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Article

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A clear sky irradiation assessment using a modified Algerian solar atlas model in Adrar city

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ABSTRACT

The solar systems technology offers a promising method for the large scale use of solar energy in the southern zone of Algeria. The magnitude of solar radiation is the most important parameter for sizing these systems. The chief goal of this investigation is to contribute to the national efforts in establishing solar radiation in Algeria. Using the Algerian solar atlas model and the experimental monthly mean Linke turbidity factor a new model for the prediction of the solar radiation in the Sahara desert area of Adrar region, Algeria is developed. In this study, the Linke turbidity factor was obtained from radiometric and meteorological data recorded in the research unit in renewable energies in the Saharan medium, during October 2012 to May 2015. This investigation finds that the newly developed model performs more accurate estimation, with smaller relative errors between measured and computed values.

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1. Introduction

Fossil fuels and especially the natural gas is the largest source of electricity production in Algeria. According to Himri et al. (2009) in 2007 about 98% of electricity is generated by the natural gas. The environmental problems caused by the use of fossil fuels are well known: air pollution, greenhouse gases and aerosol production. In the last years the electricity consumption has increased with the rapid growth in the residential, commercial and industrial sectors. Renewable energy resources especially solar energy offer interesting opportunities for facing this important increase. This strategic is motivated by the huge potential in solar energy in the south of Algeria. Marif et al. (2014) have shown that the mean yearly sunshine duration varies from a low of 2650 h on the coastal line to 3900 h in the south. In a first step hybrid concentrated solar power plant was installed in the south of Algeria (Hassi Rmel) since 2010 with electrical power of 25 MW. As referenced by Boukelia and Mecibah (2013), three further hybrid concentrated power plants will be completed in 2018 with 70 MW thermal solar power plants capacity for each one of them. These three power plants are part of the government's plan to export from thermal and photovoltaic solar power.

The study of solar radiation under cloudless skies is generally important for the utilization of solar energy and particularly for solar systems optimal design Mateos et al. (2010). In Algeria many approaches have been proposed in several studies to estimate the solar radiation. The first correlations were proposed by Capderou (1987) in the Algerian solar atlas, which developed theoretical approach based on the atmospheric Linke turbidity factor to estimate the instantaneous global solar radiation on a completely clear day conditions. Yaiche et al. (2014) created a global solar radiation map in Algeria from sunshine duration for all sky types. They found that the relative error is less than 7% between measured and computed values. Mefti et al. (2003) have estimated the global solar radiation incident on an inclined surface in any site of Algeria using monthly mean daily sunshine duration measurements, in this model the discrepancies observed between the estimated and measured values run from 10% to 35%. In order to correlating monthly mean daily diffuse solar radiation Boukelia et al. (2014) studied the performance of ten empirical models based on the ratio of monthly mean daily sunshine records to monthly daily mean daylight hours and on the ratio of monthly mean daily global solar radiation data to monthly mean daily extraterrestrial solar radiation at six Algerian stations: Algiers, Constantine, Ghardaia, Bechar, Adrar, and Tamanrasset. This study finds that the quadratic and cubic equation which based on global solar radiation data performed the best accuracy. Omar et al. (2015) compared the performance of seventeen clear-sky direct solar radiation models under Algerian

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climate to select the more accurate one, their results show that the ASHRAE model can offer more precise information. Six combined empirical models and a Bayesian neural network (BNN) model have been used by Yacef et al. (2014) to estimate daily global solar radiation from air temperature on horizontal surface in Ghardaïa city. After testing, the combined models appear to be more helpful than BNN. Based on the intelligent artificial neural network (ANN), two models have been proposed by Mellit et al. (2005, 2006) to predict the daily global solar radiation with a sufficient accuracy for any location in Algeria. Chegaar and Chibani (2001) proposed two models for estimating monthly mean daily global solar radiation on a horizontal surface in four Algerian locations (Algiers, Oran, Beni abbas and Tamanrasset). The first model is originally formulated by Barbaro et al. (1978) and modified by the authors and the second proposed model is a regression equation of the Angstrom type based on sunshine duration. Mecibah et al. (2014) correlating the monthly mean daily global solar radiation on a horizontal surface with monthly mean sunshine records and air temperature data for six Algerian cities (Algiers, Oran, Batna, Ghardaïa, Bechar, and Tamanrasset). After testing, the sunshine based models appear to be more accurate than air temperature based models.

