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Determination of a Suitable Solar Radiation Model for the Sites of Chad

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Abstract

The aim of this study is the determination of a suitable solar radiation model for the twelve cities of Chad based on meteorological data. Three appropriate models are used to estimate the solar radiation of each site. The choice of these models is based on statistical tests such as the Root Mean Square Error (RMSE), the Mean Bias Error (MBE), the Mean Percentage Error (MPE), and the Nash-Sutcliffe Equation (NSE). The obtained results show that the Angstrom-Prescott model is the most suitable for the calculation of global solar radiation in the sites of Bongor, Pala, Am-timan and Mongo. For the sites of Moundou, Sarh and Bokoro the Allen model is the most adapted for the calculation of global solar radiation. On the other hand the Sabbagh model is the most appropriate for the sites of Faya-Largeau, Abeche, N'Djamena, Ati and Moussoro. It has been revealed that Abeche is the site with the highest solar radiation value equal to 6.354 kWh/m^2 and Ati is the site where the solar radiation has the lowest value around 5.523 kWh/m^2. Based on the obtained results, it is demonstrated that the three climatic zones of Chad have a good solar potential and consequently suitable for the exploitation of the solar energy systems.

Keywords

Global Solar Radiation, Sabbagh, Allen, Angstrom-Prescott, Meteorological Data

1. Introduction

The energy sector of Chad, which is still weakly developed, is characterized by high consumption of wood fuels (wood and charcoal), which accounts for more than 90% of the total energy consumption of the country. The use of conventional energies (petroleum products and electricity) occupies a marginal part of the national energy balance. These energies, although crucial in the development of a modern economy, account for only about 10% of total energy consumption in the country. There is no interconnected network in the country. Chad, however, has significant energy potential such as hydrocarbons, biomass and renewable energies, including solar and wind energy, whose exploitation could have contributed to the development of the sector. Solar energy applications require, above all, knowledge of the global solar radiation of a site. Thus, a reliable estimation of global solar radiation for a site is fundamental. Doing this will allow adequate knowledge of how to channel such application for either electricity generation, water heating, or irrigation, to mention a few [1] [2] [3]. In a developing country, the data are recorded directly only in a few meteorological stations. In many stations, the spatial coverage of radio stations is insufficient. For example, in Chad, there is not only a lack of measuring equipment, but also of training technicians. In addition, lack of maintenance or calibration of solar radiation sensors gives erroneous measurements or missing data [4]. Researchers have developed a large number of methods to estimate global solar radiation due to lack of reliable data on solar radiation. These methods are based on an empirical model linking variables such as humidity [5] [6], temperature [7] [8] [9] [10], elevation [11] [12], duration of the sun [13] [14] [15] [16] and latitude [17] [18]. It may be easier to exploit solar energy resources when the site under consideration is equipped with a pyranometer functioning regularly for several years. However, there is need to use approximate methods to predict solar radiation characteristics if local measures do not exist. Numerous models have been developed that connect global solar radiation to extraterrestrial solar radiation in order to estimate the amount of solar energy incident on a horizontal surface. Among these models, the Angstrom-Prescott model has been developed and employed by many researchers and with certain meteorological parameters [19]. In the estimation of global solar radiation, each of these factors contributes significantly.

This study was therefore focused to develop a mathematical model to estimate the solar radiation coming from extraterrestrial radiation, with meteorological and geographical data as governing parameters. The model was validated by comparing its results with experimentally measured data across the twelve sites of Chad. The impact of this is the fact that such model can now be used to analyse and make informed decisions on solar technology applications without recourse to several years of experimental measurements around the studied sites and across the region.

2. Data Base

Solar data employed for the study were obtained from the General directorate of the National Meteorology of Chad, in June 2014 covering the period of 63 years (*i.e.* 1950-2013). They are monthly data of the relative humidity, maximum temperature, minimal temperature, and sunshine duration. The geographical coordinates of the twelve stations of the National office of Meteorology (ONM) are given in Table 1.

3. Used Models

To calculate the global solar radiation, one has recourse to the ideal models.These models are in the form of empirical relations which connect the components of the solar radiation to the principal weather parameters and the astronomical parameters. The weather parameters are the ambient temperature, the relative humidity, the sunshine duration. Amongst the astronomical parameters one has the maximum duration of the day, the variation of the sun, the variation of the ground-sun distance and the solar radiation in the extraterrestrial radiation [20]. As part of this work, these include the Angstrom-Prescott model, the Allen model and the Sabbagh model.

3.1. Estimation of Extraterrestrial Radiation, H_0

The monthly mean of the daily extraterrestrial solar radiation on a horizontal surface is determined according the following relation [21] [22] [23] [24] [25]:

$$H_0 = \frac{24}{\pi} I_{sc}\left[1+0.33\cos\left(\frac{360 D_n}{365}\right)\right] * \left[\cos L \cos\delta \sin\omega_s + \frac{2\pi\omega_s}{360}\sin L \sin\delta\right] \quad (1)$$

Table 1 Geographical locations of the sites considered.

Zones	sites	Latitude (˚N)	Longitude (˚E)	Elevation (m)
Saharan zone	Faya-Largeau	17.55	19.7	233
	Abeche	13.51	20.51	545
	N'Djamena	12.8	15.2	294
Sahelian zone	Ati	13.13	18.19	334
	Bokoro	12.23	17.3	300
	Mongo	12.11	18.41	430
	Moussoro	13.39	16.3	301
	Am-timan	11.2	20.17	432
	Bongor	10.17	16.22	328
Sudanese zone	Moundou	8.37	16.4	420
	Pala	9.22	14.55	420
	Sarh	9.9	18.23	364

where δ *and* ω_s are respectively the monthly mean of the daily solar declination and the sunshine hour angle defined by [26] [27] [28]:

$$\delta = 23.45 \sin\left[\frac{360(284 + D_n)}{365}\right] \quad (2)$$

$$\omega_s = \cos^{-1}(-\tan L \tan \delta) \quad (3)$$

where I_{sc} is the solar constant (I_{sc} =1367 W/m^2), L is the location latitude, D_n is the number of the day in the year.

