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Empirical Relationships Between Global and Diffuse Radiation and Sunshine Duration in Chad: Polynomial Regression Approach

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ABSTRACT

Chad, in regards to its geographical position is considered as one of the countries in the world that receives an important annual solar radiation over its entire territory. The average sunshine duration is about 10 hours in the North, 8 hours in the Center and 7 hours in the South. This can be used to quantify the solar radiation over the whole territory and evaluate the solar potential. In this paper, some new correlations between sunshine duration and solar radiation have proposed in four cities (Abeche, Bitkine, Mongo and Ndjamena) located in the Sahelian climate in order to have tools for quantifying all components of solar radiation. The polynomial regression model approach is used and their parameters are estimated by the ordinary least squares method. A statistical evaluation was carried out to compare the different correlations obtained. The results show that the third order polynomial approach is the most appropriate for an empirical relationship between global, diffuse and relative sunshine duration in each of the cities. Considering the long dry seasons characterized by high temperatures in this region, the consideration of the temperature variable in the functional form could improve the quality and accuracy of the models in their estimation.

1. INTRODUCTION

The sun, a very prospective energy source that is available and unlimited on the earth's surface, is being used in the last years to satisfy the energy needs in the sunny areas of the planet earth. In a context where global warming is threatening life on earth and the need for energy is increasing with the growth of the world's population, the use of renewable energy sources is very necessary at the detriment of fossil energy sources. Chad, located south of the Sahara, is one of the countries that receive a significant amount of sunshine from north to south [1-3]. Its electricity coverage rate is very low and it has thermal power plants powered by fossil energy sources. Its high solar potential can be used by all types of solar technologies [4], is so far unexploited. This has motivated research in order to propose solutions to overcome these problems [5]. Several methods of quantifying solar radiation have been developed in the literature with the aim of providing reliable, adequate and more suitable tools for different situations encountered such as the types of data available, the expected results. The Angstrom-Prescott relationship is the very first one that calculates the solar radiation from the sunshine duration [6]. This correlation requires the determination of two unknown parameters. Subsequently, several methods have been developed from this model [7], taking into account some climatological parameters influencing the solar radiation on the ground in the study zone [8, 9], thus increasing the number of model parameters to be determined. Thus, throughout the world many models are proposed, in Cameroon for the estimation of global radiation on a horizontal surface on the ground in its large climatic regions [10]; in Ghana for the estimation of global solar radiation in the Ashanti region [11]; in Burkina Faso for eight synoptic stations, simple and multiple linear regression models are developed [12]; a review of the literature has been carried out on empirical models of global radiation by Katiyar and Pandev [13]. Some authors have considered other estimation approaches using temperature and pressure as input variables to calculate global solar radiation at the ground [14, 15]. These latter have been studied in comparison with Angstrom-Prescott type models in some cities in Chad [16]. The diffuse component of solar radiation can be calculated using the same empirical relationship. It can be expressed as a function of the clearness index and the global radiation, or as a function of the relative sunshine duration and the extra-atmospheric radiation. These relationships always require the determination of the coefficients of the chosen model. This gives a variety of correlations [17]. Thus, in the literature, many correlations have been established and proposed to estimate the diffuse radiation on the ground taking into account the specificities of the climatic zones [18]. Some statistical approaches are also used to predict solar radiation [19]. In the case of Chad, models for predicting global radiation on the ground have been proposed by Soulouknga et al. [16], after a comparative study in several cities (Abeche, N'Djamena, Ati, Mongo, Bokoro, Moussoro). The results show in general that the models which are function of the temperature variable estimate the global radiation better than that function of the relative insolation duration for simple linear regression models. The applicability of these models is more complex because it requires the knowledge of several input parameters (minimum and maximum temperatures, pressure, sunshine duration, altitude, relative humidity). The Capderou model has also been proposed to modeling and estimating the solar radiation components on different surfaces in Ndjamena [20]. However, this model shows that the value of the radiation does not change from one year to another since it only needs the geographical coordinates of the location to make an estimate as input parameters. In this work, new correlations based on the polynomial regression model of different orders to predict the global and diffuse solar radiation on the ground over a horizontal surface in the cities of Abeche, Bitkine, Mongo and N'Djamena are proposed. These models are useful in that only the knowledge of the sunshine duration values allows their use. These new correlations will be submitted to a comparative study in order to appreciate the quality in the assessments of the diffuse and global radiations through a certain number of statistical criteria. This work, contrary to the work carried out in these cities in the literature, proposes new models to evaluate not only the global radiation but also the diffuse radiation and that from both the direct component can be deduced. Thus, it becomes simple to estimate the solar potential in these cities on horizontal surfaces. It will allow to project on the design of a hybrid solar-wind-battery system to produce electricity in order to improve their electricity coverage rates.

2. STUDY ZONE AND DATA

Chad is subdivided into three major climatic zones, specifically the Saharan climate in the north, the Sahelian climate in the center, and the Sudanian climate in the south (Figure 1). The four cities selected for this study are located in the Sahelian climate zone in the center of the country and their geographic coordinates are indicated in Table 1. Figure 1 provides a general overview.

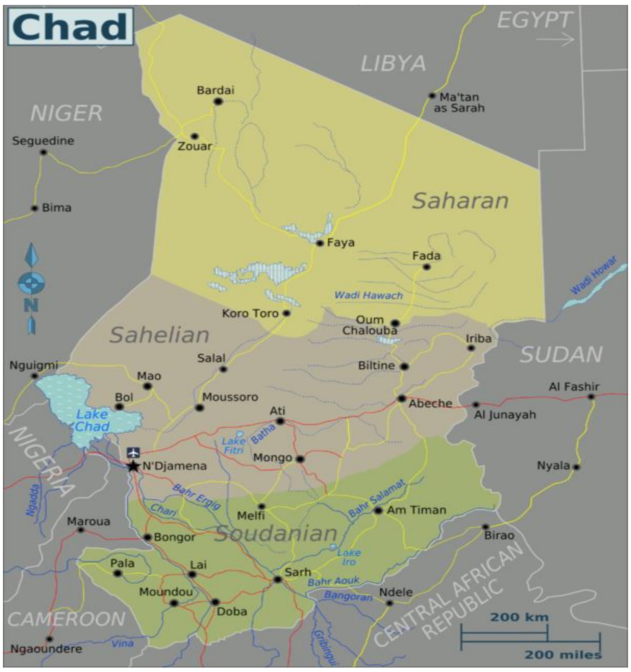

Figure 1. Division of Chad into three types of climate zones [3]

Table 1. Geographic coordinates of the study areas

Coordinates	Abeche	Bitkine	Mongo	N'Djamena
Latitude (°)	13.85	11.98	12.18	12.11
Longitude (°)	20.85	18.21	12.18	15.05
Altitude (m)	545	467	427	298

The data of the different components of solar radiation used are provided by the CAMS database in the absence of data measured by the meteorological and radiometric stations of the selected localities. They were considered for a period of ten years (2010-2020) and for a temporal resolution of one hour. Then, daily and monthly averages are calculated. The sunshine duration data used are issued from the climatological tables of each city for a temporal resolution of one month. The data are considered for different periods according to the cities and the years with missing data are not considered to avoid bias in the calculations. Thus, we considered 14 years in Abeche (1971-2002), 21 years in Bitkine (1974-2002), 10 years in Mongo (1991-2002) and 10 years in Ndjamena (1995-2004).