In this paper, a software application based on a clear-sky Algerian solar atlas model and on an experimental determination of the Linke turbidity factor is developed in order to evaluate the amount of solar radiation over different time intervals for the first time in Adrar town. In the following sections, a detail of the mathematical model, the description of the measurement station, the data series characteristics and the obtained results can be seen.

2. Mathematical formulations

2.1. Experimental Linke turbidity factor

Many solar radiation models for clear day refer to the Linke turbidity factor T_L . This parameter describes the optical thickness of the atmosphere due to both absorption by the water vapor and the absorption and scattering by the aerosol particles. A review of the literature showed that T_L can be obtained from several methods. Kasten (1980) presented a simple calculation methodology to facilitate the experimental determination of the Linke turbidity factor where the pyrheliometric measurements of the direct normal solar irradiation (DNI) on the horizontal plane are known. Cucumo et al. (1999) developed a general calculation model using experimental data of beam solar irradiation on the horizontal plane. As documented by Diabaté et al. (2003), T_L was estimated using the approach proposed by Aguiar in the European Solar Radiation Atlas ESRA (2000). In this research, the experimental Linke turbidity factor has been calculated using a method developed by Kasten, which have been used in previous papers (Djafer and Irbah, 2013; Trabelsi and Masmoudi, 2011; Li and Lam, 2002). The expression of T_L is given by the following equations:

$$T_L = T_{Lk} \frac{\frac{1}{\delta_{Ra}}}{\frac{1}{\delta_{Rk}}} \quad (1)$$

T_{Lk} is the atmospheric Linke turbidity factor under clear sky according to Kasten, δ_{Rk} is the Rayleigh integral thickness given by the same author and δ_{Ra} is the integral optical thickness given by Louche et al. (1986) and adjusted by Kasten (1996):

$$T_{Lk} = (0.9 + 9.4 \sin(h)) \cdot \ln\left(\frac{I_0 \varepsilon}{I_n}\right) \quad (2)$$

$$\frac{1}{\delta_{Rk}} = 9.4 + 0.9m_A \quad (3)$$

$$\frac{1}{\delta_{Ra}} = 6.5567 + 1.7513m_A - 0.1202m_A^2 + 0.0065m_A^3 - 0.00013m_A^4 \quad (4)$$

where h is the sun elevation angle (in degrees), ε is the Sun–Earth correction distance. I_0 and I_n are respectively the sun constant (1367 W/m^2) and the direct normal solar irradiation (in W/m^2). The atmospheric air mass m_A which depends on the sun elevation angle and local air pressure P (in Pascal), the value of m_A is given by Trabelsi and Masmoudi (2011):

$$m_A = \frac{P}{101325} [\sin(h) + 0.15(h + 3.885)^{-1.253}]^{-1} \quad (5)$$

2.2. Algerian solar atlas model

Capderou (1987) in the Algerian solar atlas has proposed mathematical equations based on the theoretical approach of Perrin de Brichambaut and Vauge (1982). The direct solar radiation expression under clear sky condition I_d (in W/m^2) is given by the following equation:

$$I_d = I_0 \varepsilon \cos \theta \exp(-T_{Lc} m_{Ac} \delta_{Rk}) \quad (6)$$

where θ is the incidence angle (in degrees). T_{Lc} and m_{Ac} are the atmospheric Linke turbidity factor and the atmospheric air mass given by Capderou respectively:

$$T_{Lc} = T_0 + T_1 + T_2 \quad (7)$$

T_0 is the atmospheric turbidity caused by water vapor absorption:

$$T_0 = 2.4 - 0.9 \sin \varphi + 0.1A_{he} (2 + \sin \varphi) - 0.2Z - (1.22 + 0.14A_{he}) (1 - \sin h) \quad (8)$$