3.2. Global Solar Radiation on a Horizontal Level with Angstrom-Prescott Model

Angstrom has been the first to propose an ideal model (linear model) to estimate the horizontal global solar radiation with in entry the data over the sunshine duration [29] [30] [31]. Prescott and Page [32] [33] have improved this model and considered the horizontal global solar radiation of the sunshine duration according to the relation (4).

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) \quad (4)$$

The parameters *a, b* are respectively defined by the Equations (5) and (6).

$$a = -0.110 + 0.235 \cos L + 0.323\left(\frac{S}{S_0}\right) \quad (5)$$

$$b = 1.449 - 0.553 \cos L - 0.694\left(\frac{S}{S_0}\right) \quad (6)$$

The possible maximum monthly mean of the daily sunshine duration is [34]:

$$S_0 = \frac{2}{15}\cos^{-1}(-\tan L \tan \delta) \quad (7)$$

3.3. Global Solar Radiation on a Horizontal Level with the Allen Model

Allen [35] [36] estimated the monthly mean of the global solar radiation as a function of H_0, the monthly mean of the maximum temperature (T_M), and the monthly mean of the minimum temperature (T_m) as:

$$\frac{H}{H_0} = K_r (T_M - T_m)^{0.5} \quad (8)$$

Where K_r is defined as:

$$K_r = K_{ra}\left(\frac{P}{P_0}\right)^{0.5} \quad (9)$$

In the relation (9), $K_{ra} = 0.17$ and P/P_0 may be defined as:

$$\frac{P}{P_0} = \exp(-0.0001184h) \quad (10)$$

where P and P_0 are respectively the values of local and standard atmospheric pressure, and h is the altitude of the place in meters.

3.4. Global Solar Radiation on a Horizontal Level with the Sabbagh Model

While being based on data relating to several countries of the Gulf, in particular, the sites of Saudi Arabia, Sabbagh et *al.* developed two empirical relations binding the various weather parameters which affect the attenuation of the solar radiation, namely: sunshineduration, relative humidity, the maximum temperature, the altitude, the geographical situation (longitude, latitude) and its situation compared to the sea and a lake of water characterized by the characteristic factor of the zone, which is given by the following relation [37]:

$$H = 1.530K * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{\max}}\right), \tag{11}$$

With:

$$K = 100\left(nT_{\max} + \psi_{ij}\cos\left(L\right)\right), \tag{12}$$

$$n = \frac{1}{\left(1 + 0.1L\right)}, \tag{13}$$

RH and T_{max} are respectively the monthly average per day of the sunshine duration, the relative humidity and the maximum average temperature of the considered month.

ψ_{ij}, climatic factor

n, number of the month considered

S, monthly average daily bright sunshine duration (h)

4. Statistical Test

In order to compare the data of the solar radiation provided by NASA (National Aeronautic and Space Administration) with those obtained from the various presented models, all the different models were implemented by creating a code using MATLAB and Excel.From each of these programs and for each studied site, on the one hand we drew up in the same graph, the values of whole-body radiation by NASA and those calculated, and in the other hand we drew up the relative error. The presented models in paragraph 3 permitted to evaluate the calculated global radiation $H_{i,c}$ in order to be compared to the measured global radiation $H_{i,m}$.

Several statistical indicators used in the literature [20] [21] [37]-[42] were employed to determine the degree of accuracy of the estimated values as compared to measured values. These indicators included:*RMSE*, *MBE*, *MPE* and *NSE*.

RMSE (Root Mean Square Errors) is a measure of the variation of calculated values; it gives information about the performance of the model and is always positive values. The model is best when its *RMSE* value is the smallest. It is defined by the relation:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(H_{i,c} - H_{i,m}\right)^2}{n}} \tag{14}$$

n is the number of the month.

The mean bias error (*MBE*) is the mean inclination error giving information on the performance of the long-term model. To this end, a negative value refers to underestimation, while positive value refers to an overestimation. It is given by Equation (15):

$$MBE = \sum_{i=1}^{n} \frac{\left(H_{i,c} - H_{i,m}\right)}{n} \tag{15}$$

The *MPE* (Mean Percentage Error) is defined by the relation:

$$MPE(\%) = \frac{1}{n} * \sum_{i=1}^{n} \frac{\left(H_{i,c} - H_{i,m}\right)}{H_{im}} * 100 \tag{16}$$

For this indicator, for a given model, an error expressed as a percentage between −10% and +10% is acceptable.

The *NSE* (Nash-Sutcliffe Equation) represents a measure of the precision of the model results. The *NSE* is defined by the relation:

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(H_{i,m} - H_{i,c}\right)^2}{\sum_{i=1}^{n} \left(H_{i,m} - \bar{H}_m\right)^2} \tag{17}$$

where: $\bar{H}_m$ is the mean measured global radiation.

5. Results and Discussions

To estimate the overall solar radiation using the Angstrom-Prescott model, apart from the geographical coordinates of the site, the average daily insolation duration was considered.

Meteorological data such as relative humidity, maximum temperature and average daily sun exposure measured the overall solar radiation using the Sabbagh model. Maximum temperature and minimum temperature were considered in the Allen model.

Figure 1 presents the map of Chad with the three climatic zones. The different sites that make up these areas can be observed.

