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Evaluation of global solar radiation from meteorological data in the Sahelian zone of Chad

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Abstract

The study focuses on the evaluation of global solar radiation on a horizontal level. The estimate of the solar layer was made on the basis of mathematical model obtained from the relations of Angstrom–Prescott, Allen and Sabbagh. The different proposed models have been implemented by using MATLAB and Excel. The models were evaluated using MPE, NSE, RMSE and MBE. The outcome of this shows that the Angstrom–Prescott model is the most suitable for the calculation of global solar radiation in the sites of Mongo with values of 5.887 kWh/m^2. For the site of Bokoro, the Allen model is the most adapted for the calculation of global solar radiation which is 5.872 kWh/m^2. On the other hand, the Sabbagh model is appropriate for the sites of Abeche, N'Djamena, Ati and Moussoro with respective values of 6.354, 5.742, 5.523 and 6.126 kWh/m^2. The obtained results show that the Sahelian zone of Chad has a good solar potential and consequently suitable for the exploitation of solar energy systems.

Keywords: Global solar radiation, Meteorological parameters, Climatic zones, Chad

Background

Country of Central Africa, located at the heart of the African continent, Chad is a vast territory of 1,284,000 km^2 with a population estimated at 11,175,915 in habitants according to the Second General Census of the population and the Habitat (GCPH2) of 2009. It extends from 7th to the 24th degree from northern latitude and 14th to the 24th of east longitude. It is characterized by its insolation because of the absence of the maritime outlets. The nearest access to the sea (Douala in Cameroon) is at 1700 km of its borders. The climate of Chad is not uniform, since it passes from the Saharan type in the north to the Sudano-Guinean type in the south, between which we distinguishes the Sahelo-Saharan, Sahelian, Sudano-Sahelian and Sudanese types. These various types of tropical climates have a common characteristic with a single raining season between July and August. This raining season hardly exceeds 2 months around the 15th northern degree and can exceed 5 months in the extreme south of the country. The climate is characterized by high average temperatures and strong thermal amplitudes, a mode of wind with northeastern predominance, a low average relative humidity and a high evaporation (Mahamat 2011).

Solar energy is a renewable energy source with potential to mitigate some of the negative environmental problems. So, with decreasing costs and rapidly improving technology, it plays a crucial role in the energy system (Despotovic et al. 2015; Freitas et al. 2015). Knowledge about solar radiation for a given location is very important. Global solar radiation on a horizontal surface is most commonly used in the prediction, study and design of solar energy systems (Hussain et al. 1999). Solar radiation are also evaluated by satellite image processing (Antonanzas-Torres et al. 2013; Linares-Rodriguez et al. 2013) or with a pyranometer for onshore measurement in meteorological stations. On the basis of readily available meteorological data, it is very important to have methods for estimating solar radiation (Al-mostafa et al. 2014; Despotovic et al. 2015). The most commonly used data are relative humidity (Yang and Koike 2002; Adaramola 2012), precipitation (Wu et al. 2007; Liu and Scott 2001), air temperature

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(Yacef et al. 2014; Dos Santos et al. 2014), air pollution (Zhao et al. 2013) and nebulosity (Tasdemiroglu and Sever 1991; Badescu and Dumitrescu 2013). Angstrom was the first to propose the global solar radiation estimation model (Angstrom 1924), which is obtained by the linear relationship between the global radiation (H) and the daylight radiation (H_c) for a given site and the ratio of the average solar radiation duration (S) to the maximum duration (S_0). Prescott (1940) finds it is easier to calculate global radiation by altering the Angstrom relationship by replacing the clear sky radiation text with extraterrestrial radiation (H_0). That replacement will therefore lead to the Angstrom–Prescott model, which is the most commonly used correlation for estimating global solar radiation.

The quantification of the potential of solar energy depends on the numerous parameters including the meteorological and astronomical parameters. Therefore, a review of the models and measurement techniques is presented (Katiyar and Pandey 2013; Pandey and Katiyar 2013; Angstrom 1924). It was noted that the first correlation suggested by Angstrom relates solar radiation to the duration of the sun. This relation was made by Page (1961) estimating mean values of short-wave radiation on vertical. Many studies have been carried out around the world, for example, Romania (Tahâs et al. 2011), Malaysia (Khatib et al. 2012), Iran (Sabziparvar 2007), China (Li et al. 2014), Ghana (Quansah et al. 2014) and Burkina Faso (Coulibaly and Ouedraogo 2016). The global solar radiation (which is the direct sum of the radiations, having crossed the atmosphere, and diffuses, coming from all the directions of the terrestrial vault) is an essential parameter of sizing for various types of projects such as solar energy systems and irrigation. The knowledge of the total radiation can be acquired by three methods: the measurements (pyranometer for the measurement of the total and diffuse radiations; pyrheliometer for the measurement of direct radiation), the mathematical models containing weather data and the satellite images (Ayangma et al. 2008). The weather stations installed in Chad have no instruments to measure the solar radiation. The current study has been stimulated by this situation of which Chad is confronted. The aim of this study is to evaluate the solar potential energy in the three climatic zones of Chad by using three mathematical models based on the climatic characteristics of each zone. It focuses in a more specific way on global radiation on a horizontal level. In this study, one determines the most precise method to calculate the global solar radiation of six cities of Chad.