T_1 is the atmospheric turbidity corresponding to the molecular diffusion:

$$T_1 = (0.89)^Z \quad (9)$$

T_2 is the atmospheric turbidity relative to the aerosol diffusion coupled with a slight absorption:

$$T_2 = (0.9 + 0.4A_{he}) (0.63)^Z \quad (10)$$

$$\text{Where : } A_{he} = \sin\left(\frac{360}{365} (n - 121)\right) \quad (11)$$

$$m_{Ac} = \frac{1}{\sin(h) + 9.4 \times 10^{-4} (\sin(h) + 0.0678)^{-1.253}} \approx \frac{(0.89)^Z}{\sin(h)} \quad (12)$$

Z : the altitude (in km)

n : the number of days in the year

φ : the latitude angle (in degrees)

The diffuse solar radiation (in W/m^2) depends on the diffusive turbidity factors T_1 and T_2 . In the case of horizontal surface:

$$I_{fh} = I_0 \varepsilon \exp\left(-1 + 1.06 \log(\sin h) + a - \sqrt{b^2 + a^2}\right) \quad (13)$$

Where $a = 1.1$ and

$$b = \log(T_1 + T_2) - 2.8 + 1.02(1 - \sin h)^2. \quad (14)$$

In the case of inclined surface the diffuse radiation is divided into two components, skies diffuse (I_{f1}) and grounds diffuse (I_{f2}):

$$I_{f1} = \delta_d \cos \theta + (I_{fh} - \delta_d \sin h) \frac{1 + \sin \beta}{2} + \left(\frac{-0.02a_h I_{dh}}{\sin h (a_h^2 + a_h b_h + 1.8)} \exp(\sin h)\right) \cos \beta \quad (15)$$

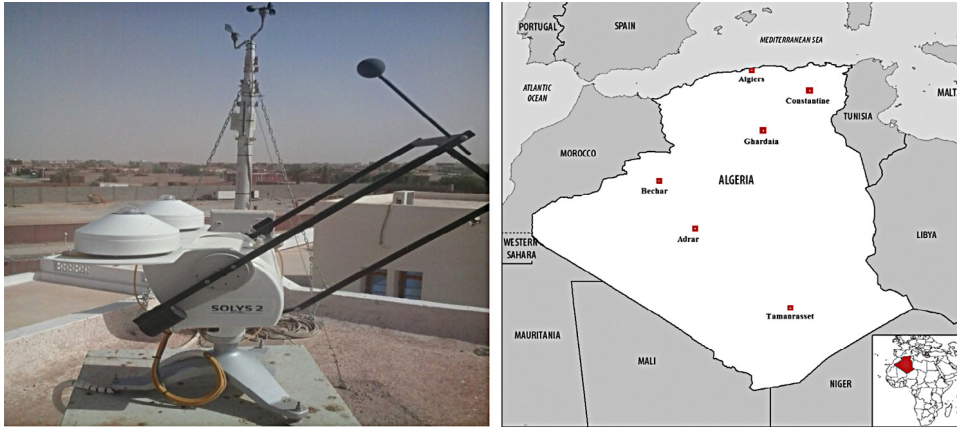


Fig. 1. Geographical location of Adrar (right part) and NEAL station instruments (left part).

$$\delta_d = I_0 \varepsilon \exp \left(-2.84 + \sin h + a_d - \sqrt{4b_d^2 + a_d^2} \right) \quad (16)$$

$$\text{where } a_d = 3.1 - 0.4b_d, \quad (17)$$

$$b_d = \log(T_1 + T_2) - 2.8 + 0.5 \log(\sin h)$$

$$\text{and } a_h = \log(T_1 + T_2) - 3.1 - \log(\sin h), \quad (18)$$

$$b_h = \exp(0.2 + 1.75 \log(\sin h))$$

$$I_{f2} = \rho (I_{dh} + I_{fh}) \frac{1 - \sin \beta}{2} \quad (19)$$

where I_{dh} is the direct solar radiation in the case of horizontal surface (in W/m^2), ρ is the ground reflectivity and β is the inclination of the surface (in degrees).

