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Research Paper

Clear Sky Global Surface Solar Irradiance Estimation from Bird & Hulstrom Radiometric Model/MODIS Atmospheric Data Combination

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ABSTRACT

Estimation of solar irradiance received on the ground is essential in many solar energy applications, particularly those relying on concentrating solar technologies. In this work, we propose a model to estimate the spatial distribution of global Surface Solar Irradiance (SSI) from a Bird & Hulstrom radiometric model/MODIS atmospheric data combination. The theoretical model selected is the radiometric model of Bird & Hulstrom, and it has been modified to take into account the effect of the atmosphere by adding a transmittance function that obeys the Beer-Lambert law, implemented with atmospheric parameters (water vapor, ozone, aerosols, etc.) from the Moderate Resolution Imaging Spectroradiometer (MODIS) atmospheric products. The effectiveness of the proposed methodology is tested on the Algerian territory. The obtained results show that the proposed approach concurs with results provided by the tested Meteosat data-based method while providing SSI maps of better spatial resolution. Moreover, the obtained solar irradiances show a root mean square error of about 140 Wh.m-2 in comparison with the Copernicus Atmosphere Monitoring Service (CAMS) radiation extracted from the Solar Radiation Database for the environment (SoDa) server.

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1. Introduction

Radiometric models for solar irradiance estimation received on the ground are theoretical, empirical, or semi-empirical models, which take into account the diffusion and absorption effects undergone by solar radiation in crossing the atmosphere. They are based on the determination of atmospheric constituent transmittance coefficients from some in-site parameters, such as meteorological parameters (relative humidity, ambient temperature, atmospheric pressure) and site geography (latitude, longitude, and altitude).

Nevertheless, these models remain theoretical which are mostly clear sky models, do not reflect the real sky conditions, and require meteorological parameters, which are not always available. The choice is then dictated by the available data nature and the sought precision. Thus, the sole use of these models can lead to unreliable estimations that can significantly influence the installation and sizing of solar systems.

The complementary approach based on satellite atmospheric data is therefore essential as a benefit to the accuracy of these estimates. In this work, the proposed approach is a parametrization method, with a known satellite-based atmosphere as well as surface state information. The parameterization schemes generally consist of schemes for clear skies and clouds (Figure 1).

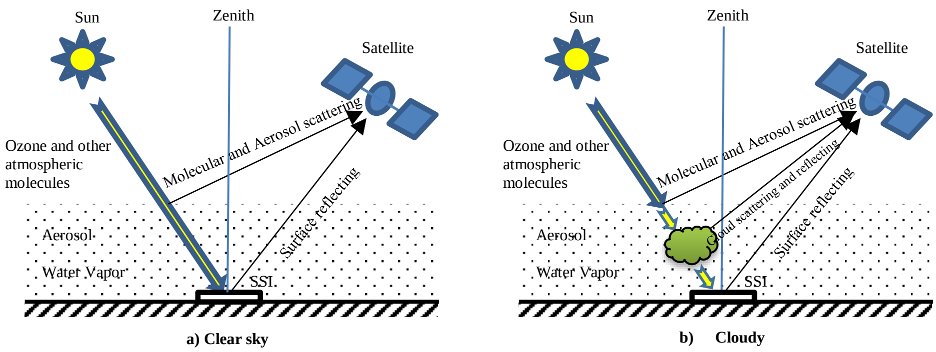

Fig 1. Simplified satellite observations of SSI according to one-dimensional radiative transfer theory for a) clear sky and b) cloudy sky [1]

In clear-sky parameterization schemes, the absorption of permanent gases, ozone absorption, water vapor absorption, Rayleigh scattering, and aerosol scattering are often parameterized separately. This means that the radiative extinctions caused by various atmospheric constituents are treated independently. This feature has at least two advantages: 1) a certain physical basis and 2) the ability to quickly identify problems when poor estimates of SSI occur. The challenge of such methods lies in their explicit requirements for atmosphere and surface parameters [1]. According to these assumptions, the developed parametrization algorithm is based on the clear-sky Bird & Hulstrom time model [2] and uses the Moderate Resolution Imaging Spectroradiometer (MODIS) atmospheric profile product [3]. MODIS atmospheric products provide satellite-based products regarding aerosols, water vapor, ozone, etc. [4], which represent better-inputting parameters for the generation of regional or even global SSI products than traditional climatological data [1].