Description of the sites and data-gathering

The present solar data used were obtained from the National Meteorological General Administration of Chad, recorded in June 2014. They are monthly data of the relative humidity, maximum temperature, minimal temperature and sunshine duration. The geographical coordinates of the six stations of the National Meteorological General Administration (NMGA) are given in Table 1.

The data collected are not the same periods; this is justified by the non-implementation of the measuring devices at the same time, the lack of qualified personnel and the equipment failure.

Thus, this is explained by the fact that the installation of the devices in these different stations did not take place in the same year. Consequently, there is no influence on the results since the data collected in the field and considered in this study are actual data.

Presentation of the studied models

To calculate the global solar radiation, the ideal models are generally used. These models are in the form of empirical relations which connect the components of the solar radiation to the principal weather parameters, such as the ambient temperature, the relative humidity, the sunshine duration and the astronomical parameters such as 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 solar radiation.

Modeling of the extraterrestrial solar radiation

The monthly mean of the daily extraterrestrial solar radiation on a horizontal plan (Yettou et al. 2009; Klein 1977) is:

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

where δ and ω_s are the monthly mean of the daily solar declination and the sunset hour angle, respectively, defined by Khorasani Zadeh and Mohammadi (2013), Okonkwo and Nwokoye (2014), Iqbal (1983) and Zekai (2008).

Table 1 Geographical locations of the six sites considered

City	Latitude (°N)	Longitude (°E)	Elevation (m)	Period
Abeche	13.51	20.51	545	1950–2008
N'Djamena	12.8	15.2	294	1950–2013
Ati	13.13	18.19	334	1951–2004
Bokoro	12.23	17.3	300	1950–2007
Mongo	12.11	18.41	430	1993–2006
Moussoro	13.39	16.3	301	1987–2007

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

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

D_n is the current date as from January 1, I_{sc} is the solar constant (equal to 1367 W/m^2 during the year), and L is the latitude of the city in degrees.

Modeling of the global solar radiation on a horizontal level with the Angstrom–Prescott model

Angstrom has been the first to propose an ideal model (linear model) to estimate the horizontal global solar radiation with input data over the sunshine duration (Gana and Akpootu 2013; Musa et al. 2012). Prescott and Page (Ayangma et al. 2008; Augustine and Nnabuchi 2010; Fariba et al. 2013) have improved this model. They considered the global horizontal and the sunshine duration according to relation (4).

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

The parameters a, b and S_0 are, respectively, defined by Eqs. (5)–(7).

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

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

The possible maximum monthly mean of the daily sunshine duration is (Khorasani Zadeh and Mohammadi 2013 and Cooper 1969)

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

Global solar radiation on a horizontal level with the Allen's model

Allen (1997) and Hargreaves and Samani (1982) 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:

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

Following Lunde (1979), $K_{ra} = 0.17$ and P/P_0 may be defined as:

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

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

Estimation of 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 cities of Saudi Arabia, Sabbagh et al. developed two empirical relations binding the various weather parameters which affect the attenuation of the solar radiation, namely sunshine duration, 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 are given by the following relation (Kerkouche et al. 2013):

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

with

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

$$n = \frac{1}{(1 + 0.1L)}, \quad (13)$$

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 (Table 2).

Statistical test

In order to compare the monthly global satellite solar radiation data provided by NASA with those determined from the various models presented, we have developed for each of the studied models a program under

Table 2 Value of $\psi_{i,j}$ according to the number of the month (J) and the climate zone (I)

I	J	1	2	3	4	5	6	7	8	9	10	11	12
1		1.28	1.38	1.54	1.77	2.05	2.30	2.48	2.41	2.36	1.73	1.38	1.17
2		1.46	1.77	2.05	2.15	2.05	2.05	2.10	2.17	2.14	1.96	1.60	1.43
3		1.60	1.81	2.00	2.17	2.25	2.26	2.24	2.20	2.10	1.92	1.74	1.60

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 irradiation by NASA and those calculated, and on the other hand we drew up the relative error.

The presented models in the previous paragraph enabled us 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 (Kerkouche et al. 2013; Yettou et al. 2009; Argungu et al. 2013) further enabled us to confront the data obtained by the mathematical models to estimate the global solar radiation with the measured data. These indicators included: RMSE, MBE, MPE and NSE.

