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Estimation of Hourly Global Solar Radiation Using MSG-HRV images

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Abstract

This study focuses on hybrid model development and validation for deriving the global horizontal solar irradiation on hourly basis, from high-resolution visible (HRV) channel of the SEVIRI (Spinning Enhanced Visible and Infrared Imager) imager on board Meteosat Second Generation (MSG) satellite. In this paper a new approach has been proposed to estimate the hourly global solar radiation based on an exponential function model integrating cloud albedo computation using an approximate form of the atmospheric radiative transfer (RT). The model evaluation process has been carried out by comparing the estimated values with experimental data performed in five radiometric stations distributing in the North and the South of Algeria, during the Year 2010. For hourly, respectively daily, values, the relative bias in absolute value ranges between 0.11% and ~4.3%, resp. ~0.6% and 1.5%, depending on the stations. The relative root-mean square error ranges between 11.3% and 31.3%, resp. 4.6% and 11.9%. The correlation coefficient ranges between 0.95 and 0.97, resp. 0.97 and 0.99. The correlation coefficients were always higher than 0.91 and 0.96, respectively for hourly and daily estimation. The best results were obtained during spring and summer seasons.

Keywords: Solar Energy, Hourly global irradiation, Satellite data, Atmospheric radiative transfer, Meteosat.

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Introduction

Currently, in most countries, the electric power demand is increasing continuously. The control of this energy becomes one of the major priorities of the states. Being located in a strategic region of the world, Algeria is one of the important solar belt countries, with an enormous potential in solar energy. The exploitation and promotion of these energy resources offers the opportunity of tackling energy-related and economic challenges, and to contribute to a sustainable development in our countries. Our government tends towards renewable energies in order to provide solutions against the environmental challenges and preservation of fossil energy resources. This strategic choice is motivated by these immense potential of solar energy. This energy has the major axis of the program dedicated to the solar thermal and solar photovoltaic. The solar energy is expected to reach more than 37% of the national electricity generation in 2030. [1]

Knowledge of the available solar resource in high spatial and temporal resolution is needed for evaluation spatiotemporal variability, especially for site qualification and design of the solar power projects. However, the major handicap has always been the spatial density of radiometric stations which is inadequate. In Algeria, the solar radiation measurements (global, beam, and diffuse) are available for only a very limited number surface observation stations [2,3]. So far no database exits which is based on long term data and high resolution.

The alternative solution to perform an assessment of the available solar resources and evaluate its spatial and temporal variabilities is to use the Meteorological satellite data to derived solar radiation model, which is considered the most accurate option for solar radiation estimation in locations at distances greater than 25km from a ground station. [4,5]. Meteosat Second Generation (MSG) is an operational Earth-observation system, which is composed of series of geostationary meteorological satellites developed by European Space Agency (ESA) and EUropean organization for the exploitation of METeorological SATellite (EUMETSAT). MSG2 main payload is the optical imaging radiometer, the so called Spinning Enhanced Visible and Infrared Imager (SEVIRI). SEVIRI has 12 spectral channels covering from visible to infrared [6], and provides measurements of the Earth-disc every 15 minutes at fixed view angles, with a horizontal resolution reaching 1 km for high-resolution visible (HRV) Channel.

Different types of models, available in the literature, which derive solar radiation on the earth's surface by processing Meteosat images [7-11]. Most of these models were modified and improved by several authors which were considered as reference models [12-19], and that were developed by processing ground measurements collected in various locations of European region, such as The GISTEL model (Gisement Solaire Par Télédétection), the SICIC (solar irradiation from cloud image classification) model and the family Heliosat models, some models were subsequently tested at some sites on North Africa [20-25]. Although the majority of the previous studies focused on the relationship between the clearness and cloud cover indexes (considered as effective cloud albedo), which is defined as a relative quantity of observed counts or radiances. In this paper a new approach has been proposed to estimate the hourly global solar radiation based on an exponential function model integrating cloud

albedo computation using an approximate form of the atmospheric radiative transfer (RT).
The exponential function was used to derive the solar radiation reaching the Earth surface on hourly basis, this approach was applied in three steps. First, the simplified clear Sky model described in W.M.O. [3] was applied including monthly mean of Linke turbidity factor. In a second step the Heliosat algorithm proposed by Cano et al. [7] with modifications described by Annette Hammer and Rolf Kuhlemann [26] was used to determine the cloud index parameter per pixel from the measurements of HRV channel, and in the third step an approximate form of the atmospheric radiative transfer (RT) equation described in [27] was used to calculate Cloud Albedo.
The final step of our study is to evaluate the performance of this model; the results have to be compared with observations obtained from five radiometric station located at different Algeria's climatic regions, during the year 2010. The estimation of the hourly and daily global solar radiation shows promising results compared with the current literature (e.g., rRMSE) between 11% and 33% on hourly basis, and between 7% and 13% on a daily basis, as cited in Refs.[15; 17-18; 22;24; 28-30].
In this paper, the proposed approach is developed and tested using MSG-HRV data and collected from four various sites in Algeria. Section 2 discusses the area; the measurements and the satellite data used, the proposed model and the techniques used to derive fundamental parameters of this model are described in detail in Section 3. Section 4 presents a brief discussion of the model performances and Section 5 presents the conclusions drawn from the results.