Validations are performed according to the Copernicus Atmosphere Monitoring Service (CAMS) radiation extracted from the Solar Radiation Database for the environment (SoDa) server24. The CAMS radiation was extracted from the SoDa server [5]. This database is made from the Heliosat-2 method, which processes Meteosat Second Generation satellite images, collected between 3:00 UT to 20:45 UT (72 images) to compute the 15-minute Global Irradiance values over a Horizontal plane (GIH) [5]. The method produced by MINES ParisTech, in November 2002, partly with the support of the European Commission (project SoDa, contract DG "INFSO" IST-1999-12245), converts images acquired by meteorological geostationary satellites, such as Meteosat (Europe), GOES (USA) or GMS (Japan), into data and maps of solar radiation received at ground level. The original Heliosat-2 method is described in [6] and [7].

The comparison with this SSI estimation source is due to that the Heliosat-2 method is a satellite images-derived model, using pyranometric measurements performed by thirty-five meteorological stations to assess the performances [5], which gives the validation more reliability and accuracy.

The remainder of this paper is organized as follows: the materials and methods used in this study are described in Sec. 2. The main obtained results and the discussions are presented in Sec. 3. Finally, conclusions are given in Sec. 4.

2. Bird & Hulstrom radiometric model/MODIS parametrization method

Key terms in the considered equations within this method are presented in Table 1. SSI can be estimated using various parameterization schemes based on prior knowledge of the atmosphere and surface state. Radiometric models are widely used in the solar community, they are composed of simple algebraic expressions, where the inputs are from readily available meteorological data, attempting to take into account the cumulative effects of aerosols, water vapor, ozone, and Rayleigh (molecular) scattering upon sunlight reaching Earth's surface [2].

Furthermore, the development of quantitative remote sensing technology, like MODIS, with satellite-based products regarding aerosols, water vapor, ozone, etc. are currently available, and they provide better-inputting choices for the generation of regional or even global SSI products than traditional climatological data. In this context, a Bird and Hulstrom model parametrization scheme from MODIS atmospheric products is proposed (Figure 2).

Table 1. Key variables in the computing scheme [2].

Term	Description
SSI	Global Solar Irradiance ($W.m^{-2}$)
T_r	Rayleigh Molecular Diffusion Atmospheric Transmittance
T_a	Aerosol Attenuation Atmospheric Transmittance
T_w	Water Vapor Absorption Atmospheric Transmittance
T_o	Ozone Absorption Atmospheric Transmittance
T_u	Uniform Gas Mixtures Atmospheric Transmittance (CO_2 and O_2)
D_r	Rayleigh Diffuse Irradiance ($W.m^{-2}$)
D_a	Aerosol Diffuse Irradiance ($W.m^{-2}$)
D_m	Earth-Atmosphere Multireflection Diffuse Irradiance ($W.m^{-2}$)
T_{aa}	Aerosol Absorption Atmospheric Transmittance
T_{as}	Aerosol Diffusion Atmospheric Transmittance
M_r	Relative Air Mass
M_a	Air Mass at Corrected Pressure

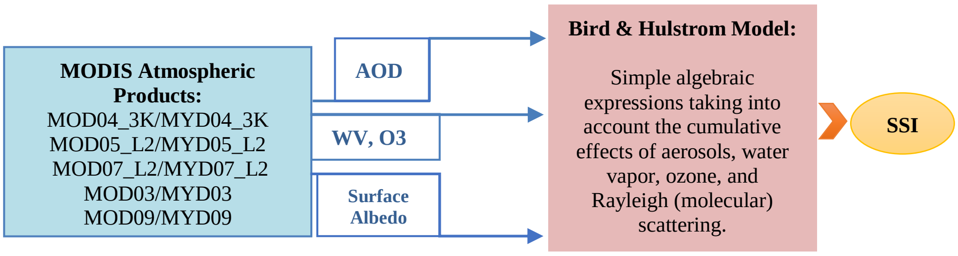

Fig 2. Diagram of Bird and Hulstrom model/MODIS parametrization scheme.

