Study of Atmospheric Turbidity on Different Algerian Sites Using a Model and MSG Satellite Images

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STUDY OF ATMOSPHERIC TURBIDITY ON DIFFERENT ALGERIAN SITES USING A MODEL AND MSG SATELLITE IMAGES

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ABSTRACT

The temporal analysis of solar radiation at ground level provides essential elements on atmospheric transmission and its evolution. This is especially important for various applications such as solar power systems, optical communications, etc. This article therefore deals on the one hand with the estimation of Global Solar Radiation at Ground Level (GSRGL) from MSG3 satellite images of different spectral channels, a very important parameter for various sites in Algeria considered as privileged areas for the conversion installation PV. The paper also deals with the estimation of the Linke factor T_l linked to the Angström parameter β which provides information on the quantity of aerosols present in the atmosphere of the sites considered. A reminder of the method previously used to estimate GSRGL is first performed. Improvements made to address outstanding issues are then outlined. We then present a new method for estimating T_l at the time of measurements, an input parameter of the clear sky-model ESRA2 useful for the improved method. The results obtained for T_l using ground meteorological measurements are presented and compared to those obtained from satellite data. The validation of the improved method from GSRGL measurements carried out in Ghardaïa (southern Algeria) is finally presented and discussed. We conclude that the presented method can now be used to estimate GSRGL for potential Algerian solar sites.

***Index Terms*—** Solar radiation, MSG , Clear-sky models, Linke turbidity factor.

1. INTRODUCTION

Radiative transfer in the Earth's atmosphere is strongly influenced by turbidity resulting from aerosols and hydrometeors. It is therefore important to know its temporal properties at a given location on the ground, especially in clear-sky conditions when the objective is to optimize the solar energy captured there. Various methodologies are available to study the turbidity at a ground site, either by using instruments dedicated to its measurements or from solar radiometric measurements and clear-sky models. The second methodology is adopted here as the previous study for the estimation of the Linke turbidity factor (T_l) in Tamanrasset (southern Algeria) [1]. It showed that the clear sky model ESRA2 was well suited to achieve this goal with solar radiometric measurements. The need to estimate T_l to land areas where there are no ground measurements is also expressed. The solution was to use space observations to estimate the Global Solar Radiation at Ground Level (GSRGL), in particular by using both satellite images and the ESRA2 model [2]. This method recalled in Section 3.1, was therefore implemented using Meteosat Second Generation (MSG) images and tested over a year of solar radiometric measurements acquired at Ghardaïa (southern Algeria). The results obtained showed its effectiveness in estimating GSRGL thanks in particular to the ESRA2 model, regardless of the used MSG spectral channel (see Section 4.1). The main advantage of using the ESRA2 model is that the key parameter on which it depends, the Linke factor T_l, can be obtained from meteorological measurements taken on site or from satellite databases (see Section 3.4). However, the developed method still presented some issues, especially in the case of the estimation of solar radiation in cloudy weather. To overcome these issues, method improvements have been made using in particular the MSG NIR channel (1.6 µm) (see Section 3.2 and 4.2).
Let us first start by presenting the ground and satellite data used in this work.

2. GROUND AND SATELLITE DATA

2.1. Ground data

The ground data are global slar radiation measurements acquired between January 1 and December 31, 2015 with the Ghardaïa radiometric station located at $32.38°N$, $3.78°E$, 450 m a.s.l. Instruments and methods for data collection are the same as those described in detail in Zaiani et al. (2021) [1]. The station is made up of three instruments to measure the direct, diffuse and global components of solar radiation every minute as well as temperature and humidity. They are calibrated every three years and cleaned two to three times a week depending on weather conditions.

2.2. MSG satellite data

The images come from the MSG geostationary satellite. It scans the full disk of the Earth 4 times per hour and provides data in 12 spectral channels: 3 solar channels (0.6, 0.8 and 1.6 µm), 8 infrared channels (3.9, 6.2 , 7.3, 8.7, 9.7, 10.8, 12.0, and 13.4 µm) and a high resolution broadband (HRV) visible channel (0.3–0.7 µm). The spatial resolution at nadir is $1 \times 1 km^2$ for the high-resolution channel and $3 \times 3 km^2$ for all other channels. The images used come from the channels VIS06 (0.6 µm), VIS08 (0.8 µm), HRV and NIR (1.6 µm).

3. METHOD FOR ESTIMATING GSRGL

Now, let us introduce Heliosat-2 and the improvement made.