Data

In the following section, the studied area, the available ground measurements and the satellite data used are presented.

Satellite Data

In this study, the High-resolution visible (HRV) measurements of the SEVIRI (Spinning Enhanced Visible and Infrared Imager) imager onboard Meteosat-9 were exploited. The SEVIRI data were retrieved from the EUMETSAT through the EUMETCast Client Software (TelliCast) and the EUMETCast Key Unit (EKU) [31], with a satellite receiving station installed at Research Unit of Renewable Energy in the Middle Saharian at Adrar (URER-MS). This data consists of geographical arrays of 11136 x 5568 pixels (N-S by E-W) and a sampling distance defined to be exactly 1x1 km^2 at the sub-satellite point, The full earth image HRV is composed by 24 segment files, each consisting of 464 lines. This framework defines the so-called High Rate Image Transmission (HRIT) segment files [32,33]. In this study, satellite images from the HRV channel throughout the available dates of year 2010, therefore we proposed to deal this year which presents a minimum of missing files. Each satellite image has been set to the study area. The time resolution used for this study is 15 minutes.
Then the pixels containing the locations of the ground stations have been selected, for each scene over a station the data was taken as an average of a small window of 3 by

3 pixels, with the station located in the middle pixel, bringing the final spatial resolution to approximately 3x3 km. the data have been processed to calculate the hourly global radiation for each hour using the trapeze integration method applied to the instantaneous data. To accomplish all these operations and treatments, some open-source tools have been implemented in UNIX System for highly automatised processing of the SEVIRI data. Among the available open-source tools used are: EUMETSAT Wavelet Transform Software [32].

Ground Based Measurements

In the present study, Ground measurements are obtained from Solar Radiation Network which is composed only five stations equipped with different types of pyranometers, the three for Algerian National Office of Meteorology (ONM) stations (DAR-EL-BEIDA, ORAN-SENIA and IN-AMENAS), and other two radiometric stations of Renewable Energy Development Center (CDER) located in GHARDAIA and ADRAR. The coordinates and station elevation in meters are listed in table 1. And the geographical distributions of these stations are illustrated in the map presented in Fig. 1.

Table 1: Geographic information of the measurement sites in Algeria.

N	Station Name	Latitude (°)	Longitude (°)	Elevation (m)
1	DAR-EL-BEIDA	36.68	3.22	25
2	ORAN-SENIA	35.63	-0.6	90
3	ADRAR	27.88	-0.28	269
4	GHARDAIA	32.4	3.8	468
5	IN-AMENAS	28.05	9.63	561

The dataset gathered for this study is composed of one year of 10-minute interval measurements from ONM stations with the help of Eppley PSP pyranometers, and two years of 1-minute interval from CDER Station by means of Kipp & Zonen pyranometers. The Global horizontal and diffuse irradiance measurements over these stations are preprocessed and used. However, to ensure high quality of the measured data, Only data for a sun elevation angle greater than 10° were considered, and in order to conduct a homogeneous comparison and analysis of the model results, the above mentioned datasets (solar irradiance values in W/m2) were transformed to an hourly solar irradiation data (in W h/m2) by means of a trapezoidal integration. The hourly data were then checked against the simple quality controls methods used by the Royal Meteorological Institute of Belgium [34]. The physicals threshold tests were applied to the global solar irradiation using extraterrestrial radiation received on a horizontal surface and the measured diffuse radiation.