$$I_{dh} = I_0 \varepsilon \sin h \exp(-T_{Lc} m_{Ac} \delta_{Rk}). \quad (20)$$

3. Site location and data collection

The data used in this study have been recorded at the New Energy Algeria station (NEAL) installed at the rooftop of the Research Unit in Renewable Energies in the Saharan Medium (URERMS) located in Adrar (latitude North $27^\circ 53'$, longitude East $0^\circ 17'$ and 264 m above the sea level). Adrar town is facing like most cities in the south of Algeria with vast areas of desert sand (Fig. 1). Its climate is characterized by very high temperature exceeding $45^\circ C$ and an intense solar radiation with a maximum of $1000 W/m^2$, measured on the horizontal surface in long summer season. Winter is short and characterized by very low precipitations. Also, winds are very common throughout the whole year.

The NEAL station shown in Fig. 1, houses many radiometric and meteorological sensors. The Direct normal solar irradiation measurements were recorded using a solar tracker (Solys-2 from Kipp & Zonen) with a CHP1 pyrheliometer, which has a 2% calibration error and its response lies in the spectral range of 200–4000 nm. In addition, two well calibrated CMP21 pyranometers (Kipp & Zonen) are mounted on the same solar tracker which measure global and diffuse measurements of solar irradiance on horizontal surface (using a shadow ball), with an error of 2% and spectral range of 310–2800 nm. The ambient temperature and the relative humidity, both are measured with a Campbell Scientific CS215 probe, which accuracy is $0.9^\circ C$ between $-40^\circ C$ and $100^\circ C$ and 4% at $25^\circ C$ for the temperature and the humidity respectively. The air pressure data were recorded by a Campbell Scientific CS100 barometric pressure sensor, which accuracy is 1.5 mb between $-20^\circ C$ and $50^\circ C$. The wind speed data were measured with NRG 40 H anemometer, which accuracy is 0.1 m/s between 5 and 25 m/s. The radiometric data referred to this study regard clear sky

conditions, 686 clear days were selected from October 2012 to May 2015. The cloudless sky criteria used by Cucumo et al. (1999) are adopted. The ratio of diffuse irradiance to global irradiance should be less than 1/3 and the direct normal irradiance is greater than $200 W/m^2$.

The daily average values of the meteorological parameters at Adrar during 2014 are presented in Fig. 2. The figure indicate that the mean daily ambient temperature varies from a maximum around to $44^\circ C$ in summer season (June to August) and a minimum around to $5^\circ C$ in winter season (December to February). The mean daily relative humidity varies from a maximum around to 80% in winter and a minimum around to 3% in summer. In this year, the amount of the mean daily pressure is 985 hPa and the maximum value of the daily average wind speed is recorded in summer, this value exceeding 10 m/s.

4. Results and discussion

4.1. Experimental Linke turbidity factor analyses

In the Sahara desert of Algeria, the Linke turbidity factor is a very convenient approximation to model the atmospheric absorption and scattering of the extraterrestrial irradiation because cloudless skies predominate in these regions. T_L can be estimated by the monthly average values (T_{lm}) the long-term measurements which are used to calculate this mean values. The present section aims to analyze the characteristics of the atmospheric Linke turbidity factor under clear skies conditions in Adrar city.

The previous equations have been implemented into a simple MATLAB software application, in order to calculate the instantaneous, daily and monthly mean Linke turbidity factor. Fig. 3 shows the data for the whole period. The figure indicates that the daily mean Linke turbidity factors show fluctuations along the year with the highest values in summer, lowest values in winter season and middle values in spring and autumn. Summer months in Adrar are characterized by the higher ambient temperature and lower relative humidity results of low cohesion of the sand particles. For this reason when the winds speed increase the desert sand present in the atmosphere, cause in this way an increase in the Linke turbidity factor.