Figure 2 presents the results of the monthly extraterrestrial radiation for the twelve sites in the three climatic zones of Chad. It can be noted in this table that the smallest value of the extraterrestrial radiation of 8.112 kWh/m^2 is found in Faya-Largeau. The highest value of 9.364 kWh/m^2 is found at Moundou.

Figure 3 presents the values of the monthly global solar radiation in the form of histograms obtained through the three appropriate models of estimation for each studied site.

Tables 2-5 present the total results obtained through the relations of Angstrom-Prescott, Allen, Sabbagh equation and Sabbagh model for the twelve sites of the three climatic zones of Chad.

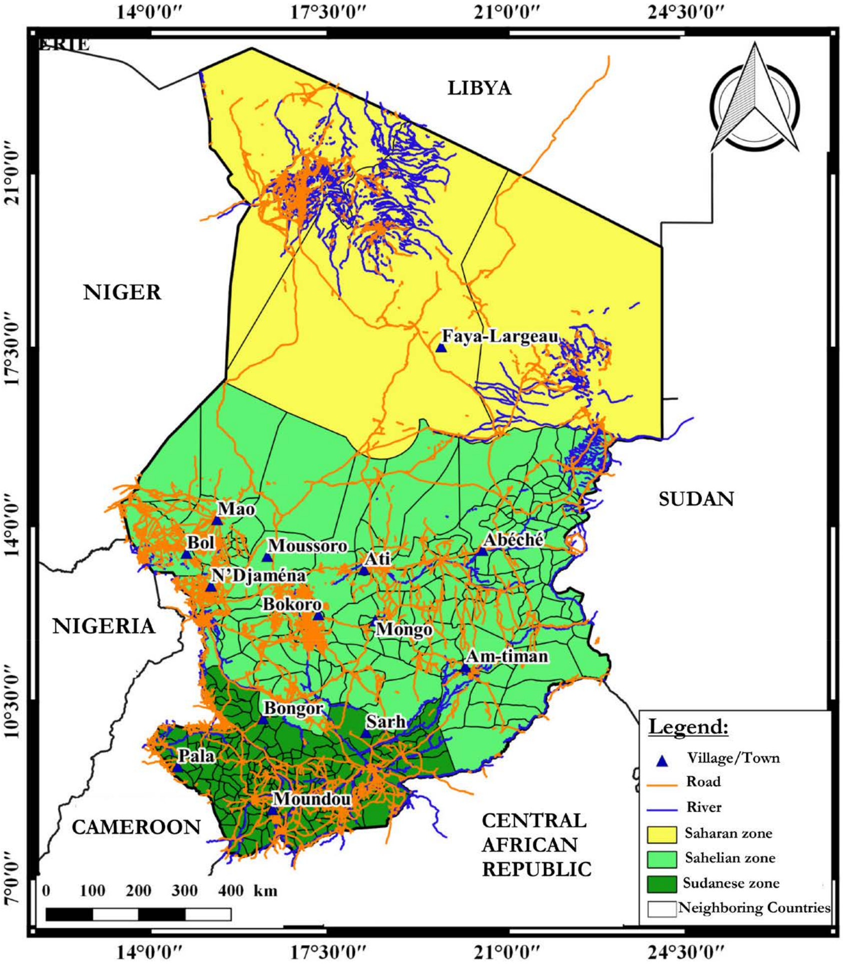


Figure 1. Presentation of the map of Chad with the three climatic zones.

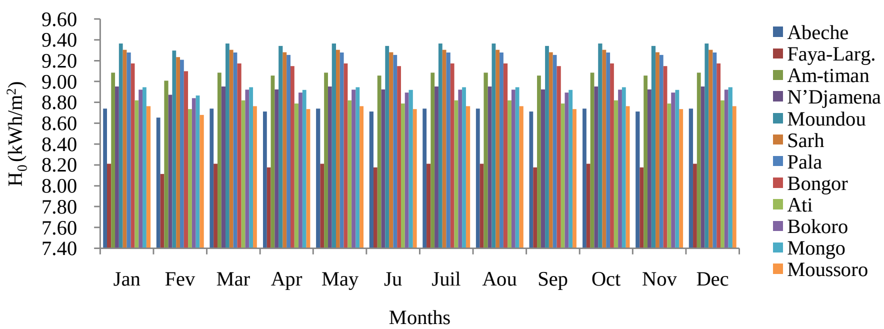
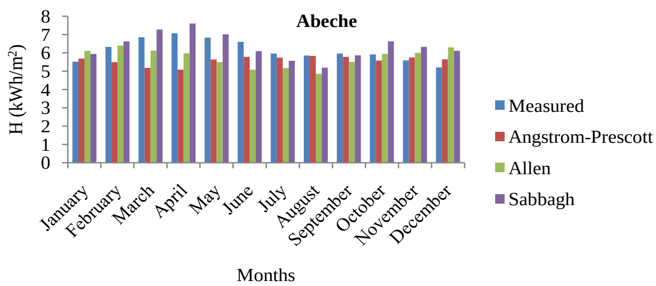
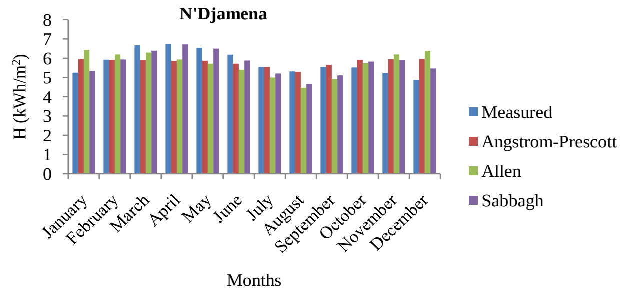


Figure 2. Monthly extraterrestrial solar radiation.