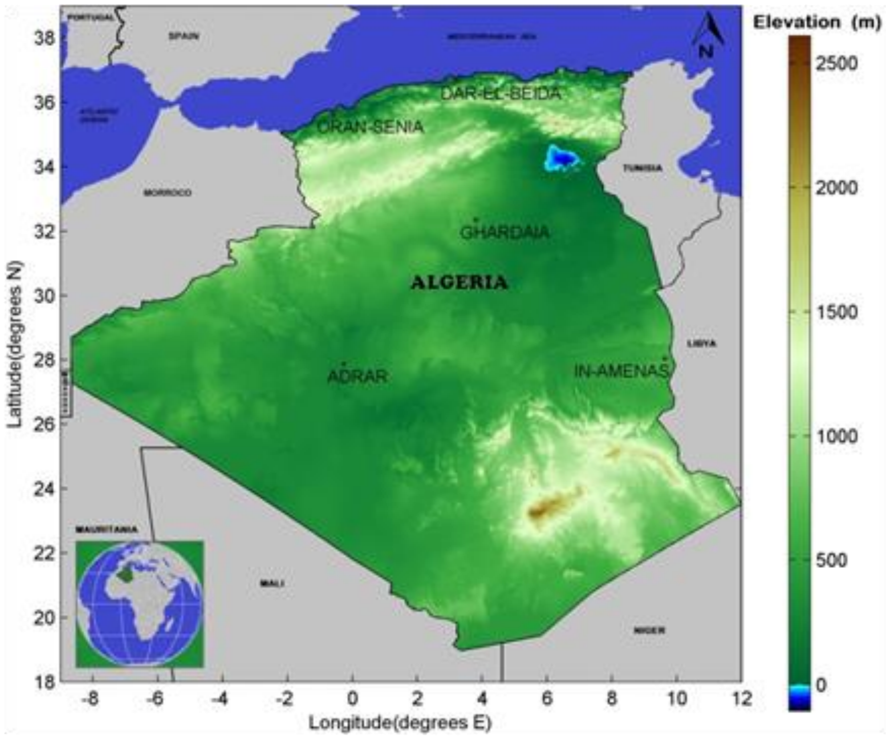

Figure 1: Elevation and Location Map of the five ground measurement stations (Basic Data of elevation map: GTOPO USGS).

Methodology

In this section, we will describe the proposed model and the techniques we will use to derive fundamental parameters of this model as the clear sky radiation from W.M.O simplified clear Sky model, the cloudy Albedo and cloud index from HRV data.

The proposal model

One of the most important factors that affect the solar radiation reached the earth's surface is the presence of cloud cover, which strongly increases both the absorption and scattering of solar radiation, varying from one cloud to another depend upon cloud type and their height. Some clouds, such as Cirrus are more transparent than others, Cumulonimbus are much more opaque to solar radiation. An exponentially decreasing model of the clear sky radiation based on cloud cover and cloud albedo is a good proxy for the estimation of global solar radiation. We thus propose the following model

$$Gn = G_{skc} e^{-2.5\, \alpha_n n_c} \tag{1}$$

Where α_n is cloud albedo and n_c is cloudiness. The value of 2.5 is a calibration constant calculated statistically from a learning statistical file, it was tuned using ground measurements at 12 UT in GHARDAIA and ADRAR during the year 2009.

The clear sky solar irradiance model

The estimation of clear sky global solar irradiance G_{skc} is based on model approved by the World Organization of Meteorology [3] in the following form, for the global solar radiation.

$$G_{skc} = (1250 - 50T_L)(1 + f)\,(\cos\theta_s)^{0.01(3T_L+10)}\ (W.m^{-2}) \tag{2}$$

With: θ is the solar Zenithal angle, T_L The Linke turbidity factor which characterizes the optical state of the pure atmosphere without clouds, and f is The Earth-Sun distance correction factor. In this model, the direct solar irradiance on a horizontal surface is given by:

$$I_{skc} = (900 - 20T_L)(1 + f)exp\left(\frac{-T_L}{12.6\ Cos\theta_s}\right)\ (W.m^{-2}) \tag{3}$$

And the diffuse radiation by clear sky is expressed as:

$$D_{skc} = 248(1 + f)(Cos\theta_v)^{\frac{T_L+5.7}{30}} \exp\left(-\frac{4}{T_L}\right)\ (W.m^{-2}) \tag{4}$$

The Linke turbidity factor TL was taken from the SoDa Web page (from Solar Data resource database at http://www.soda-is.com), created by SoDa Service database that contains climatological monthly of Linke turbidity factors processed by Remund et al. [35]. Monthly mean Linke turbidity factors for all station are averaged and applied in our study (see Table 2).

Table 2: Monthly average Linke turbidity factor

Month	Station				
	1	2	3	4	5
JAN	3.45	2.5	3.2	3.05	3.0
FEB	3.5	2.8	3.35	3.45	3.0
MAR	3.25	2.8	3.6	3.2	3.25
APR	4.0	3.3	3.75	3.85	3.35
MAY	3.95	3.45	4.05	3.95	3.65
JUN	4.05	3.9	3.95	4.2	3.55
JUL	4.25	4.1	4.1	4.45	3.65
AUG	4.0	4.1	4.1	4.5	3.65
SEP	4.15	3.8	4.0	4.15	3.6
OCT	3.3	2.9	3.75	3.85	3.45
NOV	3.4	2.6	3.6	3.35	3.05
DEC	3.0	2.25	3.5	3.25	3.0

Extraction of the model parameters from HRV data

Extraction of the albedo

The equation of radiative transfer in the upper atmosphere for a clear sky assuming there a homogeneous soil albedo α_s is given by:

$$E = E^o + \frac{G_{skc}.T(\theta_v)}{1 - s\,\alpha_s}\,\alpha_s \tag{5}$$

with: E^o $(W.cm^{-2})$ represent the diffuse radiation outside the atmosphere which can be captured by the satellite and also referred to as noise; G_{skc} represents global radiation reaching the ground by a clear sky $(W.cm^{-2})$; $T(\theta_v)$ is the total transmittance of direct radiation in direction pixel-satellite (dimensionless); θ_v angle of view of the sensor and s is the spherical albedo, and $(1 - s\,\alpha\_s)^{-1}$ is the multiple reflection the term (see Fig.2).