The Bird & Hulstrom model gives an estimate of direct and diffuse irradiance under clear sky conditions, calculated as a function of individual transmittances and scattering coefficients of major atmospheric constituents (ozone, water vapor, and aerosols) [2]. The global irradiance under clear sky G is given by [2]:

$$G = {(I_d + D)}/{(1 - r_s r_a)} \tag{1}$$

The incident direct beam irradiance under clear sky I_d is calculated as [2]:

$$I_d = I_o\ (0.9662)\ T_r\ T_a\ T_w\ T_o\ T_u\ cos\theta_z \tag{2}$$

The incident diffuses irradiance under clear sky D as [2]:

$$D = D_r + D_a + D_m \tag{3}$$

And r_s is the surface albedo, r_a is the atmospheric albedo and I_o averaged solar constant equal to *1367W.m*$^{-2}$.

Given expressions of the different components of direct beam irradiance and incident diffuse irradiance are [2]:

$$T_r = exp\left\{-0.0903\, {M_a}^{0.84}\left[1 + M_a - {M_a}^{1.01}\right]\right\}$$

$$T_a = exp\left[-\tau_a^{0.873}(1 + \tau_a - \tau_a^{0.7088}){M_a}^{0.9108}\right]$$

$$T_w = 1 - (2.4959\, w\, M_r[((1 + 79.034\, w\, M_r)^{0.6828}) + (6.385\, w\, M_r)]^{-1})$$

$$T_o = 1 - [(0.1611\, O_3\, M_r(1 + 139.48\, O_3\, M_r)^{-0.3035}) - (0.002715\, O_3\, M_r(1 + 0.044\, O_3\, M_r + 0.0003\,(O_3\, M_r)^2)^{-1})]$$

$$T_u = exp\left[-0.0127\, {M_a}^{0.26}\right]$$

$$D_r = I_o\,(0.79)\, T_u\, T_{aa}\, T_w\, T_o\, cos\theta_Z\, 0.5\, \frac{(1-T_r)}{\left(1-M_r+{M_r}^{1.02}\right)} \tag{4}$$

$$T_{aa} = 1 - \left[(1 - \omega_o).\left(1 - M_r + {M_r}^{1.06}\right).(1 - T_a)\right]$$

$$D_a = I_o\,(0.79)\, T_u\, T_{aa}\, T_w\, T_o\, cos\theta_Z\, F_c\, \frac{(1-T_{as})}{\left(1-M_r+{M_r}^{1.02}\right)}$$

$$T_{as} = \frac{T_a}{T_{aa}}$$

$$D_m = \frac{(I_d+D_a+D_r)\, r_s r_a}{(1- r_s r_a)}$$

$$M_r = [cos\theta_Z + 0.15\,(93.885 - \theta_Z)^{-1.253}]^{-1}$$

$$M_a = M_r\, exp[-0.0001184\, z]$$

Where z is the surface elevation from sea level in meters, ω_o the scattering albedo equal to *0.90* and F_c the atmosphere dispersion coefficient equal to *0.84*.

The values in parentheses in the expressions of the incident direct beam irradiance and the diffuse irradiance are the exo-atmospheric solar constants Isc, which can be calculated by the following [8]:

$$I_{SC}(n_j) = I_o \times \left[1 + 0.033 \times cos\left(\frac{360}{365}.(n_j - 3)\right)\right] \tag{5}$$

Where nj is the day number of the year (nj = 1 for January 1 and nj = 365 for December 31).

As discussed above, this method needs atmospheric inputs of the ozone column, water vapor column, aerosol Angstrom coefficients, and cloud optical thickness. The MODIS atmosphere product directly provides all the inputs except aerosol Angstrom coefficients (α and β, representing the size distribution of aerosol particles and the general haziness of the atmosphere). For the Angstrom coefficients, MODIS products only provide the Angstrom exponent α, so we use the Angstrom law to derive β and then use both α and β to calculate aerosol scattering effects following [9]:

$$k_a(\lambda) = \beta_n \, \lambda^{-\alpha_n} \quad (6)$$

To evaluate the accuracy of SSI values provided by our method, with those obtained by the other models, the Root Mean Square Error (RMSE) is calculated. RMSE represents the sample standard deviation of the differences between estimated and observed values [10, 11]. This index is defined as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_{Mod,i} - X_{Sat,i}\right)^2} \quad (7)$$

Where X_{Sat}, is the global SSI estimated from Bird/MODIS combination method, X_{Mod}, is the global SSI implemented from the Meteosat-based model, and N is the number of observations.