3.1. The Heliosat-2 method

The Heliosat-2 method has been widely used to estimate solar radiation at regional and global scales. It makes it possible to estimate the GSRGL from satellite observations. The method assumes that the reflectance at the top-of-atmosphere is approximately proportional to the cloud transmission [3].
Each MSG image pixel has its value related to the reflectance Ref [unitless]. The radiance Rad $[W/m^2/sr]$ is obtained by:

$$Rad = \frac{I * Ref}{d^2} \tag{1}$$

where d and I stand for the Sun-Earth distance $[AU]$ and the solar spectral irradiance in the selected channel. Equation (1) comes from the MSG reflectance product header.
The radiation attenuation in the Earth's atmosphere results in the clearness index factor k_c and the cloud index n, which respectively express the amount of cloudiness and the radiative extinction of clouds. The cloud index n is given by:

$$n = \frac{Ref - Ref_c}{Ref_n - Ref_c} \tag{2}$$

Ref_c and Ref_n respectively represent the reflectance of a clear sky and a completely overcast sky.
The clearness index k_c is then deduced as follows [4]:

$$n = \begin{cases} n < -0.2 & k_c = 1.2 \\ -0.2 < n < 0.8 & k_c = 1 - n \\ 0.8 < n < 1.1 & k_c = 2.0667 - 3.6667n + 1.667n^2 \\ n > 1.1 & k_c = 0.05 \end{cases}$$

Ref_c and Ref_n are calculated from a series of images taken at the same time (noon). Ref_n is then the highest value of the reflectance obtained on cloudy days while Ref_c is the lowest on cloudless days [3].
The GSRGL G_e is finally estimated by $G_e = k_c G_c$ where G_c is the GSRGL calculated from a clear-sky model.

3.2. The Heliosat-2 method, a new calibration approach

The estimation of solar radiation in cloudy day is more complex due to the attenuation and/or the low reflectivity of the solar flux by the clouds. Heliosat-2 has therefore been modified to provide a better estimate of solar radiation under different cloudy conditions. For this, the method uses the NIR spectral channel (1.6 µm) sensitive to the water content to calculate the cloud index n_{new}. It is calculated as follows:

$$n_{new} = \frac{Rad - Rad_c}{Rad_n - Rad_c} \tag{3}$$

Rad_c is the radiance of the considered day if it had been clear. It is obtained by linear interpolation from the series of clear days available. Rad_n is the radiance of the cloudiest day in the dataset. k_c and G_e are then calculated as in Section 3.1.

3.3. The clear-sky model ESRA2

Several clear-sky models dependent on the Linke turbidity factor (T_l) have recently been tested to estimate GSRGL with MSG images from the VIS06 and VIS08 channels [2]. The conclusion was that the ESRA2 model [1] was the most reliable for estimating this parameter. This work is a continuation of the GSRGL estimation using the Heliosat-2 - ESRA2 combination and HRV images from MSG. The method will first be validated for Ghardaïa to then be used on other potential Algerian sites. The hard point of using ESRA2 is that it depends on T_l which must be estimated if its values are not available for the given site. This is the subject of the next section.

3.4. Estimation of Linke's turbidity factor

The Linke turbidity factor T_l can be estimated from measurements of temperature and relative humidity taken on the ground or obtained from satellite databases. The factor T_l is indeed calculated using the following empirical formula [5]:

$$T_l = 0.1 + \beta\,(16 + 0.22 w_p) + \frac{h + 85}{39.5 exp(w_p) + 47.4} \tag{4}$$

where β, w_p, and h are respectively the Angström turbidity coefficient, precipitable water vapor, and Sun elevation angle. w_p can be obtained from ground measurements of temperature T and relative humidity ϕ with the formula below [1]:

$$w_p = 0.493\,\frac{\phi}{T}\,exp(26.23 - \frac{5416}{T}) \tag{5}$$

Total precipitable water (or column water-vapor amounts) (w_p) can also be obtained from the MODIS satellite database in the absence of meteorological measurements.
A new methodology based on MERRA 2 data (`https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/`) is proposed to calculate the Angstrom coefficient β. The Broadband Aerosol Optical Depth (BAOD) obtained from MERRA

2 is first used to deduce the transmission due to aerosols: $T_a = exp(-m_a\ BAOD)$ where m_a is the air mass.
T_a is then fitted with a model to estimate the aerosol transmittance β using a least mean squares fitting algorithm. The broadband transmission model is given by [6]:

$$T_a = (0.12445\alpha - 0.0162) + (1.003 - 0.125\alpha)\ exp[-\beta\ m_a\ (1.089\alpha + 0.5123)] \quad (6)$$

Figure 1 plots the temporal variation of T_l obtained from measurements made on the Ghardaïa site and from MODIS: a very good correlation is observed with a coefficient R=99.6%.