The monthly average theoretical Linke turbidity factor presented by Capderou compared to the experimental monthly average values obtained in Adrar are given in Table 1. The analysis of the error shows that Capderou formulas underestimate the Linke turbidity factor, with a deviation of 15.05%. This can be explained considering the relationship between the Linke turbidity factor and the local meteorological conditions. This relationship is not presented in Capderou formula.

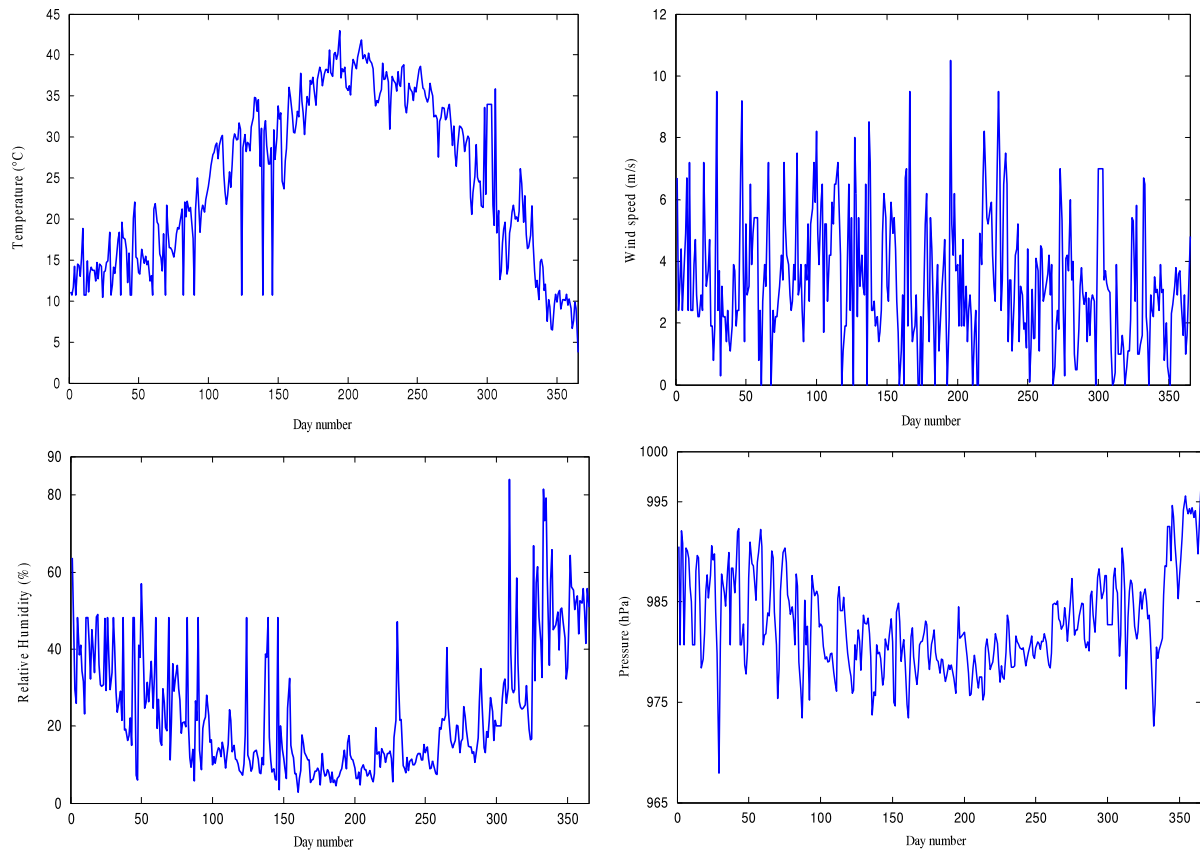


Fig. 2. Daily average variation of meteorological parameters during 2014 in Adrar.

Table 1
Comparison of the Linke turbidity factor between experimental and theoretical results.