3. Results and discussion

Implementing this model with the atmospheric inputs from the MODIS sensor, according to the scheme above (Figure 2), and by applying a Triangulated Irregular Network (TIN), an interpolation method also called Delaunay triangulation [12]. This interpolation method attempts to create a surface formed by triangles of nearest neighbor points. To do this, circumcircles around selected sample points are created and their intersections are connected to a network of non-overlapping and as compact as possible triangles [12]. The SSI for the representing month of July of 5 selected years is obtained as shown in Figure 3.

Figure 4 (right) represents the minimum value, the maximum value, and the mean value of SSI for the representative month of July of the 5 selected years. July month choice is motivated by being the month with the most average daylight hours of the year, as shown in Figure 4 (left) [13]. In addition, 2019 was marked by the maximum of SSI compared to the other years.

In Table 2, the obtained SSI values are summarized with the estimation errors. A very good agreement is obtained between the two methods, with a mean RMSE value of about 140 $Wh.m^{-2}$ with the CAMS radiation service model.

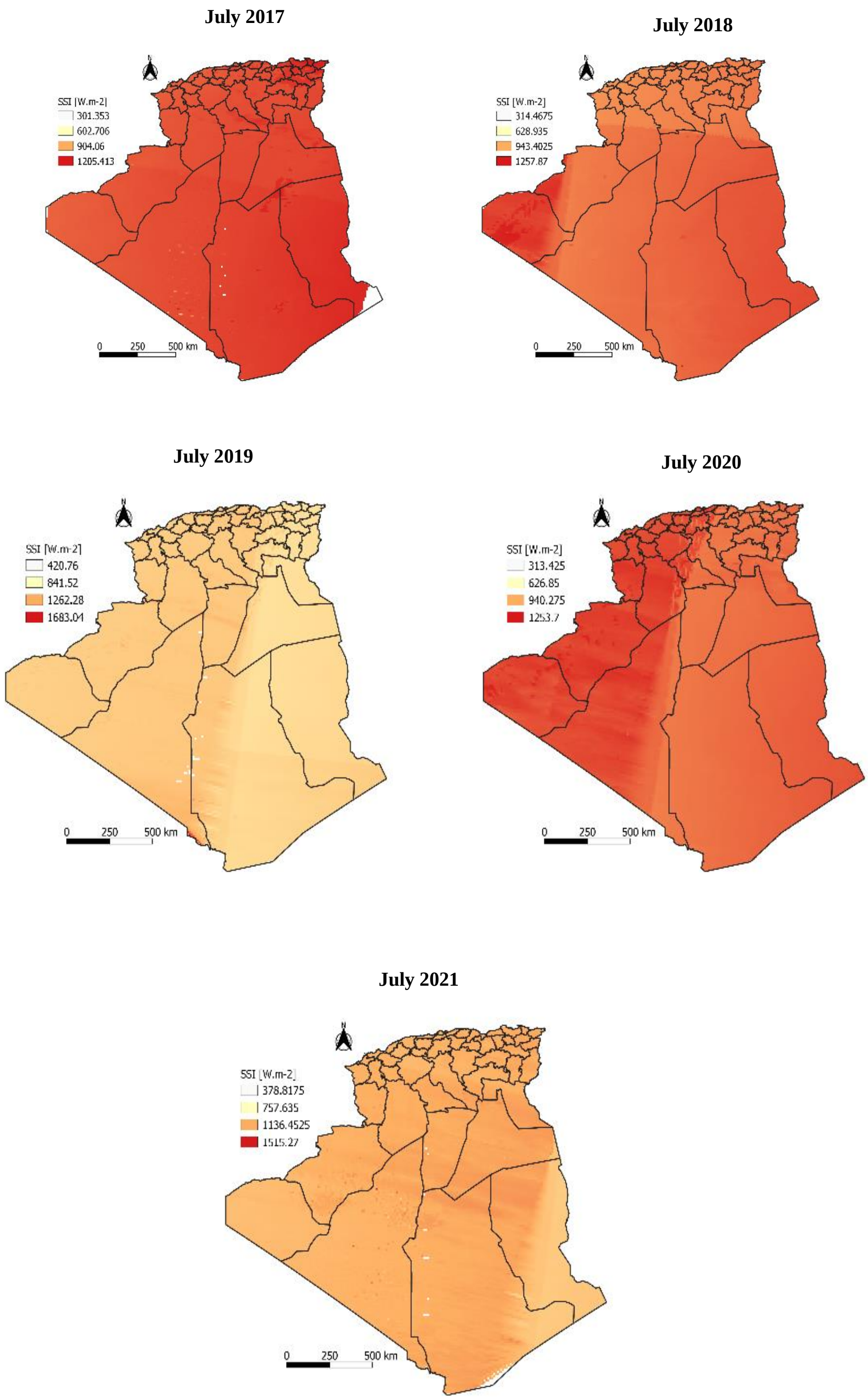

Fig 3. Mean clear sky SSI for the Algerian territory and the representing month of July of 5 years obtained from the Bird and Hulstrom model/MODIS parametrization scheme