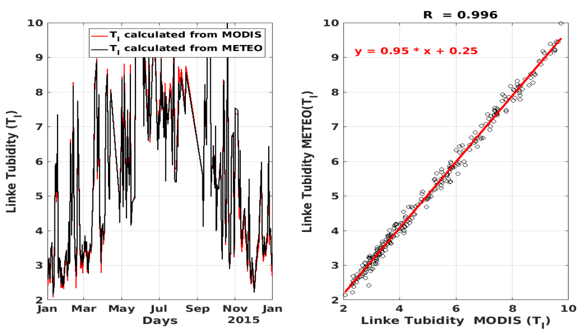

Fig. 1: Left: Temporal variation of T_l estimated from water vapor data obtained from MODIS (red line) and from meteorological measurements made in Ghardaïa (black line).
Right: good correlation between the two T_l datasets.

4. RESULTS

4.1. Using the Heliosat-2 method

MSG images from the year 2015 were processed with the method detailed in Section 3.1. The daily variations of the cumulative Hourly Global Solar Irradiance (HGSI) were calculated using MSG images from channels VIS06, VIS08 and HRV. The results were compared with those obtained from GSRGL measurements collected in Ghardaïa during the same period. Figure 2 shows, for illustrative purposes, the daily variations of the cumulative HGSI (Wh/m^2) obtained from HRV images superimposed on those obtained from measurements (left panel). The best results are obtained from the HRV images with a resolution of 3 km at nadir. An rmse of 612.57 Wh/m^2, a mape of 10.57%, an mbe of 128.69 Wh/m^2 and a correlation coefficient R of 93% were found with HRV images. Figure 2 on the right plots the linear regression between the cumulative HGSI obtained from HRV images and from measurements. The statistical error and the correlation coefficient were respectively 711.15 Wh/m^2, 10.80%, 156.96 Wh/m^2 and 91% for the channel VIS08 and equal to 671.34 Wh/m^2, 10.31%, 193.72Wh/m^2 and 92% for channel VIS06. However, this method still has some problems.

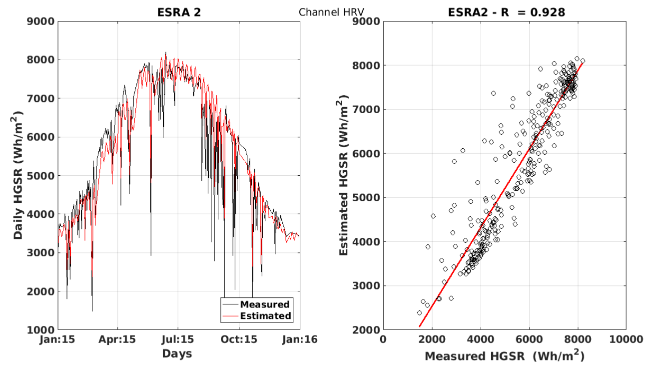

Fig. 2: Left: Daily variations of the cumulative HGSI estimated with HRV images (red) and from measurements (black). Right: Linear regression between the two quantities.

The examples in Fig. 3 on left corresponding to the clear day of January 3, 2015 show that the measured GSRGL is well estimated while the case of the completely cloudy day of February 17, 2015 shows clearly the limitations of the method (right panel). Indeed, this plot shows that the GSRGL estimate from the VIS06 channel does not present variations contrary to the measurements. However, the HRV and VIS08 channels show some variations but not in phase with the measurements.

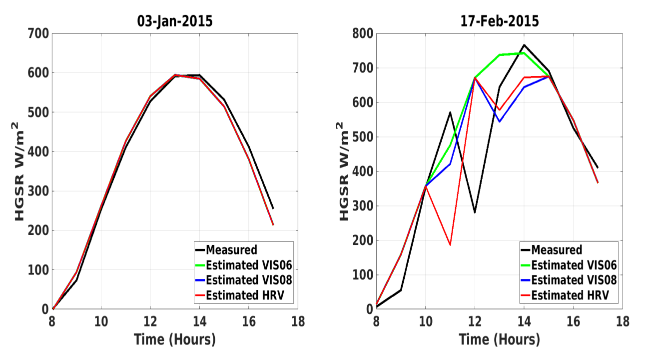

Fig. 3: Estimated GSRGL (red) superimposed on that measured (black) in a clear (left) and a cloudy (right) day.