Month	Experimental					Capderou	Error exp vs. Capderou (%)
	2012	2013	2014	2015	Mean		
J	–	–	2.45	2.26	2.35	2.24	4.68
F	–	2.68	2.66	3.22	2.85	2.28	20
M	–	3.04	3.02	2.72	2.92	2.46	15.75
A	–	3.43	3.02	3.69	3.38	2.73	19.23
M	–	3.16	3.67	4.06	3.63	3.03	16.52
J	–	3.87	4.12	–	3.99	3.27	18.04
J	–	4.14	5.07	–	4.6	3.39	26.30
A	–	3.41	4.46	–	3.93	3.36	14.50
S	–	3.88	4.33	–	4.1	3.18	22.43
O	3.24	3.57	3.9	–	3.57	2.89	19.04
N	2.54	2.51	2.74	–	2.59	2.59	0
D	2.23	2.78	2.36	–	2.45	2.35	4.085
Average							15.05

In summary, as discussed above, the Linke turbidity factor fluctuation can be influenced by the meteorological conditions and local air pollution sources such as desert dust from the Sahara and the fossil fuels exploration, as documented by [Djafer and Irbahe \(2013\)](#) and [Zakey et al. \(2004\)](#).

4.2. Modified clear sky model validation

The evolution of measured diffuse irradiation and the experimental Linke turbidity factor for cloudless day in June 9, 2014 are presented in [Fig. 4](#). The figure shows the trend similarity of the diffuse irradiation and the Linke turbidity factor. It can be seen that the attenuation of solar irradiation under cloudless sky can be controlled using this factor.

The theoretical Algerian solar atlas model was used together with the experimental monthly average Linke turbidity factor values (T_{Lm}), in order to estimate the solar irradiance. Two modifications were made to Capderou model:

1—The Rayleigh integral optical thickness (δ_{Rk}) given by Kasten in 1980 was replaced by the Rayleigh integral optical thickness (δ_{Ra}) given by Louche and adjusted by Kasten in 1996. The Eq. (6) become:

$$I_d = I_0 \varepsilon \cos \theta \exp(-T_{Lm} m_{Ac} \delta_{Ra}) . \tag{21}$$

2—To obtain the diffuse solar radiation, the diffusive turbidity factors ($T_1 + T_2$) are changed by ($T_{Lm} - T_0$) in the Eqs. (14), (17) and (18).

The validation of the present modified model was done by comparing the modified model results and the experimental data. In addition to confirm the appropriateness of the modification, the