3. METHODOLOGY

The models for estimating solar radiation on the ground from the sunshine duration are based on the empirical Angstrom-Prescott relationship where the parameters are estimated. In this paper, this empirical relation is used while extending up to order three like some authors in the literature, i.e. a 1st, 2nd and 3rd order polynomial regression model. The coefficients of these models are then estimated by the ordinary least squares method. Only models with a good adjustment coefficient are taken into account and presented. These estimated parameters take into account the climate variability specific to each city considered. Thus for each city, several new correlations are developed. The precision of each of the models is measured from the statistical indicators used to compare the difference between the estimated values of each of the correlations and the data from the CAMS database taken as the reference data in the absence of the measured data by radiometric stations. Finally, these new correlations are also compared with those selected in the literature to assess their efficiency.

3.1 Models and calculation of quantities

The multiplicity of estimation models leads to a selection of the most appropriate according to the climatic context and use. The models selected below have been developed and used in climates similar to those considered in this paper. They are shown in Table 2. The knowledge of the theoretical day length and of the non-atmospheric solar irradiation is essential. They are calculated respectively from the relations (2) and (3) given by:

$$N = \frac{2}{15}\cos^{-1}\left(-\tan\varphi\tan\delta\right) \tag{1}$$

$$H_o = \frac{24}{\pi} I_o \left(1 + 0.033\cos\left(\frac{360}{365}j\right)\right)\left(\cos\varphi\cos\delta\sin\omega_s + \left(\omega_s\frac{2\pi}{360}\right)\sin\varphi\sin\delta\right) \tag{2}$$

With:

$$\delta = 23.45°\sin\left(\frac{360}{365}(284 + j)\right) \tag{3}$$

Table 2. Models selected from the literature

	Global radiation [13]	Diffuse radiation [18]
1	$\frac{H}{H_0}=0.30+0.40\frac{s}{N}$	$\frac{H_d}{H}=0.958-0.982\frac{H}{H_0}$
2	$\frac{H}{H_0}=0.18+0.62\frac{s}{N}$	$\frac{H_d}{H}=0.99-1.43\frac{H}{H_0}+0.57\left(\frac{H}{H_0}\right)^2$
3	$\frac{H}{H_0}=0.10+0.87\frac{s}{N}-0.23\left(\frac{s}{N}\right)^2$	$\frac{H_d}{H}=1.39-4.03\frac{H}{H_0}+5.53\left(\frac{H}{H_0}\right)^2-3.11\left(\frac{H}{H_0}\right)^3$
4	$\frac{H}{H_0}=0.16+0.87\frac{s}{N}-0.61\left(\frac{s}{N}\right)^2+0.34\left(\frac{s}{N}\right)^3$	$\frac{H_d}{H_0}=0.2593-0.0978\frac{s}{N}$
5	$\frac{H}{H_0}=0.13+0.65\frac{s}{N}$	$\frac{H_d}{H_0}=0.22-0.01\frac{s}{N}-0.13\left(\frac{s}{N}\right)^2$
6		$\frac{H_d}{H_0}=0.24-0.09\frac{s}{N}+0.18\left(\frac{s}{N}\right)^2-0.22\left(\frac{s}{N}\right)^3$

δ is the solar declination and j the Klein day number [20]. The latitude of the place is defined by φ. The hour angle ω_S at sunset is calculated from the relation [21]:

$$\omega_S=\cos^{-1}\left(-\tan\varphi\tan\delta\right) \quad (4)$$

I_o is the solar constant expressed in W/m^2 and H_o in Wh/m^2.j.

H, H_d, H_0, n and N are respectively the monthly averages of global, diffuse, daily extra-atmospheric radiation, the sunshine duration and theoretical daily duration of the day, considering the number of days recommended by Klein [22]. The general form of the Angstrom-Prescott relationship is:

$$\frac{H}{H_0}=\alpha+\beta\frac{s}{N} \quad (5)$$

And can still be written:

$$\frac{H}{H_0}=f\left(\frac{s}{N}\right) \quad (6)$$

3.2 Statistical indicators

Different statistical methods allow us to choose between several models by calculating their errors, their degrees of precision and their significance at a defined threshold. These methods constitute criteria for choosing and selecting models. Five (6) of these methods are used, namely, the sum of the square of the relative error (SSRE), the mean bias error (MBE), the mean percentage error (MPE), the root mean square error (RMSE), the t-statistic (t-stat) and the correlation coefficient (r). Of all these methods, the more the values tend to zero, the better the model, except in the case of the last method.

3.2.1 The sum of the square of relative errors (SSRE)

This statistical method calculates the sum of the square of the successive differences between the estimated values and those measured throughout the year. It is given by the equation:

$$SSRE=\sum_1^n\left(\frac{H-H_m}{H_m}\right)^2 \quad (7)$$

where, n is the number of observations H_m is the measured value and H is the value estimated by the model.