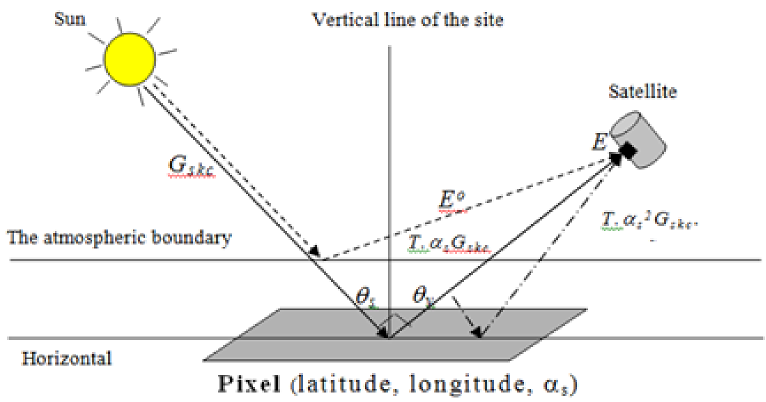

Figure 2: Sun-pixel-satellite radiative transfer model

In this study, we will use the approximate solution of the equation (5) using the approach described in Bachari [27]; the multiple reflection term is transformed to the first-order development one $(1 - s\,\alpha_s)^{-1} \approx (1 + s\,\alpha_s)$ and the equation (5) takes a parabolic shape form [23,27] given by:

$$E = E^o + G_{skc}.T(\theta_v)\,\alpha_s + s\,G_{skc}.T(\theta_v)\,\alpha_s^2 \tag{6}$$

Using solar irradiance measured at a given location on Earth with low zenith angles $(\theta_s < 30^o)$, it is usually assumed that the atmospheric ground-satellite transmittance can be approximated to sun-ground transmittance $T(\theta_v) \approx T(\theta_s)$. And for a deep blue sky, direct radiation is usually the largest contributor to the global radiation. Which gives atmospheric transmittance as follows:

$$T(\theta_s) \cong \frac{G_{skc}(1 - s\alpha_s)}{E_o(1 + f)} \tag{7}$$

And the Equation (7) was transformed to a parabolic form in function of α_s:

$$E = E^o + \left(\frac{G_{skc}^2}{E_1}\right)\alpha_s + s\left(\frac{G_{skc}^2}{E_1}\right)\alpha_s^2 \tag{8}$$

With: $E_1 = E_o(1+f)$ and E_o represents the solar constant its value 1368 $W.cm^{-2}$ and f is the correction factor of distance sun-soil (this factor depends on the number of days and $\cos(z)$ is the zenith angle). These terms was used to allow the albedo to be calculated for any given surface types [23]. And the net radiation under overcast conditions on top of the atmosphere is given by:

$$E = E^o + G'.T(\theta_v)\,\alpha_{cloud} \tag{9}$$

Where G' and T respectively global solar radiation and the atmospheric Transmittance for a clear, clean and dry atmosphere, the atmospheric transmittance can be calculated by:

$$T(\theta_v) = \frac{I_{skc}(\theta_v)}{886(1+f)Cos(\theta_v)} \tag{10}$$

Calculation of E from the Meteosat images

The HRV data stored as digital numbers coded in 10 bits, it must be transformed to a physical quantity, the following calibration equation was used to convert it to radiance values:

$$E = offset + slope.\mathrm{count} \tag{11}$$

E: is the spectral radiance measured by the SEVIRI sensor in $(\mathrm{mWm^{-2}sr^{-1}(cm^{-1})^{-1}})$. designated the reflectance in visible. offset and slope in $((\mathrm{mWm^{-2}sr^{-1}(cm^{-1})^{-1}})$ parameters are linear regression coefficients which are extracted for each channel SEVIRI from the Prolog file transmitted at the beginning of each receipt.

For a problem of homogeneity of physical units of the theoretical and satellite radiation used in the radiation model, we converted from units $(\mathrm{mWm^{-2}sr^{-1}(cm^{-1})^{-1}})$ to $(\mathrm{mWm^{-2}sr^{-1}(\mu m^{-1})^{-1}})$ which is provided by EUMETSAT [31] for MSG SEVIRI solar channels. The Conversion formula is given by:

$$\mathrm{E} = \frac{10\pi}{(\lambda_o)^2}\mathrm{E}.\Delta\lambda\ (\mathrm{Wm^{-2}}) \tag{12}$$

Where: λ_o is the central wavelength of the HRV channel and $\Delta\lambda$ its bandwidth ($\Delta\lambda = 0.88\ \mu m$). The value of solar radiation in the formula (7) is replaced by the new value in band relative to the HRV channel.