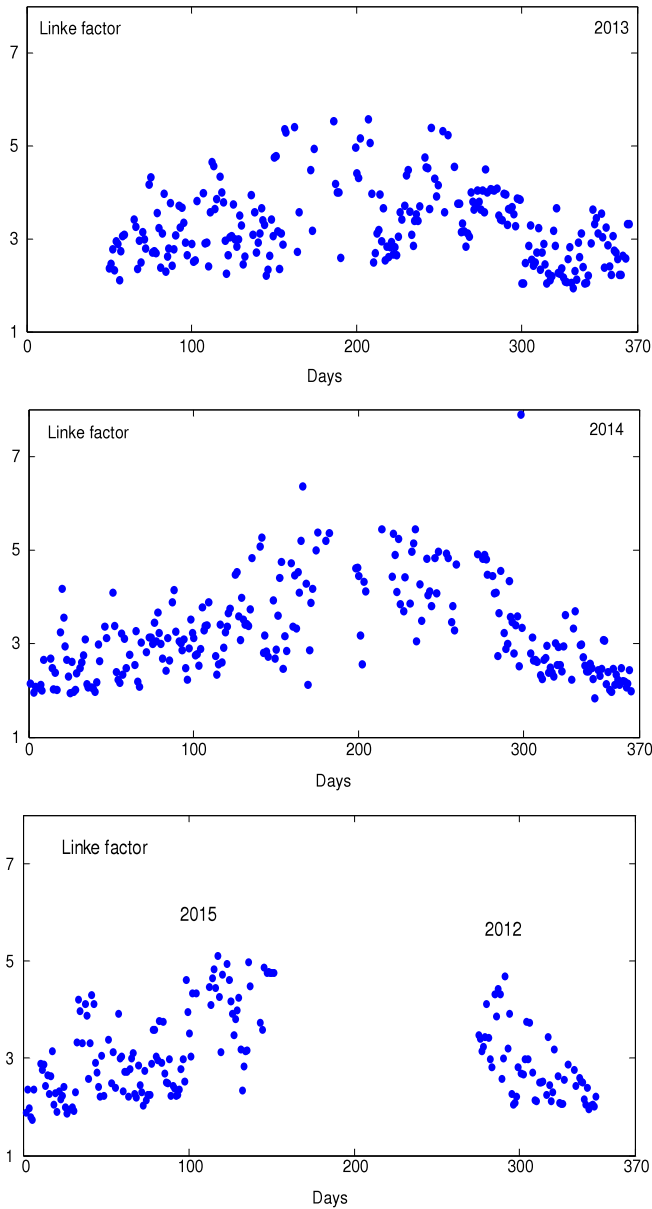


Fig. 3. Daily average values of Linke turbidity factors computed at Adrar.

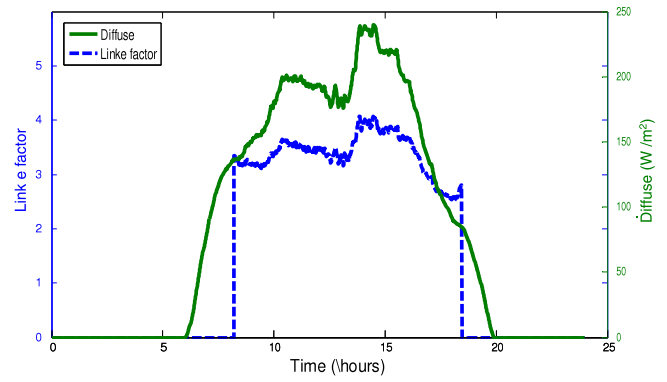


Fig. 4. Diffuse irradiation and Linke turbidity factor evolution for a typical cloudless day.

modified model results were compared with the results obtained by the theoretical Algerian solar atlas model. The evolution of global solar radiation for cloudless day in July and January are presented in Fig. 5. It is displayed that the results obtained by the modified model are in good accordance with the experimental data.

The daily average of two statistical tests, mean bias error (MBE) and root mean square error (RMSE) have been calculated for representative cloudless days in each month. MBE and RMSE have been normalized to average of database in order to obtain dimensionless indicators:

$$MBE (\%) = \frac{\frac{1}{N} \sum_{i=1}^N (x_i - \hat{x}_i)}{\frac{1}{N} \sum_{i=1}^N (\hat{x}_i)} \cdot 100, \tag{22}$$

$$RSME (\%) = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \hat{x}_i)^2}}{\frac{1}{N} \sum_{i=1}^N (\hat{x}_i)} \cdot 100$$

where x_i is the i th estimated value by the modified and theoretical Algerian solar atlas model, \hat{x}_i is the i th measured value and N is the total number of observations. The series of obtained relative errors are reported in Table 2. Comparison of the developed model results with the experimental data show that the developed model gives fairly close results, MBE varies from 0.18% to 5.57% (negative MBE indicate underestimated values) and RSME varies from 1.75% to 8.47%. For the comparison between theoretical model and experimental data, MBE varies from 5.11% to 14.26% and RSME varies from 8.35% to 21.02%.