The RMSE indicator

The root-mean-square errors (RMSEs) are a measurement of the variation of the computed values, according to each model around the measured values. The model is the best when this RMSE value is the smallest. It is defined by the relation (Glover and McCulloch 1958):

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

n represents the number of the month.

The MBE indicator

The mean bias error (MBE) which is the error of average skew is calculated starting from the relation (Robaa 2008):

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

An indication gave the average deviation of the computed values compared to the measured values. A positive value indicates an over-estimation, and a negative value indicates an under-evaluation.

The MPE indicator

The mean percentage error (MPE) is defined by the relation (Robaa 2008):

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

For this indicator, an error expressed as a percentage ranging between −10 and +10% is acceptable for the model (Robaa 2008).

The NSE indicator

The Nash–Sutcliffe equation (NSE) represents a measure of the precision of the model results. A model is more efficient when NSE is closer to 1 (Chen et al. 2004). The NSE is defined by the relation:

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

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

Results and discussion

Tables 3, 4 and 5 present the total results obtained by the relations of Angstrom–Prescott, Allen and Sabbagh for the six cities of the Sahelian zone of Chad.

Angstrom-Prescott model

Table 3 presents the obtained values of the various parameters of Angstrom–Prescott for the six cities of the Sahelian zone of Chad. This table shows that the non-constant parameters a and b differ from one city to another.

Allen model

Table 4 shows the results of the global solar radiation obtained by the Allen model. In addition, the index of clarity, relative error, maximum temperature, minimum temperature and extraterrestrial radiation are presented in the same table. Therefore, for the six stations in the Sahelian zone, the lowest maximum temperature is observed at Moussoro (35.56 °C) and the highest at Abeche (37.45 °C). The lowest minimum temperature is observed in N'Djamena (22.02 °C), and the highest temperature is recorded in Mongo (26.15 °C). The lowest extraterrestrial radiation is observed at Abeche (8.722 kWh/m^2) and the highest at N'Djamena (8.936 kWh/m^2). The lowest clarity

Table 3 Angstrom–Prescott method for the six cities

Abeche	$\frac{H}{H_0} = 0.4476 + 0.2042\left(\frac{S}{S_0}\right)$	Mongo	$\frac{H}{H_0} = 0.4603 + 0.1766\left(\frac{S}{S_0}\right)$
Ati	$\frac{H}{H_0} = 0.4608 + 0.1758\left(\frac{S}{S_0}\right)$	Moussoro	$\frac{H}{H_0} = 0.4612 + 0.1749\left(\frac{S}{S_0}\right)$
N'Djamena	$\frac{H}{H_0} = 0.3660 + 0.3793\left(\frac{S}{S_0}\right)$	Bokoro	$\frac{H}{H_0} = 0.4602 + 0.1769\left(\frac{S}{S_0}\right)$

Table 4 Allen model for the six cities

Cities	TM	Tmin (°C)	H_0 (kWh/m^2)	H/H_0	H (kWh/m^2)	Err (%)
Abeche	37.42	22.28	8.722	0.66	5.747	−5.482
N'Djamena	36.38	22.02	8.936	0.64	5.724	0.078
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	8.930	0.543	4.849	−17.506
Moussoro	35.56	22.13	8.748	0.621	5.429	−7.523

Table 5 Sabbagh model for the six cities

Sites	S	S_0 (h)	RH (%)	T_{max} (°C)	S/S_0	H (kWh/m^2)	Err (%)
Abeche	11.62	11.39	36	37.42	1.02	6.354	3.704
N'Djamena	8.74	11.47	44.85	36.38	0.76	5.742	−0.348
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

index is recorded at Mongo (0.543) and the highest at Abeche (0.66). The lowest global solar radiation is observed in Mongo (4.849 kWh/m^2) and the highest is recorded in Bokoro (5.932 kWh/m^2). The relative error varies between 0.078 and −17.506%, which means that Allen model seems to be favorable for the N'Djamena and Bokoro sites compared to the six selected cities.

Sabbagh model

Table 5 presents the different values of Sabbagh parameters. Note in this table that the minimum sunshine duration is recorded at N'Djamena (8.74) and maximum at Moussoro (12.1). The minimum duration of day is obtained in Abeche (11.39) and maximum in N'Djamena and Mongo. The minimum relative humidity is recorded in Moussoro (33.18%) and maximum in N'Djamena (44.85%). The minimum temperature is recorded at Moussoro (35.56 °C) and maximum at Abeche (37.42 °C). The minimum insolation rate is recorded in N'Djamena (0.76) and maximum in Ati and Moussoro (1.06). The global solar radiation varies between 5.742 and 6.354 kWh/m^2. Moreover, the relative error varies between −0.348 and 5.032 kWh/m^2. Thus, based on the obtained value of the error, the Sabbagh model is appropriate for the cities of N'Djamena (−0.348%) and Ati (0.356%).