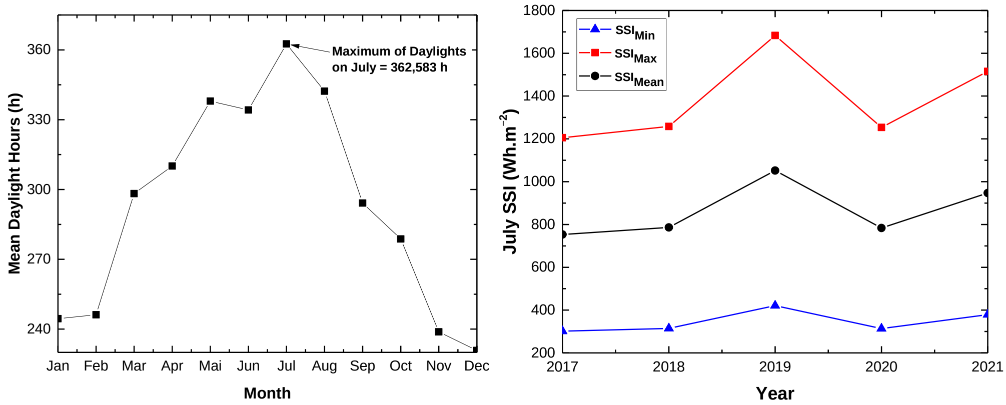

Fig 4. Averaged daylights hours as a function of the month of the year (left), the minimum value, the maximum value, and the mean value of SSI over all the Algerian territory and for the representative month of July of the 5 selected years (right)

Table 2. Mean global SSI and their estimation deviation |ΔSSI|.

Year	SSI ($Wh.m^{-2}$) [Bird/MODIS Model]	SSI ($Wh.m^{-2}$) [CAMS radiation service v2.7]	|ΔSSI| ($Wh.m^{-2}$)
2017	753,38	843,09	89,71
2018	786,17	1009,14	222,97
2019	1051,90	901,42	150,48
2020	783,56	976,98	193,42
2021	947,04	903,67	43,38

4. Conclusion

In this work, a new contribution in a satellite-SSI typical method, known as a parametrization scheme is presented. The approach is a Bird & Hulstrom model/MODIS parametrization scheme. MODIS sensor atmospheric parameters inputs showed better input for the generation of regional or even global SSI products than traditional climatological data. A comparative study is carried out with estimations obtained from Meteosat data. It was found a good agreement, with a mean RMSE value of about 140 $Wh.m^{-2}$. Thus, the investigated method shows many advantages in terms of accuracy and convenience, and the potential of the considered remote sensing data in the field of extracting surface physical parameters, in particular surface solar parameters, is demonstrated.

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