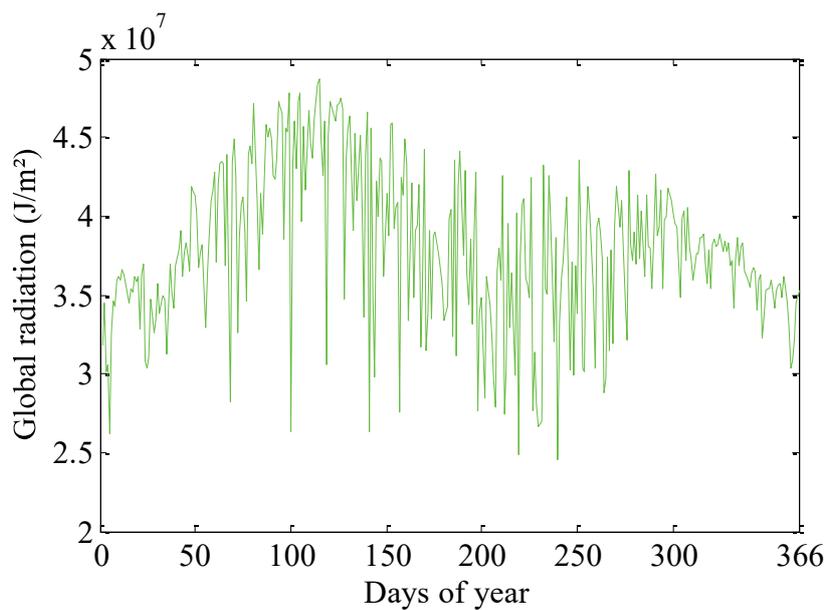


Figure 7: Daily variation in global solar radiation at Natitingou (2016)

In Figure 7, the estimated global solar radiation at the Natitingou meteorological station is of the same order of magnitude as that measured at Nalohou but varies between $2.45 \times 10^7 \text{ J/m}^2$ and $4.86 \times 10^7 \text{ J/m}^2$ (i.e. 6.80 kWh/m² to 13.5 kWh/m² or 283.56 W/m² to 562.50 W/m²) as opposed to the Nalohou site where measurements are between $1.79 \times 10^7 \text{ J/m}^2$ and $4.53 \times 10^7 \text{ J/m}^2$. The annual average global solar radiation is estimated at $3.78 \times 10^7 \text{ J/m}^2$ (10.50 kWh/m²) at Natitingou and $3.53 \times 10^7 \text{ J/m}^2$ (9.80 kWh/m²) at Nalohou. There is therefore a slight increase in GSR at Natitingou. The range of global solar radiation observed in this region of north-western Benin is therefore very useful for designers and installers of solar systems, which now have a reliable database of solar radiation that can be used for all purposes.

5 Conclusion

At the Nalohou site in northern Benin, a model for estimating global solar radiation was developed and validated using solar radiation data recorded at this site. Based on the proposed model, global solar radiation was estimated at the Natitingou site, which has climatic similarities to the Nalohou site. The main results of this study indicate that the annual average global solar radiation observed in the north-western region of Benin varies between $3.53 \times 10^7 \text{ J/m}^2$ and $3.78 \times 10^7 \text{ J/m}^2$ (9.80 kWh/m² to 10.5 kWh/m²). The proposed global solar radiation estimation model can be used with a small margin of error of 8 to 10% throughout the year. During the dry and rainy season, the model can reproduce the measurements with an error of 2% to 3% respectively. However, the model could always be improved by combining aerosol content and cloud cover data, which are two parameters that influence the radiative fluxes received on the ground in our study area.

As a result of this study, a reliable database of global solar radiation is now available to solar system designers and installers to better size their installations.

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