It should be noted that although the six cities are in the same area, the Sabbagh model is not appropriate for all these cities because this is due to different geographical coordinates and weather data.

Statistics for the validation of the selected models

Table 6 compares the three methods used for the six studied cities. The comparison between the three methods and the measured values shows that the

Table 6 Statistics for the validation of the selected models

Sites	MPE (%)	RMSE (kWh/m^2)	MBE (kWh/m^2)	NSE (kWh/m^2)
(a) Angstrom–Prescott				
Abeche	−7.8073	0.9141	−0.0781	−1.5902
N'Djamena	1.2655	0.6038	0.0127	0.2408
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				
Abeche	−5.4824	0.8835	−0.0548	−1.4197
N'Djamena	0.0784	0.8275	0.0008	−0.4261
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				
Abeche	3.7042	0.5418	0.0370	0.0899
N'Djamena	−0.3477	0.3842	−0.0035	0.6927
Ati	0.3564	0.2314	0.0036	0.8406
Bokoro	5.0317	0.3798	0.0503	0.5602
Mongo	4.8254	0.3722	0.0483	0.5432
Moussoro	3.4003	0.3879	0.0340	0.5697

Angstrom-Prescott model gives the best estimation of the global solar radiation for the cities of Mongo. The method of Allen model is appropriate for Bokoro. For the sites of Abeche, N'Djamena, Moussoro and Ati, it is the Sabbagh model which is adapted to evaluate the global solar radiation.

Global solar radiation of the six sites

Figures 1, 2, 3, 4, 5 and 6 present the results of the radiation of six cities obtained by the three methods based on climatological and measured data. Indeed, the representation in the form of a table is relevant when we use several models that have common characteristics. Also, the interest is to make a good dimensioning, to be able to compare and to quickly find information while growing the line and the column.