4.2. Using the improved method

The limitation of the Heliosat-2 method as seen in Section 4.1 led us to use the improved method (see section 3.2). The previous results showed that HRV images were appropriate for our concern. The same time series was therefore taken again with also the NIR images for comparison purposes. The same analysis as in Section 4.1 was then performed i.e. a statistical analysis between the measured and the estimated daily cumulative HGSI from the HRV and NIR channels. Better results were obtained with the NIR images. An rmse of 581.62 Wh/m^2, a mape of 9.34%, an mbe of 160.93 Wh/m^2 and a correlation coefficient R of 99.4% were found. The daily variation of the cumulative HGSI obtained from ground measurements on which is superimposed that estimated from the NIR channel are plotted in Fig. 4 (left) where all days, clear or cloudy, have been taken into account. The linear regression in Fig. 4 (right) confirms the good correlation between the cumulative HGSI from ground measurements and NIR images. The improvement is also clearly visible in Fig. 5 where the same clear and cloudy days in Fig. 3 are compared. The right panel of Fig. 5 shows that the method significantly improves the GSR estimate for the cloudy day of February 17, 2015.

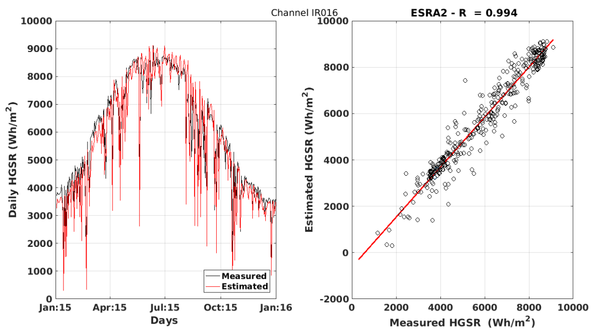

Fig. 4: Left: Cumulative HGSI estimated from NIR images (red) and ground measurements (black). Right: Linear regression between measurements and estimates.

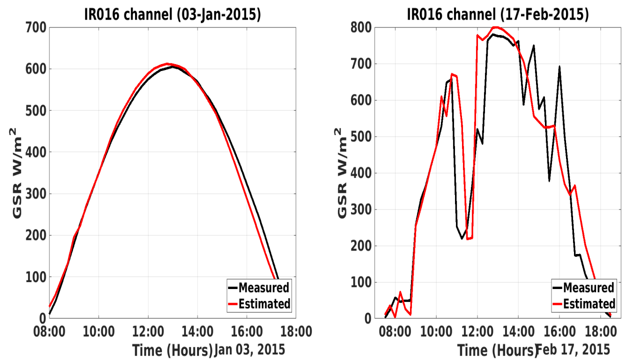

Fig. 5: Estimated GSRGL (red) superimposed on that measured (black) in a clear (left) and a cloudy (right) day.

5. CONCLUSION

The statistical method combining Heliosat-2 and the clear-sky model ESRA2 was used to estimate the GSRGL from MSG images. ESRA2 however depends on the turbidity factor at the time of observation. This therefore led us to propose a new method to estimate it everywhere from meteorological data obtained from ground or satellite databases. Solar radiation measurements carried out in Ghardaïa made it possible to evaluate the statistical method. MSG images recorded during the year 2015 and measurements taken during the same period in Gharadïa were used. The MSG VIS06, VIS08 and HRV (broadband) channels were first used to perform the comparison between measured and estimated GSRGL. The results showed that HRV images are best suited to estimate the Hourly Global Solar Irradiance (HGSI) with the statistical method. This is clearly visible when comparing the daily variation of the cumulative HGSI obtained from ground and from HRV images. The calculation of the statistical error also confirms this by obtaining the lowest values for this channel compared to the others, with in addition a better correlation coefficient with the measurements (R=92.8%). The statistical method is very promising in the case of clear days but the results are less good in the case of cloudy days. This led us to improve the statistical method by using in addition the images of the NIR channel of MSG. Using the improved statistical method with the same MSG dataset showed that the results with the NIR images are better than those obtained with the HRV ones. The correlation coefficient between measurements and estimates is 99.4%. The improved method is able now to significantly handle any day, clear or cloudy. It can now be used on all Algerian sites to estimate GSRGL.

6. REFERENCES

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