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# Parametric modeling: A simple and versatile route to solar irradiance

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## ABSTRACT

A clear-sky solar irradiance model is certainly a basic tool in the estimation of solar resources. With all the abundance of such models, there is plenty of room for searching a clear-sky solar irradiance model with general applicability, i.e. to be able to provide high-accurate estimates in most places around the world. This paper reports an upgraded version (further referred to as SIMv.2) of our parametric clear-sky solar irradiance model SIMv.1, aiming to improve the accuracy of estimates in arid environment. The new elements of SIMv.2, such as new equations for aerosol absorption and downward fraction, have been introduced targeting a better capture of the peculiarities of the solar radiation extinction by aerosols. Overall, the results of testing SIMv.2 at twelve stations located in regions with temperate, arid and tropical climate show that SIMv.2 performs much better than SIMv.1, an improvement in *nRMSE* of 37.1% for global solar irradiance and of 24.7% for the diffuse component being noticed. The comparison with other fourteen clear-sky solar irradiance models at five stations located in arid climate places SIMv.2 in the class of the best performing models. The limitation of the SIMv.2 performance in extreme weather conditions is discussed in two cases.

## 1. Introduction

Various models for estimating solar irradiance under clear-sky conditions have been developed in the last decades. While sophisticated spectral codes are proved as useful tools in atmospheric physics or photobiology, simple empirical equations are preferred in solar engineering. A clear-sky solar irradiance model combined with an Ångström-type equation [1] forms probably the most common tool used for estimating solar energy at ground level.

The simplest clear-sky solar irradiance models are fitted on radiometric data collected on an evanescent area (e.g. [2]). The atmospheric transmittance is encapsulated within the fitted parameters, which consequently entails a close connection of the models to their native place. Because of the fast changes in local and global climate, some degree of uncertainty on the persistence of the calibration of the empirical models may exist. Another class of simple solar irradiance models comprises the parametric models, which mainly originate from spectral codes. Some of the typical models in this class are: Parameter Solar Irradiance Model – PSIM [3]; Hybrid model [4]; Paulescu and Schlett – PS [5]; Meteorological Radiation Model – MRM [6]; Solar Irradiance Model version 1 – SIMv.1 [7]; model on arbitrarily oriented surfaces [8]. Within the frame of the parametric models, the atmospheric transmittance is explicitly expressed as function of surface meteorological parameters, atmospheric column content and aerosol properties. These inputs ascribe more generality and actuate an enlarging of the application area for such models. It is important to note that clear-sky solar irradiance models have to be applied carefully at higher altitude. The influence of the atmospheric parameters quality on the accuracy of clear-sky solar irradiance estimation at different altitudes is well assessed in [9].

The main limitation in the application of the parametric models is the availability of the input data. However, nowadays various programs for monitoring the atmospheric parameters with global coverage can provide data for running the parametric models. For example, the need to understand the aerosol properties has led to the continuous development of the Aerosol Robotic Network [10], best known as AERONET [11]. Currently, the network includes more than one thousand instruments covering the entire globe. Another example is the MODIS program. Looking to the Earth from space, MODIS (Moderate Resolution Imaging Spectroradiometer) [12] is a key instrument aboard the Terra and Aqua satellites, which provides a wide range of information about atmospheric properties [13].

An outstanding review of the clear-sky solar irradiance models was reported by Badescu et. al. in [14]. After testing fifty-four broadband

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models for global and diffuse solar irradiance on various sets of data, the authors conclude that there is no particular model that can be ranked as *the best*. Very simple empirical models or more complex parametric models might as well belong to the category of *good models*, but the latter generally perform better. This finding is also confirmed by [15]. After testing the performance of seventeen models at Ghardaia (Southern Algeria, arid climate), the authors concluded that the more sophisticated models are not necessarily the most accurate. The simpler models, depending on a limited number of input parameters, seem to be the more suitable for estimating the direct solar irradiance.

In this paper, we report an updated version of the clear sky solar irradiance model SIMv.1, developed by our group in the last years. Basically, SIMv.1 was constructed by averaging the spectral atmospheric transmittances from Simple Model of the Atmospheric Radiative Transfer of Sunshine – SMARTS2 [16]. In particular, each specific atmospheric transmittance $\overline{\tau}_x(h)$ was calculated as a weighted arithmetic mean of the spectral ones:

$$\overline{\tau}_x(h) = \frac{\int_0^\infty \tau_x(\lambda,h) G_{ext}(\lambda) d\lambda}{\int_0^\infty G_{ext}(\lambda) d\lambda} \tag{1}$$

were $h$ denotes the sun elevation angle. In Eq. (1) the weights are given by the spectral density of the solar irradiance $G_{ext}(\lambda)$ on the top of the atmosphere. The subscript $x$ designates a specific atmospheric attenuator (ozone absorption, nitrogen dioxide absorption, water vapor absorption, mixed gas absorption, Rayleigh scattering and aerosol extinction in case of SIMv.1)

The history of SIMv.1 began in 2011 when the first equations for the specific atmospheric transmittance were reported [17]. An upgrade of the model equations was reported in [7] where the processes of aerosol absorption and scattering were treated separately and an effective transmittance for the ozone absorption was considered. The equations of the specific transmittances of water vapor absorption and mixed gases absorption were also slightly adjusted. This set of equations was referred to as SIMv.1 for the first time in Ref. [18]. All of these papers are focused on the applications of SIMv.1 (e.g. influence of the aerosol loading of the atmosphere in the amount of collectable energy [7], evaluation of errors made in solar irradiance estimation by averaging the Ångström turbidity coefficient [18]) and not on the model structure and properties.