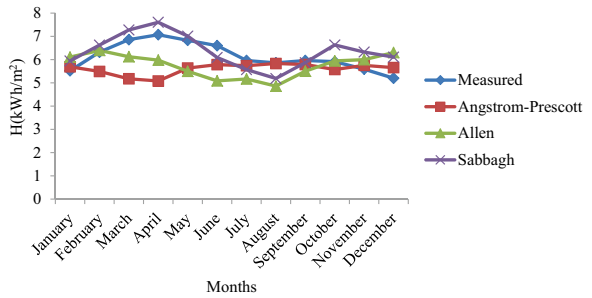

Fig. 1 Global solar radiation of Abeche

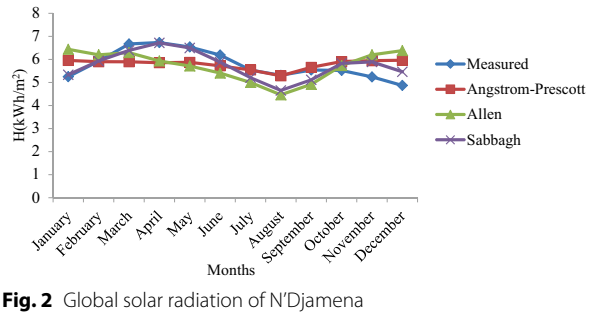

Fig. 2 Global solar radiation of N'Djamena

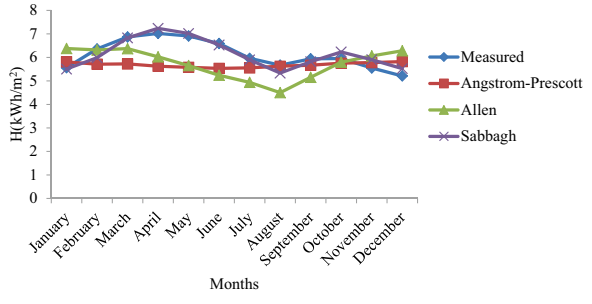

Fig. 3 Global solar radiation of Ati

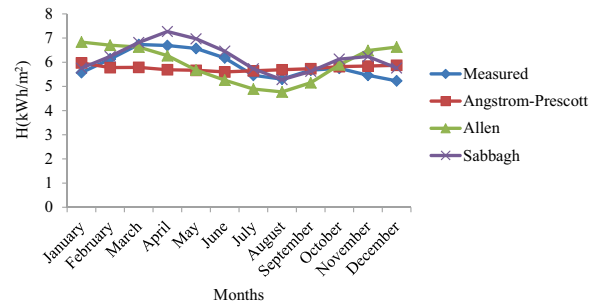

Fig. 4 Global solar radiation of Bokoro

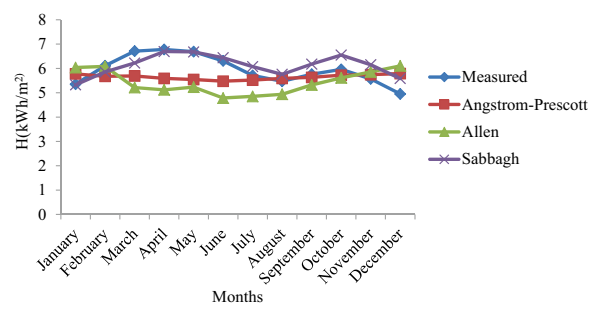

Fig. 5 Global solar radiation of Moussoro

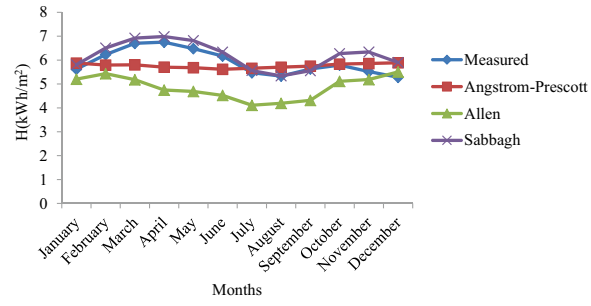

Fig. 6 Global solar radiation of Mongo

Clearness index and daily ratio of sunshine duration

Figure 7 presents the monthly changes in clearness index for each site according to the appropriate method for estimating global solar radiation. Therefore, for the six sites in the Sahelian zone of Chad, the highest clearness index of 0.8732 is recorded in Abeche in April and the lowest one of 0.5198 in N'Djamena in August. Figure 8 presents the monthly variations in the S/S_0 insolation rate of the six cities in the Sahelian zone. Thus, the maximum value in the S/S_0 insolation

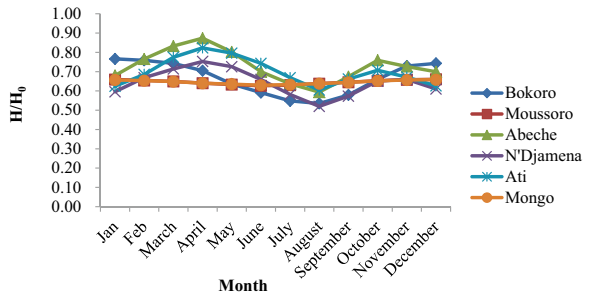

Fig. 7 Clearness index for the six synoptic stations

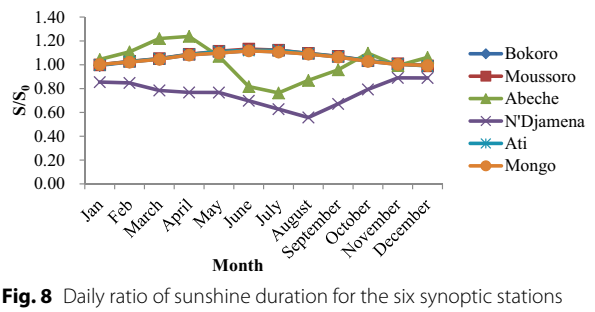

Fig. 8 Daily ratio of sunshine duration for the six synoptic stations

rate is recorded at Abeche in April (1.2384) and the minimum value is obtained at N'Djamena in August (0.5578).

Extraterrestrial solar radiation

Table 7 presents the different values of extraterrestrial solar radiation for the six cities in the Sahelian zone of Chad. This table shows that the minimum value of 8.654 kWh/m^2 of extraterrestrial radiation is observed in Abeche in February. The maximum value of 8.952 kWh/m^2 is recorded in N'Djamena in January, March, May, July, August, October and December.

Table 8 presents the monthly and average values of the error of the extraterrestrial radiation of the six cities in the Sahelian zone of Chad. Note in this table that the annual average of the error varies between −7.807 and −9.691%.

Conclusion

Chad has an electrical deficit to cover the needs of the population and continues to rely on diesel-fired power stations for the majority of the country's electricity generation. In view of the lack of available devices for the measurement of global solar radiation, the aim of this work is to find the appropriate model for estimating solar radiation in the Sahelian zone of Chad. Thus, three methods have been used, in particular the Angstrom-Prescott model, Allen and Sabbagh. The results obtained show that the Angstrom–Prescott model is appropriate for the city of Mongo whose error is −1.8291%. Allen model seems favorable for the city of Bokoro (1.1811%). As for the Sabbagh model, it is appropriate for the Abeche, N'Djamena, Ati and Moussoro cities with respective errors of 3.7042, −0.3477, 0.3564 and 3.4003%.