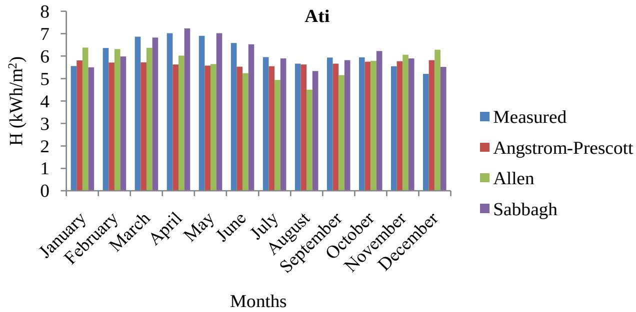
In Table 2 the values of the various parameters of Angstrom-Prescott model for the twelve sites of the three climatic zones of Chad are presented. Thus based on Angstrom-Prescott model calculation, one can conclude that Am-timan is the suitable place for the exploitation of solar energy compared to the other sites, because of his highest monthly global solar radiation of 5.917 kWh/m². The smallest value of the monthly global solar radiation calculated through Angstrom-Prescott model is 5.457 kWh/m² (obtained for the site of Faya-Largeau).


Abeche
H (kWh/m²)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

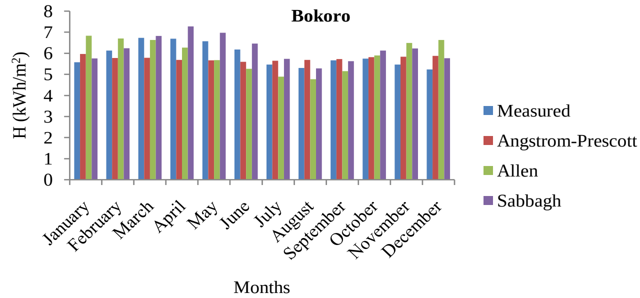
(a)


N'Djamena
H (kWh/m²)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

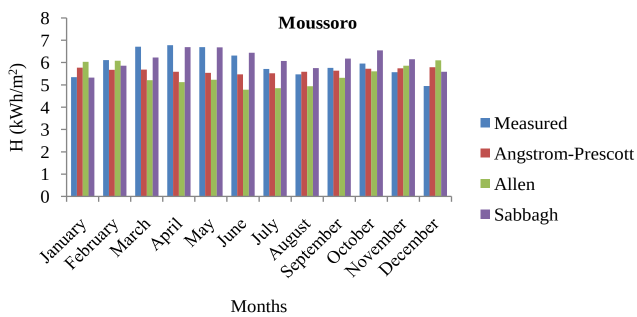
(b)


Ati
H (kWh/m²)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

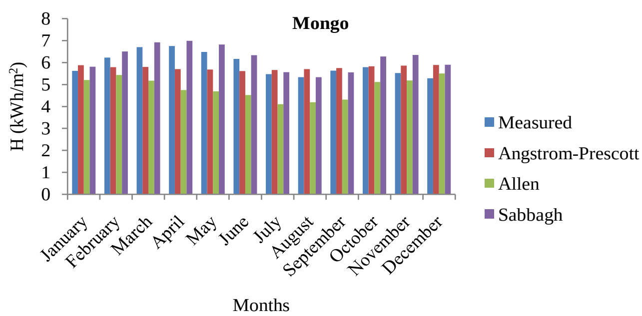
(c)


Bokoro
H (kWh/m²)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

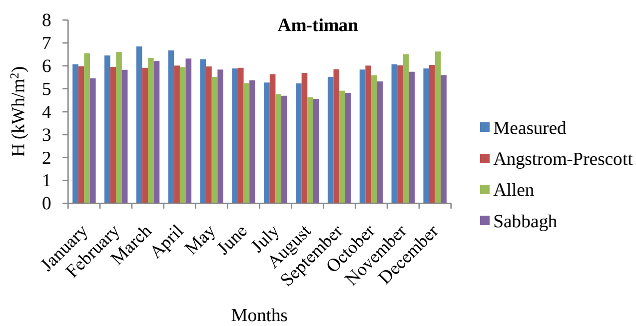
(d)


Moussoro
H (kWh/m²)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

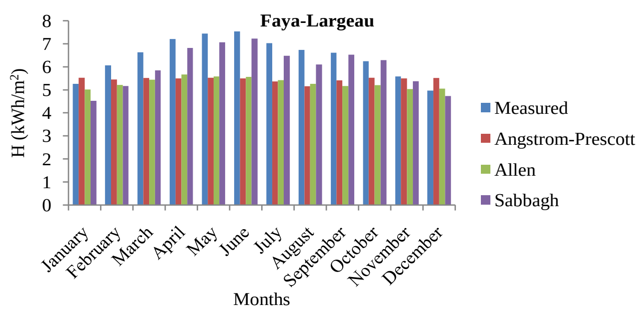
(e)


Mongo
H (kWh/m²)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

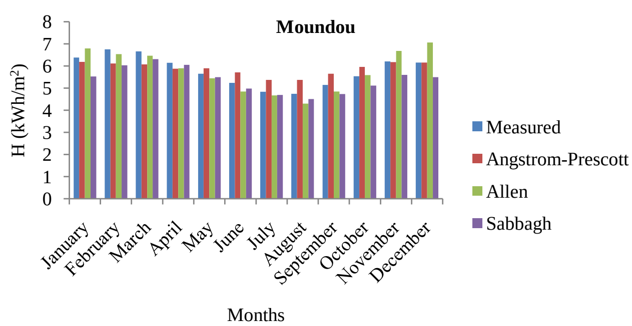
(f)