3.2.2 Mean bias error (MBE)

A statistical method very used to provide long-term information on the performance of models comparing the actual difference between successive differences of estimated values and those measured. The relation allowing its calculation is [23]:

$$MBE=\frac{1}{n}\sum_1^n\left(H-H_m\right) \quad (8)$$

3.2.3 Mean percentage error (MPE)

As the name suggests, it calculates the relative average error as a percentage (%). It is given by:

$$MPE=\frac{1}{n}\sum_1^n\left(\frac{H-H_m}{H_m}100\right) \quad (9)$$

3.2.4 The root mean square error (RMSE)

Unlike the MBE statistical method, it provides short-term information on the performance of models comparing the actual difference between successive differences of estimated values and those measured. The relation is given by:

$$RMSE=\sqrt{\frac{1}{n}\sum_1^n\left(H-H_m\right)^2} \quad (10)$$

3.2.5 The correlation coefficient (r)

The correlation coefficient is a measure of the intensity and direction of the linear relationship between two values estimated by a model and the measured values. It is defined as a value between -1 and 1. It is computed via relation [24]:

$$r=\frac{\sum_1^n\left[\left(H-\overline{H}\right)\left(H_m-\overline{H_m}\right)\right]}{\sqrt{\left[\sum_1^n\left(H-\overline{H}\right)^2\right]\left[\sum_1^n\left(H_m-\overline{H_m}\right)^2\right]}} \quad (11)$$

3.2.6 The t-statistic(t-stat)

Some researchers have used the MBE and RMSE indicators the most to evaluate the performance of a model. Stone used the MBE and RMSE indicators to propose for evaluating the significance of a model's estimation. This significance is calculated at a precise confidence level [25]. The calculated t-stat value is compared to the t-critical value obtained from the statistical law table. The estimate is said to be statistically significant when the t-stat is less than the t-critical.

$$t-stat=\left[\frac{(n-1)MBE^2}{RMSE^2-MBE^2}\right]^{1/2} \tag{12}$$

4. RESULTS ET DISCUSSIONS

The cities chosen in this work are located in the same large Sahelian climate zone in the center of the country. They receive a different amount of solar radiation on the ground and variable daily sunshine duration, which can be observed in Figure 2 and Figure 3. The global radiation is very important in Abeche and its variations can be explained by those of the relative sunshine duration according to the seasons during a year (Figure 3). The global radiation in Ndjamena is the most insignificant, with a significant part of the diffuse component. It can be observed that during the winter, in relation to the theoretical duration of the day, the insolation duration is high in comparison to other seasons and very minimal in summer. This explains well the monthly and seasonal fluctuations of the global and diffuse components (Figure 2). These cities show individual climatic heterogeneities despite belonging to the same climatic zone. It is therefore necessary to find city-specific tools to better quantify solar resources. The significance test of model estimation is carried out at a well-defined confidence level of $\alpha=0.01$, which gives $t-critic=3.106$ the read in the Statistical Law table.

4.1 Correlations for the estimation of global solar radiation on the ground

The determination of the coefficients of the 1st, 2nd and 3rd order polynomial regression models resulted in new correlations between the clearness index and relative insolation for each city. These new correlations presented in Table 3 are used to estimate the global solar radiation on the ground and the results are illustrated in Figure 4. In comparison with the models chosen from the literature against the CAMS data, on average all the new correlations show good results. All statistical results for each city are provided in Table 4.

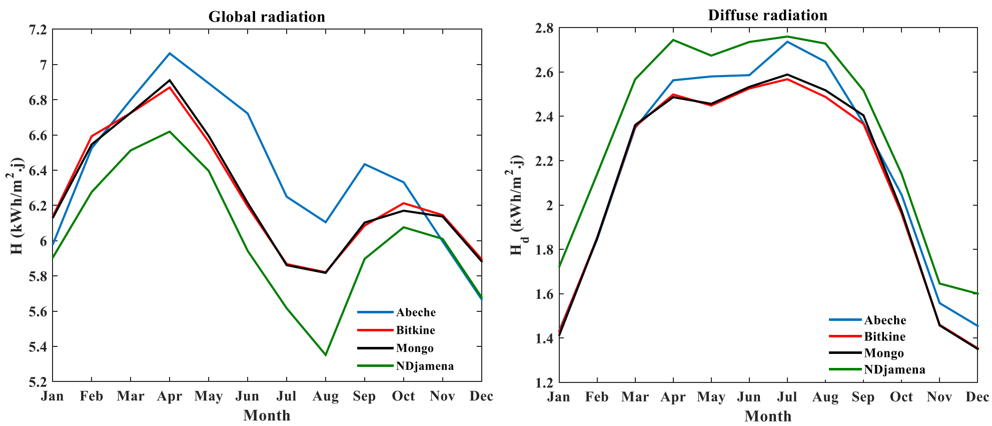

Figure 2. Monthly variation of diffuse and global radiation in cities

Table 3. The new correlations

City	Abeche	Bitkine	Mongo	Ndjamena
Model	Global solar radiation			
6	$\frac{H}{H_0}=0.24+0.53\frac{s}{N}$	$\frac{H}{H_0}=0.27+0.55\frac{s}{N}$	$\frac{H}{H_0}=0.35+0.40\frac{s}{N}$	$\frac{H}{H_0}=0.18+0.58\frac{s}{N}$
7	$\frac{H}{H_0}=0.29+0.40\frac{s}{N}+0.08\left(\frac{s}{N}\right)^2$	$\frac{H}{H_0}=0.49-0.15\frac{s}{N}+0.56\left(\frac{s}{N}\right)^2$	$\frac{H}{H_0}=0.39+0.26\frac{s}{N}+0.10\left(\frac{s}{N}\right)^2$	$\frac{H}{H_0}=0.51-0.36\frac{s}{N}+0.67\left(\frac{s}{N}\right)^2$
8	$\frac{H}{H_0}=1.6-5.01\frac{s}{N}+7.48\left(\frac{s}{N}\right)^2-3.35\left(\frac{s}{N}\right)^3$	$\frac{H}{H_0}=1.66-5.81\frac{s}{N}+9.58\left(\frac{s}{N}\right)^2-4.73\left(\frac{s}{N}\right)^3$	$\frac{H}{H_0}=0.99-2.55\frac{s}{N}+4.41\left(\frac{s}{N}\right)^2-2.14\left(\frac{s}{N}\right)^3$	$\frac{H}{H_0}=-1.85+9.91\frac{s}{N}-14.02\left(\frac{s}{N}\right)^2+6.92\left(\frac{s}{N}\right)^3$
Model	Diffuse solar radiation			
7	$\frac{H_d}{H}=1.3-1.5\frac{H}{H_0}$	$\frac{H_d}{H}=1.16-1.29\frac{H}{H_0}$	$\frac{H_d}{H_0}=0.242-0.09\frac{s}{N}+0.18\left(\frac{s}{N}\right)^2-0.218\left(\frac{s}{N}\right)^3$	$\frac{H_d}{H}=0.932-0.738\frac{s}{N}$
8	$\frac{H_d}{H}=-2.3+9.7\frac{H}{H_0}-8.6\left(\frac{H}{H_0}\right)^2$	$\frac{H_d}{H}=-1.09+5.91\frac{H}{H_0}-5.70\left(\frac{H}{H_0}\right)^2$	$\frac{H_d}{H}=1.18-1.32\frac{H}{H_0}$	$\frac{H_d}{H}=-0.27+2.76\frac{s}{N}-2.48\left(\frac{s}{N}\right)^2$
9	$\frac{H_d}{H_0}=0.46-0.31\frac{s}{N}$	$\frac{H_d}{H_0}=0.37-0.25\frac{s}{N}$	$\frac{H_d}{H}=-1.04+5.79\frac{H}{H_0}-5.63\left(\frac{H}{H_0}\right)^2$	$\frac{H_d}{H_0}=0.38-0.21\frac{s}{N}$
10	$\frac{H_d}{H_0}=-0.55+2.4\frac{s}{N}-1.8\left(\frac{s}{N}\right)^2$	$\frac{H_d}{H_0}=-0.32+2.01\frac{s}{N}-1.78\left(\frac{s}{N}\right)^2$	$\frac{H_d}{H_0}=0.005+0.86\frac{s}{N}-0.79\left(\frac{s}{N}\right)^2$	$\frac{H_d}{H_0}=-0.45+2.22\frac{s}{N}-1.73\left(\frac{s}{N}\right)^2$
11	$\frac{H_d}{H_0}=2.1-8.5\frac{s}{N}+13\left(\frac{s}{N}\right)^2-6.73\left(\frac{s}{N}\right)^3$	$\frac{H_d}{H_0}=-1.43+5.76\frac{H}{H_0}-4.94\left(\frac{H}{H_0}\right)^2$	$\frac{H_d}{H_0}=0.61-1.99\frac{s}{N}+3.57\left(\frac{s}{N}\right)^2-2.17\left(\frac{s}{N}\right)^3$	