The Cloudiness information

Cloud index n_c [7,36] giving the attenuation of irradiance under clouds, is derived from the normalized instantaneous counts $\rho^t(i,j)$ for the time t and pixel (i,j), the most frequent low count of a given pixel for a given month $\rho^t_{ground}(i,j)$ and the most frequent high numerical count $\rho^t_{cloud}(i,j)$.

The cloud index for a time series can be written as follows:

$$n_c^t(i,j) = \frac{\rho^t(i,j) - \rho_{ground}^t(i,j)}{\rho_{cloud}^t(i,j) - \rho_{ground}^t(i,j)} \quad (13)$$

Several previous works have studied and discussed the cloud index extraction from Meteosat satellite image [36,37] Based on the method described in Hammer (2000) [36], adapted from Meteosat-7 to Meteosat-8 by Annette Hammer and Rolf Kuhlemann [26], the normalized counts $\rho^t(i,j)$ for the VIS and HRV Band are given by:

$$\rho = \frac{C - C_r}{\cos(\theta)} \quad (14)$$

C : is the numeric count, C_r: the radiometer offset determined for each channel (here HRV), $C_r = 51$, and we replaced the $\rho_{cloud}^t(i,j)$ by ρ_{max} given by:

$$\rho_{max} = \max(650, \rho_{cloud}^t(i,j)) \quad (15)$$

ρ_{max}: is the account correspondent a completely overcast sky, According to its optimisation within the SoDa project it should be defined in the way that 96% of all counts are below this value [38], transformed by Annette Hammer and Rolf Kuhlemann at the University of Oldenburg [26] from 8-bit values of Meteosat-7 (160) to 10-bit values of Meteosat-8. Cloud index is then defined by:

$$n_c^t(i,j) = \frac{\rho^t(i,j) - \rho_{ground}^t(i,j)}{\rho_{max} - \rho_{ground}^t(i,j)} \quad (16)$$

Results and Discussion

To validate our results, a comparison between the estimated and measured values is important. The ground measurements recorded in five different stations, two located in the North, with semi-arid Mediterranean climate (DAR-EL-BEIDA and ORAN-SENIA), two more located in South into the warm desert region (ADRAR and IN-AMENAS), and one located in an intermediate area (GHARDAIA) which is considered an arid and dry area. The instantaneous measure of the solar irradiance values expressed as W/m^2 were transformed to an hourly solar irradiation data (in Wh/m^2) by means of a trapezoidal integration. And the hourly estimated values result from the integration of instantaneous radiation from the MSG data on a time series with periodicity of instantaneous values (e.g. 00, 15, 30 and 45 minutes). Only data with three valid records in given hour were retained. The daily values are obtained by summing of the results of hourly values.

The evaluation was carried out using some statistical scores and the correlation coefficient, this statistical measures are the most commonly applied to the evaluation of the models of solar radiation estimations [39]. The basis of the statistical scores like Mean Bias Error (MBE), root-mean square error (RMSE) and correlation coefficient (CC) are used. They are given by the following relations:

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(X_{Est,i} - X_{Meas,i}\right) \tag{17}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_{Est,i} - X_{Meas,i}\right)^2} \tag{18}$$

$$CC = \frac{\sum_{i=1}^{N}\left(X_{Est,i} - \bar{X}_{Est}\right)\left(X_{Meas,i} - \bar{X}_{Meas}\right)}{\sqrt{\sum_{i=1}^{N}\left(X_{Est,i} - \bar{X}_{Est}\right)^2} \times \sqrt{\sum_{i=1}^{N}\left(X_{Meas,i} - \bar{X}_{Meas}\right)^2}} \tag{19}$$

Here the indices *Meas* and *Est* are respectively the hourly or daily Measured/Estimated from irradiation values and N is the number of evaluated pair's data. Besides these scores, there are the corresponding normalized ones, the relative MBE and relative Root Mean Square Error (RMSE) rMBE and rRMSE, respectively. The two normalized score are computed as follows:

$$rMBE = 100 \times \left(\frac{1}{N}\sum_{i=1}^{N}\left(\frac{X_{Est,i} - X_{Meas,i}}{X_{Meas,i}}\right)\right) \tag{20}$$

$$rRMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{X_{Est,i} - X_{Meas,i}}{X_{Meas,i}}\right)^2} \tag{21}$$

Hourly Data

The results of validation of the satellite-estimated model with ground measurements were reported in Fig. 3, Fig. 4 and Fig.5. Scatter graphs between estimated values for the hourly global solar irradiation and ground measurements values over all study period for each station. The linear regression lines (red), the equations for the regression lines are also given together with the number of evaluated pair's data used in each calculus (NDATA), the relative MBE errors, the relative RMS errors and the correlation coefficients.