Am-timan
H (kWh/m²)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

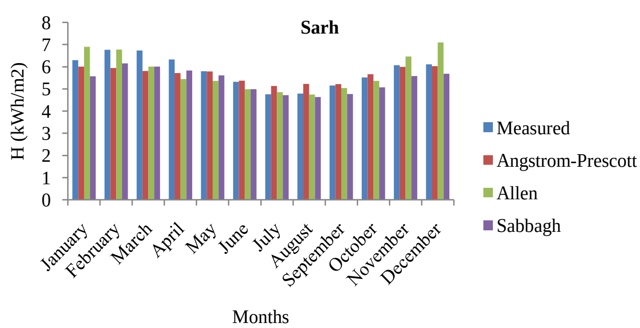
(g)


Faya-Largeau
H (kWh/m²)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

(h)


Moundou
H (kWh/m²)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

(i)


Sarh
H (kWh/m2)
Months
January February March April May June July August September October November December
Measured
Angstrom-Prescott
Allen
Sabbagh

(j)

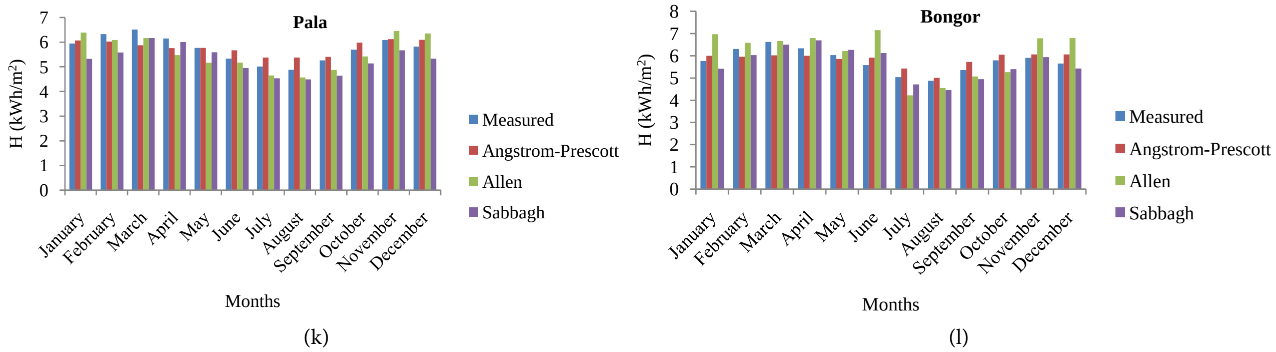


Figure 3. Monthly global solar radiation of the twelve sites.

Table 2. Angstrom-Prescott model for the twelve sites.

Sites	a	b	H_0	$S(h)$	$S_0(h)$	H/H_0	S/S_0	H (kWh/m²)	Err (%)
Faya-Largeau	0.39	0.33	8.19	9.59	11.2	0.67	0.86	5.457	−13.791
Abeche	0.45	0.2	8.722	11.62	11.39	0.64	1.02	5.600	−7.807
Am-timan	0.37	0.36	9.069	8.97	11.52	0.65	0.78	5.917	−0.887
N'Djamena	0.37	0.38	8.936	8.74	11.47	0.65	0.76	5.791	1.265
Bongor	0.35	0.41	9.158	8.3	11.55	0.64	0.72	5.839	1.590
Moundou	0.34	0.43	9.351	7.97	11.62	0.63	0.68	5.88	1.482
Pala	0.34	0.44	9.265	7.77	11.59	0.62	0.67	5.792	2.454
Sarh	0.32	0.47	9.29	7.17	11.6	0.61	0.62	5.658	−1.765
Ati	0.46	0.18	8.802	12.09	11.42	0.65	1.06	5.681	−6.446
Bokoro	0.46	0.18	8.905	12.08	11.46	0.65	1.05	5.748	−1.547
Mongo	0.46	0.18	8.93	12.09	11.47	0.65	1.05	5.763	−1.829
Moussoro	0.46	0.17	8.748	12.1	11.4	0.65	1.06	5.646	3.400

Table 3. Allen model for the twelve sites.

Sites	T_M	T_{min} (˚C)	H_0	H/H_0	H (kWh/m²)	Err (%)
Faya-Largeau	35.65	21.13	8.19	0.65	5.3	−16.723
Abeche	37.42	22.28	8.722	0.66	5.747	−5.482
Am-timan	34.78	20.54	9.069	0.64	5.771	−3.958
N'Djaména	36.38	22.02	8.936	0.64	5.724	0.078
Bongor	36.42	20.74	9.158	0.665	6.085	5.154
Moundou	34.525	21.066	9.351	0.616	5.76	−3.074
Pala	33.925	21.266	9.265	0.601	5.563	−0.844
Sarh	35.083	21.55	9.29	0.619	5.751	−0.878
Ati	36.22	21.41	8.802	0.651	5.726	−5.825
Bokoro	36.73	21.13	8.905	0.666	5.932	1.181
Mongo	36.45	26.15	8.93	0.543	4.849	−17.506
Moussoro	35.56	22.13	8.748	0.621	5.429	−7.523

The Angstrom-Prescott model is the most suitable for the calculation of global solar radiation based on the relative error with NASA data especially for the sites: Bongor (1.590%), Pala (1.482%), Am-timan (−0.887%) and Mongo (−1.829%).

Table 4. Sabbagh equations model for the twelve sites.

$$\text{Am-timan}: H = 3.6080 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Mongo}: H = 3.7637 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Sarh}: H = 3.6497 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Pala}: H = 3.5344 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{N'Djamena}: H = 3.7575 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Faya-Largeau}: H = 3.6463 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Abeche}: H = 3.8466 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Ati}: H = 3.7346 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Bongor}: H = 3.7742 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Moundou}: H = 3.5982 * 10 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Moussoro}: H = 3.6668 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

$$\text{Bokoro}: H = 3.7893 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

Table 5. Sabbagh model for the twelve sites.