The average global maximum solar radiation is recorded at Abeche (6.354 kWh/m^2), while the lowest average at Ati (5.523 kWh/m^2).

The average of the maximum extraterrestrial solar radiation is recorded in N'Djamena (8.936 kWh/m^2) and minimal in Abeche (8.723 kWh/m^2).

In view of all these results, it can be said that, on a given site, the direct use of a model proposed in the literature can lead to incorrect values which can considerably influence the dimensioning of solar systems and hence over sizing or the under-dimensioning of the system under consideration. The choice of the model depends strongly on the climate characteristics of the

Table 7 Extraterrestrial solar radiation H_0

H_0 (kWh/m^2)	Abeche	N'Djamena	Ati	Bokoro	Mongo	Moussoro
January	8.739	8.952	8.819	8.921	8.946	8.764
February	8.654	8.872	8.735	8.841	8.866	8.680
March	8.739	8.952	8.819	8.921	8.946	8.764
April	8.711	8.925	8.790	8.894	8.919	8.736
May	8.739	8.952	8.819	8.921	8.946	8.764
June	8.711	8.925	8.790	8.894	8.919	8.736
July	8.739	8.952	8.819	8.921	8.946	8.764
August	8.739	8.952	8.819	8.921	8.946	8.764
September	8.711	8.925	8.790	8.894	8.919	8.736
October	8.739	8.952	8.819	8.921	8.946	8.764
November	8.711	8.925	8.790	8.894	8.919	8.736
December	8.739	8.952	8.819	8.921	8.946	8.764

Table 8 Error (%) between the measured and estimated values of extraterrestrial solar radiation (H_0) of the six cities

Month	Abeche	N'Djamena	Ati	Bokoro	Mongo	Moussoro
January	3.543	4.214	4.491	3.853	4.144	3.839
February	−6.746	−5.517	−5.873	−5.847	−5.58	−6.466
March	−13.475	−11.366	−12.683	−11.673	−11.426	−13.228
April	−17.038	−15	−16.286	−15.295	−15.057	−16.8
May	−17.557	−14.743	−16.802	−15.038	−13.981	−17.321
June	−17.038	−14.183	−16.286	−14.481	−14.24	−16.8
July	−16.771	−13.923	−16.01	−14.221	−13.981	−16.533
August	−16.771	−13.923	−16.01	−14.221	−13.981	−16.533
September	−14.598	−12.5	−13.824	−12.804	−12.559	−14.353
October	−8.011	−6.555	−7.168	−6.879	−6.618	−7.747
November	0.939	1.884	1.854	1.53	1.815	1.228
December	7.227	7.855	8.209	7.482	7.783	7.534
Average	−9.691	−7.813	−8.866	−8.133	−7.807	−9.432

site considered in relation to those on which it is envisaged to be applied.

From the point of view of application, although these models were confronted on sites belonging to the Sahelian zone, we consider that the three models have given satisfactory satisfaction.

Due to the data currently available, the study was carried out only for the six cities in the Sahelian zone of Chad. In perspective, it is envisaged to extend the work on other zones of Chad.

List of symbols

$H_{i,c}$, $H_{i,m}$	calculated and measured values of H (kWh/m^2)
NASA	National Aeronautic and Space Administration
a, b	non-constant coefficients
H_0	monthly average daily extraterrestrial radiation on horizontal surface (kWh/m^2)
S_0	monthly average maximum possible daily sunshine duration (h)
S	monthly average daily bright sunshine duration (h)
h	height (km)
D_n	current date as from January 1
I_{sc}	solar constant (equal to 1367 W/m^2)
L	latitude of the location (°)
S/S_0	the sunshine duration
H/H_0	clearness index
H	monthly mean daily global radiation on horizontal surface (kWh/m^2)
n	number of the month considered
ψ_{ij}	climatic factor
K	factor dependent on latitude and the altitude of the site
T_M	monthly mean maximum temperature (°C)
T_m	monthly mean minimum temperature (°C)
K_r, K_{ra}	empirical coefficients
SGPH	second general census of the population and the habitat
RMSE	root-mean-square error
MBE	mean bias error
MPE	mean percentage error
NSE	Nash–Sutcliffe equation

Greek letters

δ	solar declination (deg)
ω_s	sunset hour angle (deg)

Authors' contributions

The major part of the works was done by corresponding author; however, co-authors also contributed significantly. The first co-author OC contributed to outlining the paper, methodology and associated theories and related description. The second co-author SYD helped also with data some analysis. The third co-author TCK contributed to format of the paper and its alignment with themes of the journal and revisions of the manuscript. Corresponding author is grateful to co-authors for their fruitful contribution in this work. All authors read and approved the final manuscript.