In terms of hourly estimation, the model underestimates the irradiation values with relative rMBE of 0.36% in IN-AMENAS, and overestimates the values of the other stations with rMBE placed in the range of 0.6-1.7%, the lowest value recorded in ADRAR (0.66 %), and the highest value recorder in DAR-EL-BEIDA (~1.7 %).

In the south region, the rRMSE is in the range of 12-15% (see Figures 4 and 5). For the North station the model exhibits a quite large rRMSE which is greater than 19%.

The correlation between estimated and measured values for all stations ranges between 0.94-0.98. Table 3 shows the statistical scores of hourly values for the all station

Table 3: annually comparison between measured and estimated hourly irradiation data (The number of evaluated pairs data, MBE, RMSE and R).

Station	1	2	3	4	5
N	3397	3269	3411	3438	2579
MBE (Wh/m^2)	7,27	5,19	3,30	3,32	-2,01
rMBE (%)	1,71	1,11	0,66	0,69	-0,36
RMSE (Wh/m2)	90,52	89,93	71,20	72,92	71,18
rRMSE (%)	21,28	19,15	14,15	15,08	12,65
R	0,946	0,958	0,972	0,968	0,977

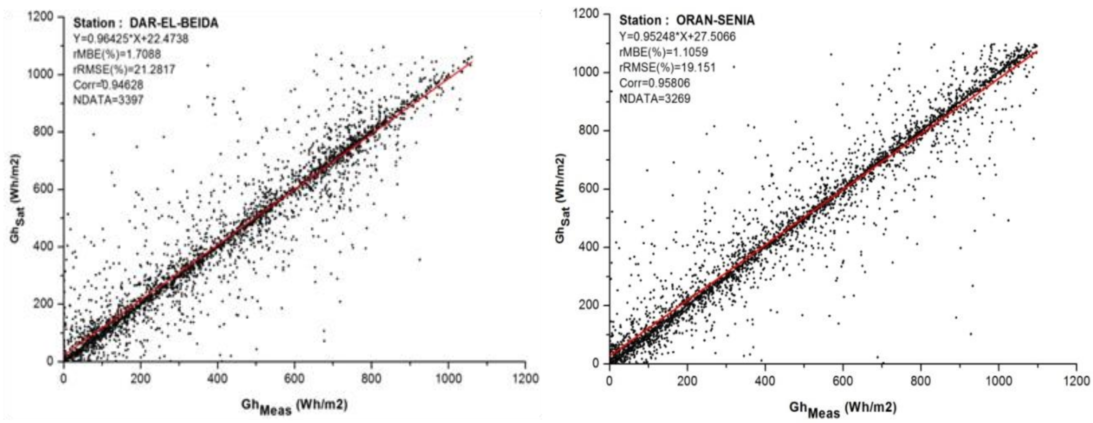

Figure 3: Density scatter plot of Estimated vs. Measured hourly irradiation in DAR-EL-BEIDA and ORAN-SENIA