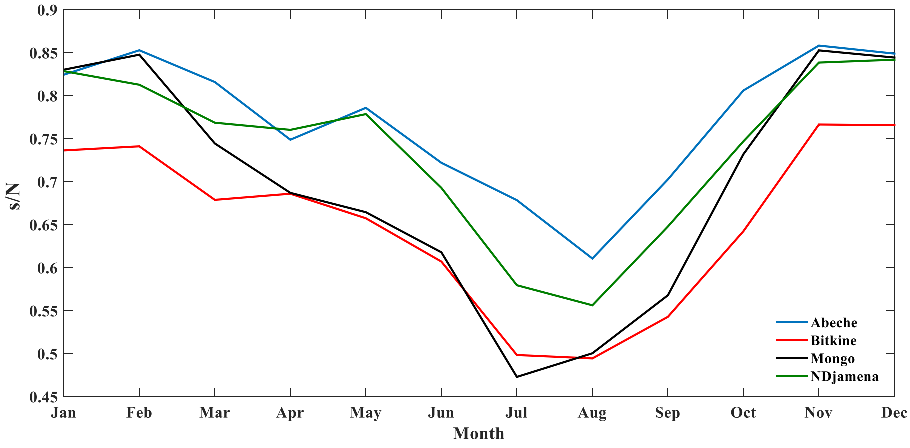

Figure 3. Monthly evolution of the relative sunshine duration

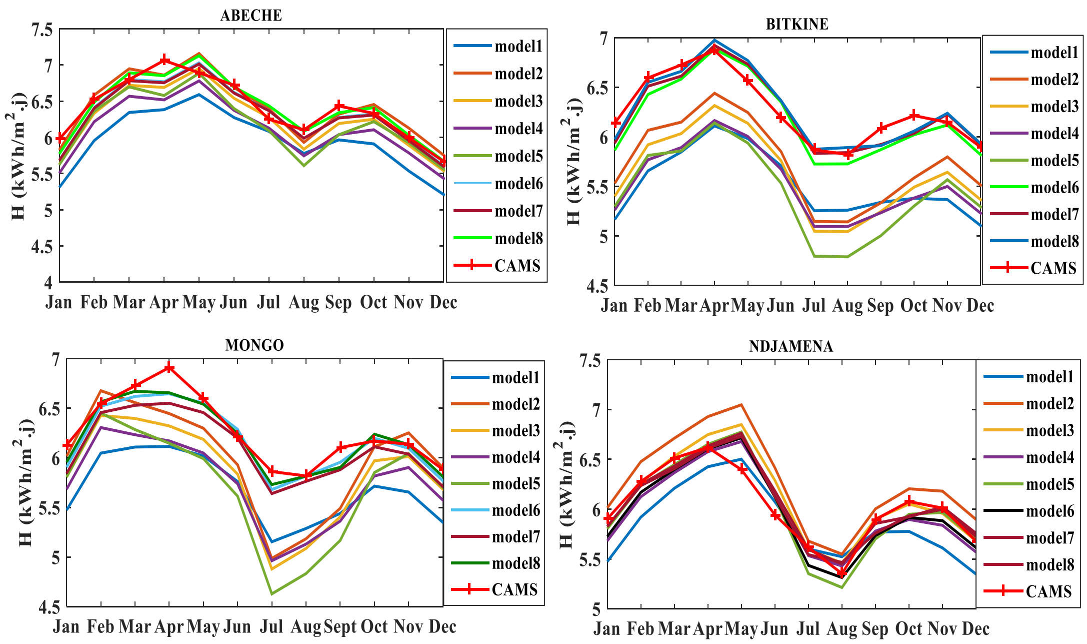

Figure 4. Graphical comparison of estimated global radiation of the different correlations with CAMS data