Although the estimates of SIMv.1 are highly accurate in continental temperate climate (see e.g. Appendix A from [18]), its performance in arid climate is moderate. For example, Ref. [19] evaluates the performance of 24 clear-sky models used to estimate the direct-normal irradiance (DNI) under arid condition at 1-min time resolution. SIMv.1 model is included in the list of the 24 models under the name *Calinoiu*. The models are classified into five classes according to the number and accessibility of the input parameters related to aerosols: Class E – no aerosol input; Class D – Linke turbidity factor; Class C – AOD at one wavelength; Class B – both AOD at one wavelength and Ångström exponent; and Class A – the same inputs as those of Class B, but with the physical algorithm of the RRTMG model used for benchmarking purposes. A description on the models and references can be read in [19]. The models were tested against data measured at seven stations located in arid climate. Fig. 1 displays a summary of the results from [19]. Visual inspection shows that the performance of the simple parametric models decreases substantially when subjected to the turbidity conditions outside of what is typical under temperate continental climate. The mean performance of SIMv1 is exactly on the average of the whole class C to which it was assigned and slightly below the average of the more complex models. Some individual models from the same class C, like MMAC, Ineichen and METSTAT perform consistently well for all stations.

These observations are supported by the mean ($\mu$) and median ($M$) values of *nRMSE* data series, which are under five percents [19]: MMAC ($\mu = 2.1\%$, $M = 2.3\%$), Ineichen ($\mu = 4.1\%$, $M = 3.5\%$), METSTAT ($\mu = 3.9\%$, $M = 3.8\%$) while the same values for SIMv.1 exceed 6 percents: ($\mu = 6.3\%$, $M = 6.7\%$). Overall, Fig. 1 motivates the searching for an improvement in SIMv.1 performance. From a broader perspective, in order to assess correctly the performance of the models, one should also look at the way in which a model splits the global solar irradiance into its diffuse and beam components, which this study does.

To the end of this introductory section, it is important to highlight two conclusions drawn in [20] after testing 18 clear-sky solar irradiance models against high-quality data: (1) the estimation of diffuse horizontal irradiance is particularly deficient in most models and (2) estimates uncertainties under ideal clear-sky conditions can propagate and affect all-sky estimates. The first conclusion can be understood in relation with an observation from [21]: the bias patterns in solar irradiance estimations can be largely linked to the inaccuracies inherent to the sources of aerosol optical depth data.

Starting from these facts, in this paper we report the work on improving SIMv.1. The resulted equations are further referred to as SIMv.2. The improvement is on the overall performance of SIMv.1, but a special attention was paid for capturing the specificity of the diffuse radiation. For this, the equations of the aerosol extinction were adjusted and two specific parameters that characterize the aerosol were added to the model input. The two parameters are: (1) the single scattering albedo as a measure of the relative contribution of the scattering and absorption processes to the extinction of the solar radiation beam and (2) the aerosol asymmetry factor, which strongly influences the downward fraction of solar radiation in the aerosol scattering process.

The paper is organized as follows. After this introduction, the relevant data used to build SIMv.2 are presented. SIMv.2 equations are described in detail in Section 3, emphasizing its novel elements and the new additions made to SIMv.1. Section 4 is devoted to assess the SIM.v2 performance.

## 2. Database

Two types of data have been used for developing SIMv.2: information about the atmospheric column content, required for running the model, and radiometric data, required for adjusting the model and for evaluating the accuracy of the estimations. The inputs (the ozone, nitrogen dioxide and water vapor column content as well as the aerosols' optical parameters) were retrieved from the AERONET [11]. Global and diffuse solar irradiance data at high-quality standards were retrieved from the Baseline Surface Radiation Network BSRN [22].

Data have been collected from 16 stations. The single criterion used in the selection of these stations was that a BSRN station has to be collocated with an AERONET station. Table 1 lists the stations, their geographical coordinates, local climate (according to the Köppen-Geiger climate classification [23]) and the number of the measurement points from every station used in the adjustment and evaluation of the SIMv.2 equations. Six stations are located in zones with arid climate. More information on the stations can be read in Table ESM-1 from the Electronic Supplementary Material. Fig. 2 shows the spreading of the stations on the map, superimposed on the climate zones defined by the Köppen-Geiger classification.

SIMv.2 is basically a clear sky-model. By general acceptance, the clear sky is defined by the absence of any visible cloud on the celestial vault. Unfortunately, BSRN and AERONET do not indicate if a data was measured under clear sky or under sunny sky (with clouds on the sky but without covering the sun). So, we had to explore a huge quantity of data in order to identify the clear sky periods from all solar irradiance measurements data series. The process was performed in three steps: (1) A preliminary test based on fractal dimension of the radiometric data recorded in a day. The procedure from Ref. [24] was applied to the entire database. The days with fractal index below 1.1 were selected for further processing. (2) Comparison with a simple clear sky model. If a sign of cloud enhancement was detected the whole day was removed from the database and (3) Visual inspection of the solar irradiance curves measured at both AERONET and BSRN stations. This procedure