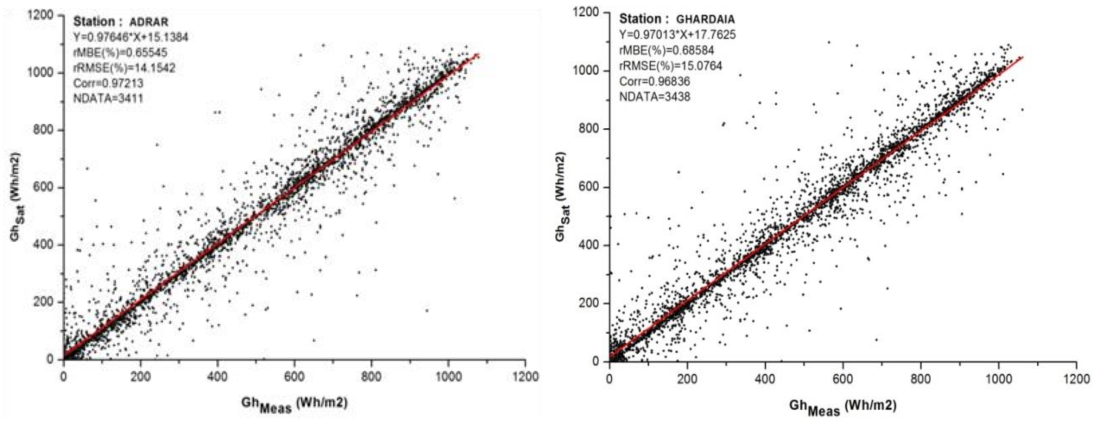

Figure 4: As for Figure 2, but for GHARDAIA and ADRAR

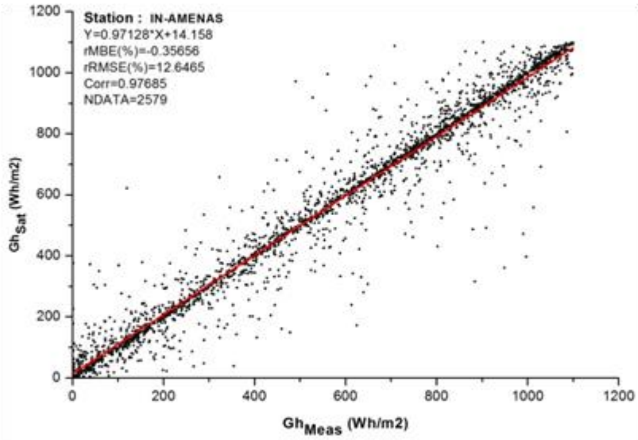

Figure 5: As for Figure 2, but for IN-AMENAS

During the selected period, the seasonal variation and distribution of statistic score values (rMBE, rRMSE and R) were calculated for each station. The results are presented in Table 4. The seasonal values of relative MBE error variation differ on the five selected of stations, with a mix of positive and negative, indicating respectively, overestimation and underestimation, except DAR-EL-BEIDA and ADRAR where the value is positive all over the year. The rMBE in its absolute value ranges between 0.1 and ~4.3. Additionally the MBE values are positive for all the station in autumn.

During spring and summer, the model has the smaller relative RMSE almost all stations, a maximum of 17.3% is observed in DAR-EL-BEIDA. In this period, the climate is the most stable of the year; the sky is usually clear and solar irradiations derived from satellite data are similar to ground measurements. On the other hand, the winter and autumn have the greater relative RMSE, with a perturbed climate marked by frequent cloudy periods more marked in the Northern sites, except in IN-AMENAS where the values does not exceeded 14% over the year.

Similarly, the best correlation coefficients between estimated and measured values are obtained in spring and summer for all the stations, except IN-AMENAS which shows the higher values in autumn. This region is characterized by the sand winds phenomenon, but it is less frequent during this period of the year.

Table 4: As for Table 3, but for Seasonal evaluation.

N_{st}	N	MBE(Wh/m^2)	rMBE(%)	RMSE(Wh/m2)	rRMSE(%)	R
W I N T E R						
1	700	13,31	4,29	97,23	31,36	0,914
2	541	10,95	3,68	82,16	27,61	0,930
3	723	6,36	1,62	73,73	18,75	0,956
4	686	6,90	1,86	76,66	20,72	0,948
5	634	-2,14	-0,38	80,00	14,09	0,972

S P R I N G						
1	871	7,31	1,80	87,50	21,57	0,952
2	922	5,03	1,01	96,73	19,45	0,954
3	924	1,43	0,27	66,47	12,34	0,977
4	928	0,83	0,15	66,17	12,33	0,976
5	665	-1,54	-0,29	70,55	13,22	0,977
S U M M E R						
1	928	5,77	1,10	90,55	17,30	0,950
2	974	-3,54	-0,60	85,84	14,48	0,964
3	977	0,67	0,11	66,12	11,37	0,979
4	961	-0,94	-0,17	75,25	13,40	0,969
5	601	-7,46	-1,28	69,44	11,91	0,977
A U T U M N						
1	898	4,06	0,94	87,91	20,31	0,939
2	832	11,85	2,92	91,61	22,55	0,944
3	787	5,94	1,28	79,79	17,16	0,959
4	863	7,89	1,83	74,15	17,23	0,959
5	679	2,49	0,44	64,25	11,29	0,982

Daily data

The following subsections present the evaluation results related to the daily values of global solar irradiation. The values of daily irradiation calculated from this model were compared with those obtained from the measurements. The results were reported in Fig. 6, which represent estimated versus measured values for the validation data set over all study period and for all the station, and the statistic results are presented in Table 5.

As shown in Table 5, the model overestimates the daily values with rMBE placed in the range of ~0.6-1.5% at most of station, except in IN-AMENAS, the model underestimates the values with the rMBE of 0.6%.

The rRMSE is in the range of 4.6-12.9%, as it can be seen in Table 5, for the North station the model exhibits a quite large MBE and RMSE. The correlation between estimated and measured values is 0.96-0.98.

Table 5: Comparison between measured and estimated daily irradiation data.