Table 4. Statistical evaluation of global solar irradiation models

	ABECHE								MONGO						
Model	**SSRE**	**MPE**	**RSE**	**MBE**	**RMSE**	**t**	**r**	**Model**	**SSRE**	**MPE**	**RSE**	**MBE**	**RMSE**	**t**	**r**
1	0.0050	-0.5873	0.0203	-0.4517	0.4727	10.7498	0.9419	**1**	0.0086	-0.7734	0.0268	-0.5808	0.5900	18.5604	0.9527
2	0.0000	0.0318	0.0011	0.0243	0.1489	0.5477	0.9407	**2**	0.0018	-0.3539	0.0123	-0.2704	0.4085	2.9287	0.8100
3	0.0006	-0.2068	0.0072	-0.1596	0.2052	4.1066	0.9535	**3**	0.0045	-0.5576	0.0193	-0.4236	0.4972	5.3970	0.8514
4	0.0021	-0.3862	0.0134	-0.2965	0.3226	7.7339	0.9506	**4**	0.0067	-0.6815	0.0236	-0.5140	0.5537	8.2815	0.8661
5	0.0013	-0.3010	0.0104	-0.2310	0.2827	4.6999	0.9225	**5**	0.0075	-0.7223	0.0250	-0.5481	0.6537	5.1025	0.7670
6	0.0001	-0.0821	0.0028	-0.0635	0.1438	1.6319	0.9533	**6**	0.0002	-0.1175	0.0041	-0.0875	0.1318	2.9410	0.9578
7	0.0002	-0.1102	0.0038	-0.0849	0.1540	2.1914	0.9528	**7**	0.0007	-0.2143	0.0074	-0.1596	0.1875	5.3846	0.9577
8	**0.0000**	**0.0054**	**0.0002**	**0.0037**	**0.1303**	**0.0936**	**0.9536**	**8**	**0.0001**	**-0.0929**	**0.0032**	**-0.0689**	**0.1184**	**2.3733**	**0.9597**
	BITKINE								**NDJAMENA**						
	SSRE	MPE	RSE	MBE	RMSE	t	r	**Model**	SSRE	MPE	RSE	MBE	RMSE	t	r
1	0.0142	-0.9923	0.0344	-0.7450	0.7595	16.7287	0.8988	**1**	0.0008	-0.2406	0.0083	-0.1709	0.2699	2.7136	0.8335
2	0.0070	-0.6951	0.0241	-0.5264	0.5473	11.6388	0.9398	**2**	0.0016	0.3298	0.0114	0.2353	0.2860	4.8046	0.9444
3	0.0104	-0.8498	0.0294	-0.6427	0.6578	15.1975	0.9454	**3**	0.0001	0.1009	0.0035	0.0708	0.1749	1.4684	0.9330
4	0.0137	-0.9754	0.0338	-0.7346	0.7432	21.6913	0.9477	**4**	0.0001	-0.0770	0.0027	-0.0560	0.1616	1.2255	0.9231
5	0.0168	-1.0787	0.0374	-0.8156	0.8341	15.4841	0.9216	**5**	0.0000	-0.0359	0.0012	-0.0306	0.1675	0.6159	0.9487
6	0.0002	-0.1096	0.0038	-0.0843	0.1551	2.1478	0.9456	**6**	0.0001	-0.0709	0.0025	-0.0538	0.1574	1.2068	0.9423
7	0.0000	-0.0276	0.0010	-0.0213	0.1254	0.5725	0.9412	**7**	0.0000	0.0204	0.0007	0.0142	0.1420	0.3339	0.9350
8	**0.0000**	**0.0105**	**0.0004**	**0.0069**	**0.1240**	**0.1853**	**0.9443**	**8**	**0.0000**	**0.0359**	**0.0012**	**0.0266**	**0.1384**	**0.6497**	**0.9336**

Abeche: Models 2, 6, 7, 8 are all significant and with insignificant errors. The values of the statistical indicators show that model 8 is the best with a more significant estimation than the others.

Bitkine: Only the new correlations developed are significant because their different t-stat values are inferior to the t-critic. Model 8 has statistical values all approaching zero and is therefore considered the best among the others.

Mongo: Several models have significant correlation coefficients but their estimations are not all statistically significant. Differences are observed between their different calculated errors (RMSE, SSRE). However, model 8 is the one that has results above zero and is considered the best model for estimating global solar radiation on the ground.

N'Djamena: Of all models, only model 2 has a t-stat superior to the t-critic, with significant values of the calculated errors. Models 5, 7 and 8 are more significant in terms of estimation and have good results overall. From the RMSE and SSRE values, it can be observed that model 8 is very around to the ideal values, i.e. the values of its estimate are closer to those from CAMS.

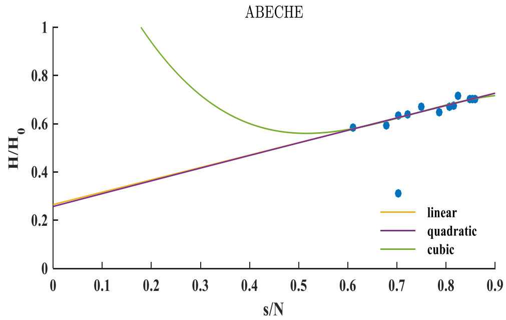

Figure 5. Relationship between the relative insolation time and the clearness index in Abeche

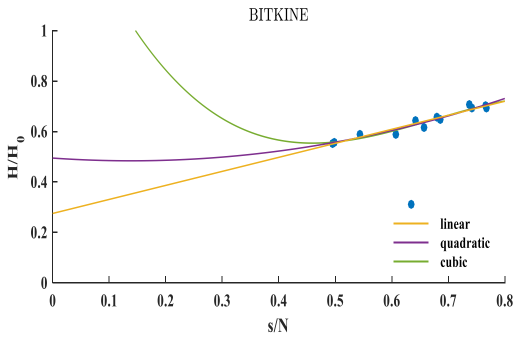

Figure 6. Relationship between the relative insolation time and the clearness index in Bitkine

It can be observed that with the exception of Ndjamena, the models tend to underestimate the solar radiation in the other cities, including some new models. This may be due to the specification of the functional form of the models and also the omission of some input variables. This can be observed from the correlation coefficient values (Table 4). In general, it should be noted that the correlations based on the 1st and 2nd order polynomial regression model provide satisfactory results but those derived from the 3rd order polynomial regression are around to the CAMS values. Their results are around to the ideal values of the indicators used. In comparison to the others, they are chosen as the best correlations in all cities for estimating the global solar radiation at ground level on a horizontal plane. Thus, the third-order polynomial approach is more appropriate for empirical relationships between the clearness index and relative insolation in the Sahelian zone. Figures 5, 6, 7 and 8 show the goodness of fit of the point cloud by the different polynomial approaches.