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References

Adaramola, M. S. (2012). Estimating global solar radiation using common meteorological data in Akure, Nigeria. *Renewable Energy, 47,* 38–44.

Allen, R. G. A. (1997). Self calibrating method for estimating solar radiation from air temperature. *Journal of Hydrologic Engineering, 2,* 56–57.

Al-mostafa, Z. A., Maghrabi, A. H., & Al-shehri, S. M. (2014). Sunshine-based global radiation models: A review and case study. *Energy Conversion and Management, 84,* 209–216.

Angstrom, A. (1924). Solar and terrestrial radiation. Report to the international commission for solar and atmospheric radiation. *Quarterly Journal of the Royal Meteorological Society, 50,* 121–126.

Antonanzas-Torres, F., Cañizares, F., & Perpiñán, O. (2013). Comparative assessment of global irradiation from a satellite estimate model (CM SAF) and on-ground measurements (SIAR): A Spanish case study. *Renewable and Sustainable Energy Reviews, 21,* 248–261.

Argungu, G. M., Bala, E. J., Momoh, M., Musa, M., Dabai, K. A., & Zangina, U. (2013). Statistical analysis of wind energy Resource potentials for power generation In Jos, Nigeria, Based on Weibull distribution function. *The International Journal of Engineering and Science, 2,* 22–31.

Augustine, C., & Nnabuchi, M. N. (2010). Analysis of some meteorological data for some selected cities in the eastern and southern zone of Nigeria. *African Journal of Environmental Science and Technology, 4,* 092–099.

Ayangma, F., Nkeng, G. E., Bonoma, D. B., & Nganhou, J. (2008). Evaluation du potentiel en énergie solaire au cameroun: cas du nord cameroun. *African Journal of science and technology, 9,* 32–40.

Badescu, V., & Dumitrescu, A. (2013). New models to compute solar global hourly irradiation from point cloudiness. *Energy Conversion and Management, 67,* 75–91.

Chen, R., Ersi, K., Yang, J., Lu, S., & Zhao, W. (2004). Validation of five global radiation models with measured daily data in China. *Energy Conversion and Management*, *45*, 1759–1769.

Cooper, P. I. (1969). The absorption of radiation in solar stills. *Solar Energy, 12,* 333–346.

Coulibaly, O., & Ouedraogo, A. (2016). Correlation of global solar radiation of eight synoptic stations in Burkina Faso based on linear and multiple linear regression methods. *Journal of Solar Energy*, Article ID 7870907.

Despotovic, M., Nedic, V., Despotovic, D., & Cvetanovic, S. (2015). Review and statistical analysis of different global solar radiation sunshine models. *Renewable and Sustainable Energy Reviews, 52,* 1869–1880.

Dos Santos, C. M., De Souza, J. L., Ferreira, J. R. A., Tiba, C., de Melo, R. O., & Lyra, G. B. (2014). On modeling global solar irradiation using air temperature for Alagoas State, North eastern Brazil. *Energy, 71,* 388–398.

Fariba, B., Dehghan, A. A., & Faghih, A. R. (2013). Empirical models for estimating global solar radiation: A review and case study. *Renewable and Sustainable Energy Reviews, 21,* 798–821.

Freitas, S., Catita, C., Redweik, P., & Brito, M. (2015). Modelling solar potential in the urban environment: State-of-the-art review. *Renewable and Sustainable Energy Reviews, 41,* 915–931.

Gana, N. N., & Akpootu, D. O. (2013). Angstrom type empirical correlation for estimating global solar radiation in north-eastern Nigeria. *The International Journal of Engineering and Science, 2,* 58–78.

Hargreaves, G. H., & Samani, Z. A. (1982). Estimating potential evapotranspiration. *Journal of Irrigation and Drainage Engineering, 108*(IR3), 223–230.

Hussain, M., Rahman, L., & Mohibur Rahman, M. (1999). Techniques to obtain improved predictions of global radiation from sunshine duration. *Renew Energy, 18,* 263–275.

Iqbal, M. (1983). *An introduction to solar radiation*. New York, NY: Academic Press.

Katiyar, A. K., & Pandey, C. K. (2013). A review of solar radiation models-part I. *Hindawi Publishing Corporation Journal of Renewable Energy*, Vol. 2013, Article ID 16804811.

Kerkouche, K., Cherfa, F., Hadj, A., Arab Bouchakour, S., Abdeladim, K., & Bergheul, K. (2013). Evaluation de l'irradiation solaire globale sur une surface inclinée selon différents modèles pour le site de Bouzaréah. *Revue des Energies renouvelables, 16,* 2269–2284.

Khatib, T., Mohamed, A., Sopian, K. & Mahmoud, M. (2012). Solar energy prediction for Malaysia using artificial neural networks. *International Journal of Photoenergy*, Article ID 419504.