Station	1	2	3	4	5	All
N	336	313	337	326	313	1625
MBE(Wh/m^2/Day)	59,96	29,33	32,50	30,03	-26,21	25,76
rMBE(%)	1,50	0,67	0,67	0,64	-0,63	0,58
RMSE(Wh/m^2/Day)	475,78	452,35	227,94	234,52	193,60	339,48
rRMSE(%)	11,89	10,28	4,70	4,98	4,64	7,67
R	0,965	0,974	0,989	0,988	0,985	0,979

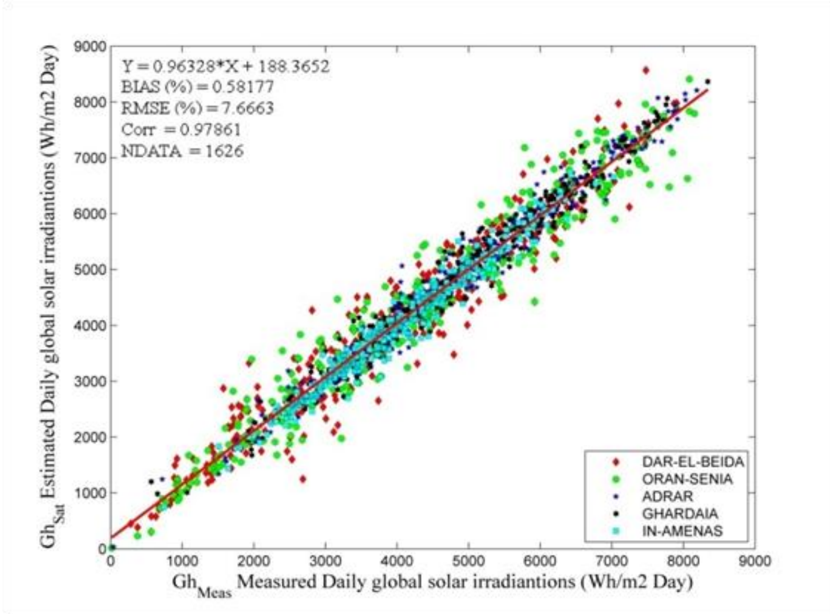

Figure 6: Density scatter plot of Estimated vs. Measured daily irradiation for all stations

The estimation of the hourly and daily global solar radiation shows promising results compared with the current literature (e.g., rRMSE) between 11% and 33% on hourly basis, and between 7% and 13% on a daily basis, as cited in Refs. [15; 17-18; 22;24; 28-30]. The performance of the different methods cited in literature that use the Meteosat data and ground measurements of some stations in Europe and North Africa are summarized in Table 6, by their relative RMSE and the correlation coefficient, on the hourly and daily time scale.

Table 6: Summarizes the results of several authors use Meteosat data.

Method	Temp. Res.	rRMSE	R	Reference
Heliosat 1	Hourly	14%-30%	-	Rigollier et al. (2004) (Europe 1983-2003)
Heliosat 2	Daily	9%-16%	-	
	Hourly	18%-45%	0.83-0.90	Rigollier et al. (2004) (Europe 1995)
	Hourly	18%-45%	0.83-0.90	Moradi et al., (2009)
	Daily	10%-20%	0.94-0.95	(Iran 2004)
Heliosat 3	Hourly	17%-46%	0.86-0.98	Beyer et al. (2009) (Europe 1995)
		-	0.90-0.98	P. Ineichen, May 2009 (Europe 2006)
Solemi (MESoR)	Hourly Daily	-	0.91-0.98 0.98-0.99	Beyer et al. (2009) (Europe 1996-2000)

GISTEL SICIC	Hourly Daily	7%-23% 9%-30%	0,88-0,97 0,81-0,94	Mefti et al. (2008) Algeria (1994-1995)
GISTEL	Daily	-	0,96	Chaabane et al. (2002) (Tunisia, 1995)
Modified Heliosat	Hourly Daily	17%-21% 8%-10%	0.96 0,98	Haurant et al. (2012) (Corsica 2004-2006)
GISTEL	Hourly Daily	- -	0,77 0,96	Meziani et al. (2013) (Algeria, 2011)

Conclusion

The proposed model for global solar radiation estimation has been evaluated using five Algerian ground-based measurements during the Year 2010. This model is in part based on an exponential function model integrating cloud albedo computation using an approximate form of the atmospheric radiative transfer (RT), that are described in the methodology section.

The Initial results show that the standard deviation obtained with this method is similar to that obtained with current methods. In general, the relative error does not exceed 10% of the global irradiation. For hourly values of the global horizontal irradiation, the coefficient of correlation ranges from 0.91 to 0.98. The relative MBE comprises between-2% and +4%, and the RMSE between 11% and 31%.

In the case of daily estimations, the accuracy is better than for hourly values, the results in south stations show a general positive bias with a slightly tend to overestimation excepting for IN-AMENAS with negative bias. For the north stations, it is observed that the model produce a quite large bias. The model provides estimates of daily values, with an excellent level of correlation with the values measured (CC greater than 0.96) and with relative RMSE smaller than 12%.

Comparisons with other models from the literature show that our model offers similar or sometimes better performances for daily values, compared with the recommended statistic score values. We concluded that the results depend on the geographical location of the site and the treated period.

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