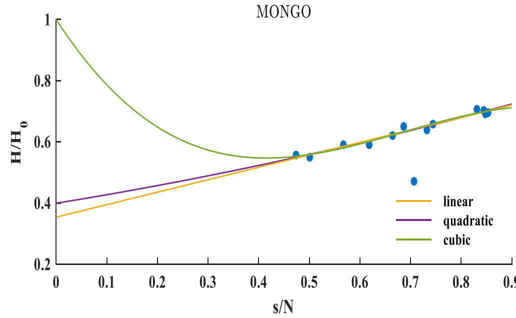

Figure 7. Relationship between the relative insolation time and the clearness index in Mongo

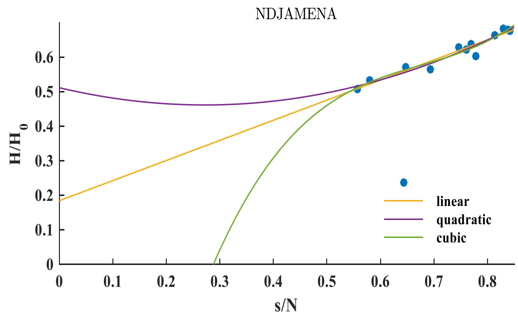

Figure 8. Relationship between the relative insolation time and the clearness index in Ndjamena

4.2 Correlations for the estimation of diffuse solar radiation on the ground

After obtaining correlations for global radiation, the determination of correlations for diffuse solar radiation is very important since the solar technologies (non-concentrated solar photovoltaic) without a tracking system focus their captation surfaces to receive the maximum from this component of radiation considering its potential in these cities (Figure 2). The diffuse radiation in more of being expressed as a function of the sunshine duration and the extra-atmospheric irradiation can also be expressed as a function of the clearness index. It can be in several functional forms depending on the polynomial approach applied. These are shown in Table 3. The new correlations obtained adapted to each city are used to estimate the diffuse radiation and comparing their estimates with those of other models selected in the literature and the CAMS data (Figure 9). The results of the calculated statistical indicators are reported in Table 5.

Abeche: Graphically, most models underestimate diffuse radiation from spring to summer. However, most of their estimations are not significant, although they have good correlations with the CAMS data. Considering the results reported in Table 5, the indicator values obtained show that model 8 is the best.

Bitkine: On average, there is a similar approach between the estimated values and the ideal values of radiation. With the exception of models 3,5, all estimations are significant. Models 7 and 8 stand out from the others. However, in comparing all the calculated values of the statistical indicators (Table 5), on average model 7 is preferred to model 8.

Table 5. Statistical evaluation of diffuse solar irradiation models

ABECHE								MONGO							
Model	**SSRE**	**MPE**	**RSE**	**MBE**	**RMSE**	**t**	**r**	**Model**	**SSRE**	**MPE**	**RSE**	**MBE**	**RMSE**	**t**	**r**
1	0.0110	-0.8749	0.0303	-0.2004	0.2744	3.5454	0.9865	1	0.0014	-0.3087	0.0107	-0.0461	0.1833	0.8614	0.9767
2	0.0237	-1.2834	0.0445	-0.2976	0.3889	3.9408	0.9945	2	0.0108	-0.8644	0.0299	-0.1765	0.3035	2.3708	0.9893
3	0.0814	-2.3775	0.0824	-0.5998	0.6460	8.2916	0.9885	3	0.0540	-1.9361	0.0671	-0.4658	0.5197	6.6994	0.9798
4	0.0349	-1.5557	0.0539	-0.3728	0.4490	4.9420	0.9814	4	0.0145	-1.0032	0.0348	-0.2218	0.3096	3.4051	0.9698
5	0.1603	-3.3363	0.1156	-0.8640	0.8987	11.5768	0.9345	5	0.0948	-2.5651	0.0889	-0.6514	0.6771	11.6718	0.9375
6	0.0410	-1.6873	0.0585	-0.4197	0.4697	6.5953	0.9624	6	0.0147	-1.0097	0.0350	-0.2377	0.2886	4.8189	0.9686
7	0.0090	-0.7902	0.0274	-0.2009	0.2427	4.8970	0.9605	7	0.0001	-0.0882	0.0031	-0.0079	0.1394	0.1880	0.9562
8	**0.0000**	**-0.0159**	**0.0006**	**0.0032**	**0.0875**	**0.1215**	**0.9835**	8	**0.0003**	**0.1439**	**0.0050**	**0.0467**	**0.1169**	**1.4471**	**0.9733**
9	0.0001	-0.0692	0.0024	0.0010	0.1702	0.0186	0.9355	9	0.0003	-0.1480	0.0051	-0.0211	0.1616	0.4373	0.9405
10	0.0001	-0.0774	0.0027	-0.0053	0.1379	0.1287	0.9596	10	0.0007	-0.2182	0.0076	-0.0494	0.1250	1.4270	0.9689
11	0.0169	-1.0824	0.0375	-0.2852	0.3234	6.2049	0.9462	11	0.0006	-0.2080	0.0072	-0.0456	0.1198	1.3660	0.9718
BITKINE								NDJAMENA							
Model	**SSRE**	**MPE**	**RSE**	**MBE**	**RMSE**	**t**	**r**	**Model**	**SSRE**	**MPE**	**RSE**	**MBE**	**RMSE**	**t**	**r**
1	0.0010	-0.2658	0.0092	-0.0360	0.1781	0.6840	0.9729	1	0.0092	-0.8011	0.0277	-0.2015	0.2666	3.8296	0.9732
2	0.0098	-0.8253	0.0286	-0.1670	0.2938	2.2915	0.9870	2	0.0284	-1.4049	0.0487	-0.3634	0.4321	5.1581	0.9840
3	0.0521	-1.9021	0.0659	-0.4562	0.5090	6.6998	0.9761	3	0.0781	-2.3293	0.0807	-0.6328	0.6725	9.2223	0.9762
4	0.0101	-0.8387	0.0291	-0.1720	0.2948	2.3823	0.9686	4	0.0468	-1.8029	0.0625	-0.4790	0.5352	6.6527	0.9536
5	0.0739	-2.2655	0.0785	-0.5552	0.6007	8.0232	0.9274	5	0.1646	-3.3809	0.1171	-0.9415	0.9709	13.1617	0.8850
6	0.0076	-0.7257	0.0251	-0.1478	0.2614	2.2736	0.9682	6	0.0498	-1.8604	0.0644	-0.5046	0.5454	8.0889	0.9341
7	**0.0001**	**-0.0696**	**0.0024**	**-0.0023**	**0.1416**	**0.0544**	**0.9531**	7	0.0002	-0.1262	0.0044	-0.0109	0.2055	0.1768	0.8928
8	0.0003	0.1337	0.0046	0.0446	0.1204	1.3210	0.9697	8	0.0001	0.0657	0.0023	0.0349	0.1718	0.6873	0.9257
9	0.0012	-0.2859	0.0099	-0.0499	0.1979	0.8643	0.9126	9	0.0026	-0.4246	0.0147	-0.0990	0.2145	1.7251	0.9115
10	0.0005	0.1880	0.0065	0.0648	0.1477	1.6186	0.9593	10	**0.0002**	**-0.1179**	**0.0041**	**-0.0193**	**0.1396**	**0.4625**	**0.9541**
11	0.4627	-5.6684	0.1964	-1.5714	1.6767	8.9134	0.8516								