Khorasani Zadeh, H., & Mohammadi, K. (2013). Introducing the best model for predicting the monthly mean global solar radiation over six major cities of Iran. *Energy, 51*, 257–266.

Klein, S. A. (1977). Calculation of monthly average insolation on titled surfaces. *Solar Energy, 19,* 325–329.

Li, H., Cao, F., Wang, X., & Ma, W. (2014). A temperature-based model for estimating monthly average daily global solar radiation in china. *The Scientific World Journal*, *2014*, 9.

Linares-Rodriguez, A., Ruiz-Arias, J. A., Pozo-Vazquez, D., & Tovar-Pescador, J. (2013). An artificial neural network ensemble model for estimating global solar radiation from Meteosat satellite images. *Energy, 61,* 636–645.

Liu, D. L., & Scott, B. J. (2001). Estimation of solar radiation in Australia from rainfall and temperature observations. *Agricultural and Forest Meteorology, 106*(1), 41–59.

Lunde, P. J. (1979). *Solar thermal engineering: Space heating and hot water systems*. New York, NY: Wiley.

Mahamat Djimadingar Présentation du Tchad. (2011). Atelier sur les statistiques de l'environnement, Ministere de l'environnement et des Ressources Halieutiques.

Musa, B., Zangina, U., & Aminu, M. (2012). Estimation of global solar radiation in Maiduguri, Nigeria using Angstrom model. *ARPN Journal of Engineering and Applied Sciences, 7*(12), 1623–1627.

Glover, J., & McCulloch, J. S. (1958). The empirical relation between solar radiation and hours of sunshine. *Journal of Royal Meteorological Society*, *84*, 172–175.

Okonkwo, G. N., & Nwokoye, A. O. C. (2014). Relationship between global solar radiation and sunshine hour duration for Bida in Nigeria. *International Journal of Renewable and Sustainable Energy, 3*(2), 43–46.

Page, J. K. (1961). The estimation of monthly mean values of daily total short wave radiation on vertical and inclined surfaces from sunshine records for latitudes 400N–400S. In *Proceedings of the United Nations conference on new sources of energy* (Vol. 98, pp. 378–390).

Pandey, C. K., & Katiyar, A. K. (2013). Solar radiation: Models and measurement techniques. *Journal of Energy*, Article ID 305207.

Prescott, J. (1940). Evaporation from a water surface in relation to solar radiation. *Transactions of the Royal Society of South Australia, 64,* 114–118.

Quansah, E., Amekudzi, L. K., Preko, K., Aryee, J., Boakye, O. R., Boli, D., et al. (2014). Empirical models for estimating global solar radiation over the Ashanti region of Ghana. *Journal of Solar Energy*, Article ID 897970.

Robaa, S. M. (2008). Evaluation of sunshine duration from cloud data in Egypt. *Energy*, *33*, 785–795.

Sabziparvar, A. A. (2007). General formula for estimation of monthly mean global solar radiation in different climates on the south and north coasts of Iran. *International Journal of Photo Energy*, Article ID 94786.

Tahâş, S. V., Ristoiu, D., & Cosma, C. (2011). Trends of the global solar radiation and air temperature in Cluj-Napoca, Romania (1984–2008). *Romanian Journal of Physics, 56,* 784–789.

Taşdemiroğlu, E., & Sever, R. (1991). An improved correlation for estimating solar radiation from bright sunshine data for Turkey. *Energy Conversion and Management, 31*(6), 599–600.

Wu, G., Liu, Y., & Wang, T. (2007). Methods and strategy for modeling daily global solar radiation with measured meteorological data—A case study in Nanchang station, China. *Energy Conversation Management, 48*(9), 2447–2452.

Yacef, R., Mellit, A., Belaid, S., & Sen, Z. (2014). New combined models for estimating daily global solar radiation from measured air temperature in semi-arid climates: Application in Ghardaïa, Algeria. *Energy Conversion and Management, 79,* 606–615.
Yang, K., & Koike, T. (2002). Estimating surface solar radiation from upper-air humidity. *Solar Energy, 72*(2), 177–186.
Yettou, F., Malek, A., Haddadi, M., & Gama, A. (2009). Etude comparative de deux modèles de calcul du rayonnement solaire par ciel clair en Algérie. *Revue des Energies Renouvelables, 12,* 331–346.
Zekai, S. (2008). *Solar energy fundamentals and modeling techniques: Atmosphere, environment, climate change and renewable energy*. Berlin: Springer.
Zhao, N., Zeng, X., & Han, S. (2013). Solar radiation estimation using sunshine hour and air pollution index in China. *Energy Conversion and Management, 76,* 846–851.

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