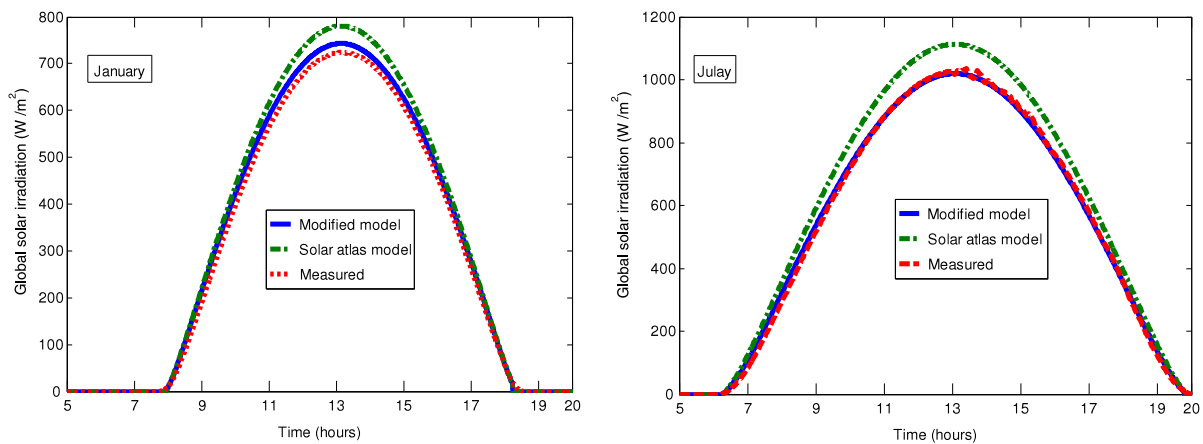


Fig. 5. The evolution of global solar radiation for cloudless day in July and January.

Table 2
Daily average values of relative MBE and RMSE.

Month	MBE (%)		RMSE (%)	
	Capderou model	Combined model	Capderou model	Combined model
J	7.66	2.47	12.85	4.30
F	6.62	0.18	11.14	1.75
M	8.98	2.30	14.50	4.10
A	5.29	−1.82	8.35	2.96
M	12.93	4.94	18.08	7.99
J	5.11	−2.76	7.60	5.20
J	14.26	4.83	20.23	7.03
A	5.56	−2.25	8.37	4.51
S	14.26	5.57	21.02	8.47
O	6	−1.31	10.13	5.41
N	4.52	−0.95	8.47	4.51
D	8.44	3.09	15.09	8.47

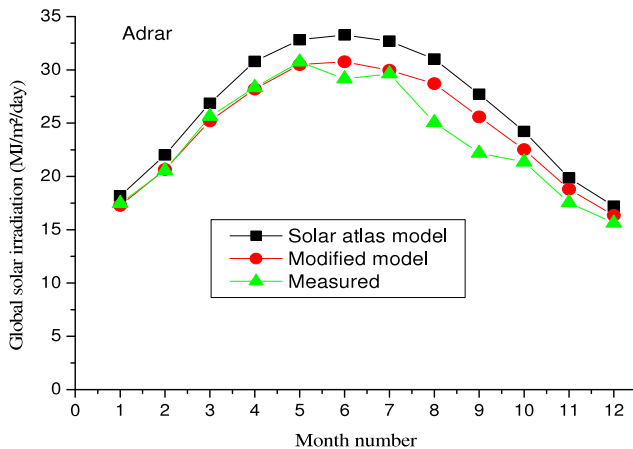


Fig. 6. Comparison of the monthly mean daily global solar radiation.

The monthly average daily global radiation values have been computed and presented in Fig. 6. For the proposed model, it should be noted that the maximum error was 13.25% and the minimum error was 0.47% with a mean deviation of $\pm 4.43\%$. Compared to the solar Atlas model, the maximum error was 25.94% and the minimum error was 4.08% with a mean deviation of $\pm 11.78\%$. The full agreement shows that the proposed model is suitable for the estimation of the global solar radiation under Adrar climates conditions. The maximum error observed during August and September can be explained considering the data quality in these two months.

5. Conclusions

In the present work, a program able to estimate the solar radiation in Adrar region situated in the south of Algeria has been developed. The use of the solar atlas model together with an experimental Linke turbidity factor based on the original Kasten method is encouraged to increase the accuracy of prediction. Two main findings are summarized as follows:

- There is a high correlation between the atmospheric Linke turbidity factor caused by aerosols and meteorological parameters especially ambient temperature, relative humidity and wind speed which can transport and elevate sand particles.
- Based on the obtained results, it could be concluded that the present paper is important to engineers and researchers who are interested in the solar radiation prediction methods. The relative error observed between the estimated and measured monthly average daily global solar radiation values run from 0.43% to 13.25%.

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