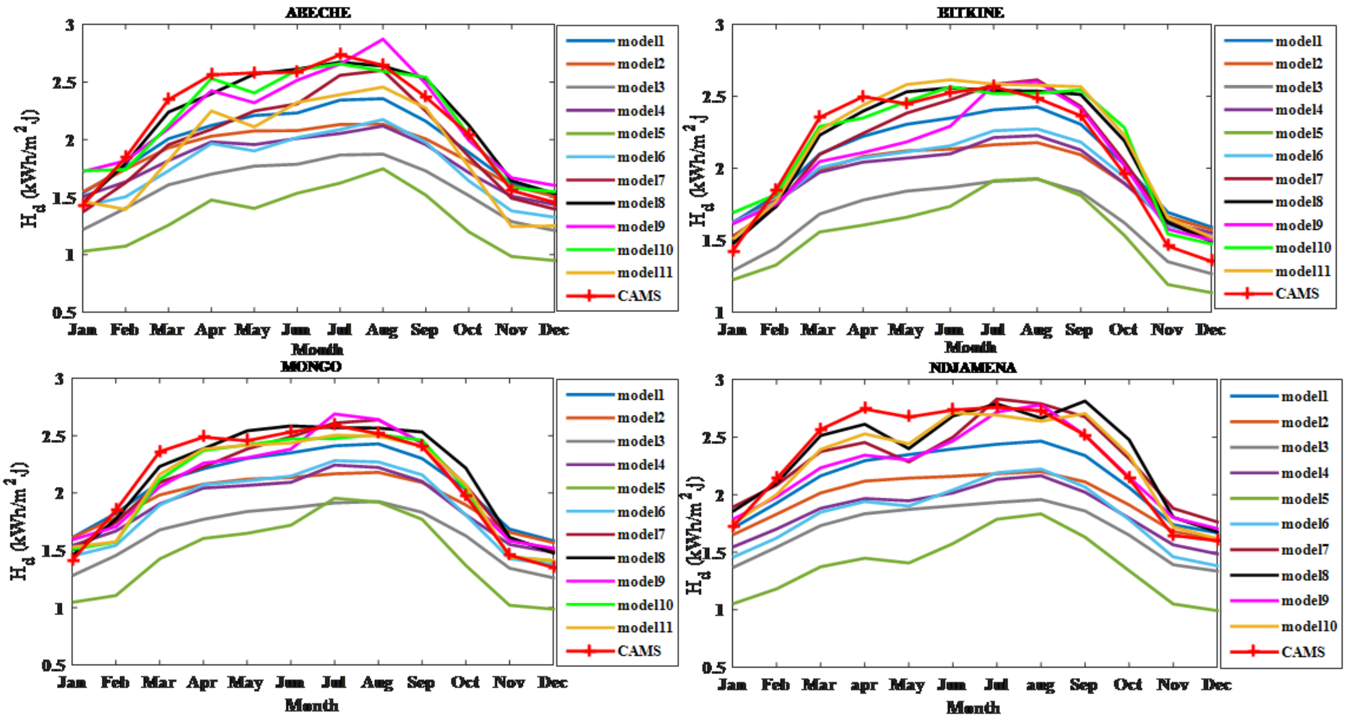

Figure 9. Graphical comparison of estimated diffuse radiation of the different correlations with CAMS data

Mongo: All the new models obtained have statistically significant estimation results. Models 1, 7 and 9 have t-stats very approximate to the ideal value compared to model 8. The different forms of error calculated allow us to distinguish model 8 from the others. On average, it is preferred as the best.

Ndjamena: The same analyses carried out graphically in the previous cases are valid here. The four new correlations are significant and are very approximate to the CAMS data. The model10 according to the values of the statistical indicators is the one with values that approach the ideal values (Table 5). Therefore, it is chosen as the best model for estimating diffuse radiation in this locality.

In the four cities, only the model validated in Ndjamena has a different functional form from the others in which the diffuse radiation is expressed as a function of the relative insolation. On the other hand, the other correlations given can be rewritten like the model given in Ndjamena using Eq. (6). This leads us to a polynomial form of order greater than 1. The polynomial approach is well suited in determination of the correlations of calculation of global and diffuse radiation in the Sahelian climate zone. However, the differences between the estimated solar radiation values and those obtained from CAMS show that only the sunshine duration cannot well explain the solar radiation in these cities. The Sahelian climate zone is characterized by long dry seasons with high temperatures. Taking into account temperature as an explanatory variable in an appropriate way could improve the values obtained from correlation coefficients, i.e. by making the estimation quality of the models better. In addition, the shading effect of the relief of the cities could also be taken into account in the models. The importance of using temperature as a variable in the Sahelian climate zone was highlighted by Soulouknga et al. [16] in their work using radiation models based on knowledge of the temperature (minimum, maximum and the mean).

5. CONCLUSIONS

The objective of this work is to propose new correlations between diffuse, global radiation and sunshine duration in the Sahelian zone of Chad. A polynomial approach was used to find polynomial regression models and four cities in this climatic zone were selected. After a statistical evaluation, the results show that in all these cities, the correlations obtained from the polynomial regression models of order greater than 1 estimate well the values of global and diffuse radiation in comparison with the data from CAMS. In view of the deviations observed between the estimated values of solar radiation and those obtained from CAMS, the inclusion of the temperature variable in the functional form could improve the quality and accuracy of the models in their estimation of solar irradiation, as it is one of the parameters that characterize the Sahelian climate zone. In addition, the shading effect of the relief of the cities should be taken into account. This work can also be extended to other cities in order to have the most accurate estimation tools that are better adapted to the climatic characteristics of each city or region.