Sites	S	S_0 (h)	RH (%)	T_{max} (˚C)	S/S_0	H (kWh/m²)	Err (%)
Faya-Largeau	9.59	11.2	20.37	35.65	0.857	6.013	−6.766
Abeche	11.62	11.39	36	37.42	1.02	6.354	3.704
Am-timan	8.74	11.47	44.85	36.38	0.76	5.742	−8.837
N'Djamena	8.74	11.47	44.85	36.38	0.76	5.742	−0.348
Bongor	8.3	11.55	56.83	36.42	0.72	5.656	-2.162
Moundou	7.97	11.62	59.09	34.52	0.68	5.377	−7.879
Pala	7.76	11.59	52.93	33.92	0.67	5.285	−6.892
Sarh	7.17	11.6	59.31	35.08	0.62	5.385	−6.946
Ati	12.09	11.42	39.52	36.22	1.06	6.151	0.356
Bokoro	12.08	11.46	42.13	36.73	1.05	6.189	5.032
Mongo	12.09	11.47	36.37	36.45	1.05	6.195	4.825
Moussoro	12.1	11.4	33.18	35.56	1.06	6.126	3.4

Table 3 presents the estimation of the global solar radiation through the relation of Allen shows that it is Bongor which has the best solar potential with a value of 6.085 kWh/m², compared to the other sites of Chad.On the other hand, one notices that in term of relative error with measured data, the Allen model is more adapted for the calculation of the global solar radiation of N'Djamena, Pala and Sarh, respectively with a mean relative error of 0.078%, 0.844% and 0.878%.Moreover, Abeche is the site where the temperature is the highest with a value of 37.42˚C while the lowest temperature is 20.54˚C (in the site of Am-timan).

Table 4 presents the obtained values of the Sabbagh equations for the twelve sites of Chad. Thus, we note in this table the variation of the coefficients which is of the order of $3.5344 * 10^3$ to Pala and $3.8466 * 10^3$ to Abeche.

Table 5 presents the obtained values of the parameters of Sabbagh model for the twelve sites of Chad. Abeche is the site where the sunshine duration is the highest (11.62 h); the smallest value is observed in Sarh (7.17 h).The highest value of the duration of the day is noted in Moundou (11.62 h) while the lowest value is observed in Faya-Largeau (11.20 h).For the relative humidity, it is in Sarh which has the highest value (59.31%); the smallest value is observed in Faya-Largeau (20.37%). In addition, the highest value of the maximum temperature is observed in Abeche (37.42˚C) and the lowest value is observed in Pala (33.92˚C).The highest valueof sunshine rate is observed in Abeche (1.02) and the lowest value is observed in Sarh (0.62).The estimation of the global solar radiation for all sites through Sabbagh model shows that the highest value is observed in Abeche (6.354 kWh/m^2) and the lowest value is observed in Pala (5.285 kWh/m^2). The various results show indeed that the three zones of Chad do not have the same climatic conditions.

The Sabbagh model is the most suitable for calculating global radiation based on the relative error with NASA data especially for the sites: Faya-Largeau (−6.766%), Abeche (3.704%), N'Djamena (−0.348%), Ati (0.356%) and Moussoro (3.400%).

It can also be noted that all three models can only be applied if weather data and geographic parameters are available for a given site. The reliability of these models is the correct estimate of global solar radiation without going through direct and diffuse radiation. Moreover, it is observed that the solar radiation is affected by the meteorological parameters because the decrease of the parameters such as the temperature and the relative humidity leads to the reduction of the solar radiation. For example, the month of August seems the most unfavorable because the more it rains, the more radiation decreases.

Table 6 compares the three models used for the twelve studied sites.The comparison between the obtained results through the three models of calculation and the measured data shows that the Angstrom-Prescott model gives the best estimation of the global solar radiation for the sites of Bongor (MPE (%) = 1.5902; $RMSE$ = 0.3368; MBE = 0.0159; NSE = 0.6999), *Pala* (MPE (%) = 1.4822; $RMSE$ = 0.3338; MBE = 0.0148; NSE = 0.7241), Am-timan (MPE (%) = −0.8875;

Table 6. Statistics for the validation of the selected models (kWh/m²).

(a)

	Angstrom-Prescott			
Sites	*MPE*(%)	*RMSE* (kWh/m²)	*MBE* (kWh/m²)	*NSE* (kWh/m²)
Abeche	−7.8073	0.9141	−0.0781	−1.5902
Faya-Largeau	−13.791	1.289	−0.1379	−1.2293
Am-timan	−0.8875	0.4256	−0.0089	0.291
N'Djamena	1.2655	0.6038	0.0127	0.2408
Moundou	2.4541	0.4353	0.0245	0.6596
Sarh	−1.7654	0.4417	−0.0177	0.6453
Pala	1.4822	0.3338	0.0148	0.7241
Bongor	1.5902	0.3368	0.0159	0.6999
Ati	−6.4463	0.7823	−0.0645	−0.8224
Bokoro	−1.5466	0.5834	−0.0155	−0.0377
Mongo	−1.8291	0.5609	−0.0183	−0.0373
Moussoro	−4.1310	0.6887	−0.0413	−0.3560

(b)