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REFERENCES

[1] Goni, S., Adanno, H.A., Diop, D., Kriga, A., Khayal, M.Y., Nebon, B., Beye, A.C., Abdoul Aziz Niang, S., Drame, M.S. (2019). Observation and simulation of available solar energy at N'Djamena, Chad. Smart Grid and Renewable Energy, 10(6): 165-178. https://doi.org/10.4236/sgre.2019.106011

[2] Goni, S., Adannou, H.A., Diop, D., Drame, M.S., Tikri, B., Barka, M., Beye, A.C. (2019). Long-Term variation of sunshine duration and their inter-action with meteorogical parameters over Chad, central Africa. Natural Resources, 10(3): 47-58. https://doi.org/10.4236/nr.2019.103004

[3] Hassane Babikir, M., Njomo, D., Khayal, M.Y., Temene, H.D., Joel, D.T. (2018). Estimation of direct solar radiation of Chad. Energy and Power Engineering, 10(5): 212-225. https://doi.org/10.4236/epe.2018.105015

[4] Babikir, M.H., Njomo, D., Barka, M., Chara-Dackou, V.S., Kondji, Y.S., Khayal, M.Y. (2021). Thermal modelling of a parabolic trough collector in a quasi-steady state regime. J. Renewable Sustainable Energy, 13(1). https://doi.org/10.1063/1.5145272

[5] Babikir, M.H., Chara-Dackou, V.S., Njomo, D., Barka, M., Khayal, M.Y., Kamta Legue, D.R., Gram-Shou, J.P. (2020). Simplified modeling and simulation of electricity production from a dish/stirling system. International Journal of Photoenergy, 2020: 7398496. https://doi.org/10.1155/2020/7398496

[6] Black, J.N., Bonython, C.W., Prescott, J.A. (1954). Solar radiation and the duration of sunshine, Adelaide, South Australia, 80(344): 231-235. https://doi.org/10.1002/qj.49708034411

[7] Suehrcke, H., Bowden, R.S., Hollands, K.G.T. (2013). Relationship between sunshine duration and solar radiation. Solar Energy, 92: 160-171. http://dx.doi.org/10.1016/j.solener.2013.02.026

[8] Augustine, C., Nabuchi, M.N. (2009). Empirical models for the correlation of global solar radiation with meteorological data for Enugu, Nigeria. The Pacific Journal of Science and Technology, 10(1).

[9] Falayi, E.O., Adepitan, J.O., Rabiu, A.B. (2008). Empirical models for the correlation of global solar radiation with meteorological data for Iseyin, Nigeria. International Journal of Physical Sciences, 3(9): 210-216. https://doi.org/10.5897/IJPS2020.4929

[10] Mbiake, R., Wakata, B., Mfoumou, E., Ndjeuna, E., Fotso, L., Tiekwe, E., Kaze Djamen, J.R., Bobda, C. (2018). The Relationship between global solar radiation and sunshine durations in Cameroon. Open Journal of Air Pollution, 7(2): 107-119. https://doi.org/10.4236/ojap.2018.72006

[11] Quansah, E., Amekudzi, L.K., Preko, K., Aryee, J., Boakye, O.R., Boli, D., Salifu, M.R. (2014). Empirical models for estimating global solar radiation over the Ashanti region of Ghana. Journal of Solar Energy, 2014: 897970. https://doi.org/10.1155/2014/897970

[12] 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, 2016: 7870907. https://doi.org/10.1155/2016/7870907

[13] Pandey, C.K., Katiyar, A.K. (2013). A review of solar radiation models—Part I. Journal of Renewable Energy, 2013: 168048. http://dx.doi.org/10.1155/2013/168048

[14] Allen, R.G.A. (1997). Self-calibrating method for estimating solar radiation from air temperature. Journal of Hydrologic Engineering, 2(2): 56-57. http://doi.org/10.1061/(ASCE)1084-0699(1997)2:2(56)

[15] Hargreaves, G.H., Samani, Z.A. (1982). Estimating potential evapotranspiration. Journal of Irrigation and Drainage Engineering, 108(3): 223-230. https://doi.org/10.1061/JRCEA4.0001390

[16] Soulouknga, M.H., Coulibaly, O., Doka, S.Y., Kofane, T.C. (2017). Evaluation of global solar radiation from meteorological data in the Sahelian zone of Chad. Renewables, 4. https://doi.org/10.1186/s40807-017-0041-0

[17] Aras, H., Balli, O., Hepbasli, A. (2006). Estimating the horizontal diffuse solar radiation over the Central Anatolia Region of Turkey. Energy Conversion and Management, pp. 2240-2249. http://dx.doi.org/10.1016/j.enconman.2005.11.024

[18] Ulgen, K., Hepbasli, A. (2009). Diffuse solar radiation estimation models for Turkey's big cities. Energy

Conversion and Management, 50(1): 149-156. https://doi.org/10.1016/j.enconman.2008.08.013
[19] Kaplan, A.G., Kaplan, Y.A. (2020). Developing of the new models in solar radiation estimation with curve fitting based on moving least-squares approximation. Renewable Energy, 146: 2462-2471. https://doi.org/10.1016/j.renene.2019.08.095
[20] Babikir, M.H., Njomo, D., Barka, M., Khayal, M.Y., Goron, D., Chara-Dackou, V.S., Tiague Martial, T., Kamta Legue, D.R., Gram-Shou, J.P., Nzadi, S.E. (2020). Modeling the incident solar radiation of the city of N'Djamena (Chad) by the Capderou method. International Journal of Photoenergy, 2020: 6292147. https://doi.org/10.1155/2020/6292147
[21] Mousavi Maleki, S.A.M., Hizam, H., Gomes, C. (2017). Estimation of hourly, daily and monthly global solar radiation on inclined surfaces: Models re-visited. Energies, 10(1): 134. https://doi.org/10.3390/en10010134
[22] Klein, S.A. (1977). Calculation of monthly average insolation on tilted surfaces. Solar Energy, 19(4): 325-329. https://doi.org/10.1016/0038-092X(77)90001-9
[23] Sarkar, M.N.I. (2016). Estimation of solar radiation from cloud cover data of Bangladesh. Renewables, 3. https://doi.org/10.1186/s40807-016-0031-7
[24] Enríquez-Velásquez, E.A., Benitez, V.H., Obukhov, S.G., Félix-Herrán, L.C., Lozoya-Santos, J.D.J. (2020). Estimation of solar resource based on meteorological and geographical data: Sonora state in northwestern territory of Mexico as case study. Energies, 13(24): 6501. https://doi.org/10.3390/en13246501
[25] Stone, R.J. (1993). Improved statistical procedure for the evaluation of solar radiation estimation models. Solar Energy, 51(4): 288-291.

NOMENCLATURE

CAMS	Copernicus Atmosphere Monitoring Service
$kWh/m^2.j$	kilowatt hour per square meter per day
W/m^2	watt per square meter
$Wh/m^2.j$	watt hour per square meter per day
H	average daily global solar radiation
s	average sunshine duration
SSRE	sum of the square of relative error
MBE	mean bias error
MPE	mean percentage error
RSE	relative standard error
RMSE	root mean square Error
t-stat	statistical significance test
t-critic	critical value of the statistical significance test
r	correlation coefficient
n	number of observations
N	theoretical length of the day
J	number of the day
I	solar constant

Greek symbols

α	parameter
β	parameter
φ	latitude
δ	Solar declination

Subscripts

m	measured
S	solar
0	extra-atmospheric
d	diffuse