	Allen			
Sites	*MPE* (%)	*RMSE* (kWh/m²)	*MBE* (kWh/m²)	*NSE* (kWh/m²)
Abeche	−5.4824	0.8835	−0.0548	−1.4197
Faya-Largeau	−16.724	1.297	−0.1672	−1.256
Am-timan	−3.9584	0.5638	−0.0396	−0.2442
N'Djamena	0.0784	0.8275	0.0008	−0.4261
Moundou	−0.8437	0.3962	−0.0084	0.7181
Sarh	−0.8779	0.5114	−0.0088	0.5245
Pala	−3.0737	0.4175	−0.0307	0.5684
Bongor	5.1543	0.7879	0.0515	−0.6421
Ati	−5.8254	0.9031	−0.0583	−1.4289
Bokoro	1.1811	0.799	0.0118	−0.9464
Mongo	−17.506	1.2438	−0.1751	−4.1008
Moussoro	−7.523	1.0278	−0.0752	−2.0198

(c)

	Sabbagh			
Sites	*MPE* (%)	*RMSE* (kWh/m²)	*MBE* (kWh/m²)	*NSE* (kWh/m²)
Abeche	3.7042	0.5418	0.037	0.0899
Faya-Largeau	−6.7662	0.513	−0.0677	0.6468
Am-timan	−8.8376	0.5406	−0.0884	−0.1439
N'Djamena	−0.3477	0.3842	−0.0035	0.6927
Moundou	−6.8922	0.475	−0.0689	0.5949
Sarh	−6.9461	0.4677	−0.0695	0.6023
Pala	−7.8795	0.4787	−0.0788	0.4327
Bongor	−2.1625	0.3344	−0.0216	0.7042
Ati	0.3564	0.2314	0.0036	0.84056
Bokoro	5.0317	0.3798	0.0503	0.5602
Mongo	4.8254	0.3722	0.0483	0.5432
Moussoro	3.4003	0.3879	0.034	0.5697

Table 7. Comparison between measured and estimated monthly global solar radiation (kWh/m^2). (a) Site of Abeche; (b) site of Faya-Largeau; (c) site of Am-timan; (d) site of N'Djamena; (e) site of Moundou; (f) site of Sarh; (g) site of Pala; (h) site of Bongor; (i) site of Ati; (j) site of Bokoro; (k) site of Mongo; (l) site of Moussoro.

(a)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	3.080	10.634	7.663
February	−13.117	1.203	4.810
March	−24.563	−10.714	6.064
April	−28.133	−15.446	7.581
May	−17.467	−19.488	2.635
June	−12.379	−22.939	−7.667
July	−3.725	−13.289	−6.577
August	−0.478	−17.065	−11.451
September	−2.886	−7.701	−1.493
October	−5.668	0.541	12.200
November	2.898	7.263	13.184
December	8.750	21.212	17.500
Average	−7.807	−5.482	3.704

(b)

Month	Angstrom-Presott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	4.981	−4.696	−14.049
February	−10.066	−13.944	−14.802
March	−16.757	−17.934	−11.84
April	−23.745	−21.456	−5.409
May	−25.766	−24.973	−5.040
June	−27.056	−26.26	−4.164
July	−23.684	−22.859	−7.781
August	−23.314	−21.857	−9.331
September	−18.124	−21.876	−1.256
October	−11.506	−16.619	0.865
November	−1.523	−9.839	−3.638
December	11.066	1.630	−4.748
Average	−13.791	−16.724	−6.766

(c)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	−1.433	7.941	−10.148
February	−7.705	2.388	−9.643
March	−13.606	−7.328	−9.358
April	−9.865	−10.885	−5.277
May	−5.056	−12.162	−7.138
June	0.458	−10.951	−8.829
July	7.021	−9.677	−10.911
August	8.853	−11.415	−12.83
September	6.033	−10.906	−12.736
October	2.911	−4.298	−8.870
November	−0.807	7.331	−5.371
December	2.547	12.462	−4.941
Average	−0.887	−3.958	−8.838

(d)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	13.41	22.629	1.562
February	−0.372	4.730	0.186
March	−11.604	−5.652	−4.183
April	−13.001	−11.828	−0.208
May	−10.214	−12.63	−0.673
June	−7.577	−12.649	−4.943
July	0.054	−9.729	−5.975
August	−0.414	−15.951	−12.373
September	2.094	−11.264	−7.69
October	6.993	3.877	5.543
November	13.416	18.321	12.405
December	22.402	31.088	12.177
Average	1.265	0.078	−0.348

(e)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	−3.103	6.442	−13.401
February	−9.452	−3.185	−10.681
March	−8.754	−2.913	−5.300
April	−4.235	−3.925	−1.482
May	4.319	−3.628	−2.690
June	9.065	−7.576	−5.019
July	11.074	−3.554	−3.079
August	13.418	−9.262	−4.873
September	9.981	−5.778	−7.918
October	7.635	0.776	−7.708
November	−0.58	7.585	−9.871
December	0.081	14.894	−10.683
Average	2.454	−0.844	−6.892

(f)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	−4.619	9.429	−11.667
February	−12.012	0.148	−9.068
March	−13.67	−10.817	−10.758
April	−9.747	−14.028	−7.899
May	−0.293	−7.534	−3.224
June	1.015	−6.222	−6.241
July	7.899	1.870	−0.819
August	9.040	−0.939	−3.173
September	1.184	−2.175	−7.359
October	2.645	−2.844	−8.134
November	−1.252	6.524	−8.023
December	−1.375	16.056	−6.989
Average	−1.765	−0.878	−6.946

(g)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	2.205	7.542	−10.337
February	−4.787	−3.902	−11.801
March	−9.800	−5.223	−5.330
April	−6.407	−11.008	−2.358
May	0.000	−10.572	−3.085
June	6.398	−3.002	−7.167
July	7.265	−7.126	−9.541
August	10.123	−6.311	−8.012
September	2.662	−7.319	−11.73
October	4.860	−4.947	−9.877
November	0.542	5.895	−6.880
December	4.725	9.089	−8.436
Average	1.482	−3.073	−7.879

(h)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	4.184	20.972	−6.024
February	−5.381	4.397	−4.397
March	−9.154	0.619	−1.888
April	−5.276	7.283	5.703
May	−2.985	2.952	3.947
June	6.093	28.100	9.677
July	7.579	−16.349	−6.528
August	2.731	−6.715	−8.501
September	6.972	−5.271	−7.645
October	4.542	−9.119	−6.753
November	2.538	14.805	0.423
December	7.239	20.177	−3.965
Average	1.590	5.154	−2.162

(i)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	4.478	14.712	−1.007
February	−10.204	−0.692	−5.881
March	−16.710	−7.263	−0.582
April	−19.872	−14.188	3.091
May	−19.276	−18.22	1.563
June	−16.039	−20.470	−0.926
July	−6.829	−17.148	−1.074
August	−0.811	−20.635	−5.961
September	−4.613	−13.249	−2.054
October	−3.277	−2.588	4.739
November	4.090	9.261	6.360
December	11.708	20.576	6.008
Average	−6.446	−5.825	0.356

(j)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbag hErr (%)
January	7.217	22.675	*3.303*
February	−5.759	9.364	*1.811*
March	−14.027	−1.516	*1.322*
April	−14.948	−6.278	*8.685*
May	−13.775	−13.623	*6.088*
June	−9.417	−14.903	*4.531*
July	3.333	−10.421	*4.963*
August	7.321	−9.962	*-0.415*
September	1.058	−9.171	*-0.847*
October	1.183	2.487	*6.609*
November	6.978	18.791	*14.158*
December	12.275	26.73	*10.172*
Average	−1.547	1.181	*5.032*

(k)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	4.537	−7.438	3.292
February	−7.030	−12.777	4.462
March	−13.418	−22.701	3.269
April	−15.481	−29.689	3.481
May	−12.33	−27.670	5.216
June	−9.011	−26.694	2.707
July	3.419	−24.881	1.682
August	6.998	−21.351	0.150
September	2.043	−23.357	−1.314
October	0.743	−11.710	8.325
November	6.087	−6.051	14.855
December	11.496	4.242	11.780
Average	−1.829	−17.506	4.825

(l)

Month	Angstrom-Prescott Err (%)	Allen Err (%)	Sabbagh Err (%)
January	7.963	12.822	−0.430
February	−7.087	−0.491	−4.157
March	−15.216	−22.28	−7.258
April	−15.537	−24.469	−1.283
May	−17.130	−21.794	−0.179
June	−13.249	−24.216	2.076
July	−3.327	−15.079	6.375
August	2.194	−9.744	5.229
September	−2.222	−7.622	7.257
October	−3.993	−5.872	9.899
November	3.124	5.135	10.467
December	16.909	23.333	12.808
Average	−4.131	−7.523	3.400

RMSE = 0.4256; *MBE* = −0.0089; *NSE* = 0.291) and Mongo (*MPE* (%) = −1.8291; *RMSE* = 0.5609; *MBE* = −0.0183; *NSE* = −0.0373).

The Allen model is appropriate for Moundou (*MPE* (%) = −0.8437; *RMSE* = 0.3962; *MBE* = −0.0084; *NSE* = 0.7181), Sarh (*MPE* (%) = −0.8779; *RMSE* = 0.5114; *MBE* = −0.0088; *NSE* = 0.5245) and Bokoro (*MPE* (%) = 1.1811; *RMSE* = 0.799; *MBE* = 0.0118; *NSE* = −0.9464). For the cities of Faya−Largeau (*MPE*(%)= −6.7662; *RMSE* = 0.513; *MBE* = −0.0677; *NSE* = 0.6468), Abeche (*MPE*(%) = 3.7042; *RMSE* = 0.5418; *MBE* = 0.037; *NSE* = 0.0899), N'Djamena (*MPE* (%) = −0.3477; *RMSE* = 0.3842; *MBE* = −0.0035; *NSE* = 0.6927), *Ati* (*MPE*(%) = 0.3564; *RMSE* = 0.2314; *MBE* = 0.034; *NSE* = 0.5697) and Moussoro (*MPE*(%) = 3.4003; *RMSE* = 0.3879; *MBE* = −0.0677; *NSE* = 0.6468), it is the Sabbagh model which is adapted for the calculation of the global solar radiation.

We can justify that one model is more suitable than another if the statistical values tend towards zero.

The Comparison between the measureddataandthe estimated values of the monthly global solar radiation is presented in Table 7.

6. Conclusions

In this work, the most adapted mathematical model of estimating the global solar radiation has been determined for twelve sites of Chad. The main results show that Abeche, a site in the Sahelian zone, has an radiation of 6.354 kWh/m^2, while Ati has solar radiation of 5.523 kWh/m^2. In the Saharan zone to the north, Faya-Largeau has the best solar radiation potential around 6.013 kWh/m^2. In southern of Chad, the site with highest solar radiation is Bongor (with 5.839 kWh/m^2), but Sarh is the site with the lowest solar radiation of 5.751 kWh/m^2. Three models, including the Angstrom-Prescott, Sabbagh and Allen models have been used to estimate the global solar radiation of each city, and these methods have been compared to the various statistical tests used to choose the appropriate model.

In terms of theoretical contributions, three equations were chosen:

$$\text{Angstrom-Prescott Model}: H/H_0 = 0.3721 + 0.3659\left(S/S_0\right)$$

$$\text{Allen Model}: H = 0.6160 * H_0$$

$$\text{Sabbagh Model}: H = 3.7575 * 10^3 * \exp L\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$$

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