# Monte Carlo based estimation of the effect of different aerosol classes on solar irradiance in African atmospheric conditions

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**Abstract.** We present a study of the impact of aerosols on the ground level solar irradiance through their scattering and absorption of solar light. The degree of direct solar beam attenuation, as well as the angular and wavelength dependence of the diffuse (scattered sunlight) sky brightness strongly depends on the concentration, size distribution and nature of aerosol class. Aerosols common in the atmosphere in African conditions, such as biomass burning-generated smoke, wind-generated dust and urban-mixed (mixed particles from urban environment) all influence incoming sunlight in different ways. In this paper, a Monte Carlo approach is employed to track the movement of photons from the top of the atmosphere to the Earth's surface for a variety of atmospheric compositions characteristic of typical African localities. The results illustrate how variations in aerosol types change the amount of direct solar radiation reaching the ground, as well as the angular and spectral distribution of the diffuse light.

## 1. Introduction

The intensity and spectral distribution of solar radiation reaching the Earth's surface depends not only on solar position, but also on the local thickness (i.e. altitude) and composition of the atmosphere. The influence of atmospheric aerosols on solar spectral irradiance has been investigated in various studies and those studies show that aerosols have a big impact on incoming solar radiation attenuation due to their optical properties [1, 2]. A new method is applied to interpret this issue and it is presented in this the work.

An aerosol is defined in its simplest form as a solid or liquid particle suspended in a gas, and it includes a wide range of manifestations such as dust, smoke, fog, haze and smog [2]. Atmospheric aerosols range in size from a few nanometers to tens of micrometers in diameter [3].

Aerosols interact both directly and indirectly with solar light to affect the Earth's radiation budget and climate. They directly scatter sunlight to a new direction of propagation. This results in sky brightening or in radiation being returned back to space. As an indirect effect, aerosols in the lower atmosphere can modify the size of cloud particles, changing how the clouds reflect and absorb sunlight, thereby affecting the Earth's energy budget [1, 3].

The range and nature of the aerosol size distributions reveal the origin of their formation [4]. The scattering characteristics of atmospheric aerosols may change rapidly with time and meteorological conditions due to evolution of the aerosol component. Aerosols have a range of sizes and reflective characteristics, meaning that they have different optical and physical properties such as the scattering phase function, the single scattering albedo, and the aerosol optical depth (AOD), all of which are wavelength dependent [5]. Those optical properties affect the impact of aerosols on atmospheric radiation, and as result play a major role in the solutions to the radiative transfer equation [4, 6, 7].

There are two fundamental approaches for measuring solar radiation reaching the ground. The first one is direct measurement which is based on ground based solar radiation readings, and it is the most accurate. This one requires a large number of measurements for a range of wavelengths over a representative time period and with adequate spatial coverage [5]. Such measurements are currently not available in the required quantity and quality for most locations, especially in Africa. The second approach is mathematical or computational modelling, which is usually the most viable approach to generate a complete set of local solar irradiance estimates. And it has to be validated by observed data.

Different studies have determined aerosol optical properties from microphysical quantities such as the particle complex refractive index and size distribution based on Mie scattering theory, which assumes that all particles are spherical and homogeneous [3, 5, 6].

In this paper, we investigate the spectral effect of the aerosol optical depth (AOD) on solar irradiance. We focus on the typical characteristics of the AOD for three types of aerosols commonly found in Africa: i) biomass burning generated smoke, ii) wind- generated dust and iii) urban –mixed [4, 6]. In this context we are looking at the distribution of scattering angle as function of scattered photons. The contribution of atmospheric aerosols effect on ground solar irradiance based on scattering angle is a concept which has not been adopted in previous studies. A Monte Carlo method is used here to simulate photons' walk and their new direction based on Henyey-Greenstein phase function. The number of photons scattered at given range of scattering angles determines how much solar light reaches the ground and how much is scattered back in atmosphere. This is the new approach which is studied here and it is well detailed in section3.

## 2. Mathematical formulation

We investigate computationally the influence of atmospheric aerosols on solar spectral irradiance. The incident flux from the top of the atmosphere passes through the atmosphere and gets attenuated by atmospheric constituents (including aerosols). The attenuated solar radiation is partly determined by the aerosol optical depth, which in turn depends on aerosol characteristics and total aerosol loading (i.e. aerosol optical depth).

Light is absorbed as it passes through the atmosphere and at the same time it is subject to scattering. Suppose that the spectral radiation intensity at wavelength $\lambda$ outside the Earth's atmosphere is $I_0(\lambda)$ and the airmass is $m$. The amount of solar radiation transmitted through the atmosphere is calculated according to Lambert-Bouguer-Beer's law as follows:

$$I(\lambda, m, \tau) = I_0(\lambda)\exp(-m\tau) \tag{1}$$

In the equation above $\tau$ is a parameter describing atmospheric turbidity and is referred to as the optical depth. The exponential part corresponds to the transmission fraction, defined as that part of the solar beam unaffected by extinction in the atmosphere, and expressed as

$$T = \exp(-\tau m) \tag{2}$$

Another interpretation of this quantity is as the probability of a single solar photon passing through the atmosphere without deflection and $T$ is therefore in the interval $0 \leq T \leq 1$.

The optical depth can be written as the sum of optical depth components $\tau = \sum \tau_i$. One of the mechanisms for light scattering in the atmosphere is Rayleigh scattering, which is caused by molecules in the atmosphere. Rayleigh scattering is particularly effective for short wavelength light (blue light) since its optical depth $\tau_R$ has a $\lambda^{-4}$ dependence.

In addition to Rayleigh scattering, aerosols and dust particles are the major source of light attenuation in the visible range, and contribute to the scattering of solar light known as Mie scattering, which is the subject of this study. Light scattered by aerosols is characterized by a phase function $P(\xi, \lambda)$ which describes the angular dependence of light scattering and it is scattering angle ($\xi$) and wavelength ($\lambda$) dependent.

The aerosols' optical depth $\tau_a$ , which is a measure of the size and number of particles present in a column of air in the atmosphere, can be parameterized using the formula suggested by Ångstrom which defines this quantity in terms of an Ångstrom turbidity coefficient $\beta$ and a wavelength exponent $\alpha$ [2].

$$\tau_a(\lambda) = \beta\lambda^{-\alpha} \tag{3}$$

The Ångstrom wavelength exponent characterizes the wavelength dependence of the AOD, and provides basic information on the aerosol size distribution. It is the slope of the logarithm of aerosol optical depth versus the logarithm of wavelength:

$$\alpha = \frac{d(\ln\tau_a)}{d(\ln\lambda)} \tag{4}$$

The single scattering albedo $\omega_0(\lambda)$ is a measure of the fraction of light intercepted and scattered by a single particle. It largely depends on complex part of refractive index, and particle size. For aerosol scattering, the Henyey-Greenstein phase function is used to determine the scattering angle distribution [7]

$$p_{aer}(\xi) = \frac{1-g_\lambda^2}{\left(1+g_\lambda^2-2g_\lambda\cos\xi\right)^{3/2}} \quad , \tag{5}$$

where $g$ is referred to as the asymmetry factor. This lies in the range $-1 \leq g \leq 1$ , which represents backscattering ($g = -1$) through isotropic scattering ($g = 0$) to forward scattering ($g = 1$). It indicates the portion of the light scattered forward and the portion scattered backward.

## 3. The modelling method and algorithm

We apply Monte Carlo simulations to estimate the solar irradiance in a horizontally homogeneous and plane parallel atmosphere with optical thickness $\tau(\lambda)$, illuminated by incident monochromatic flux $I_0(\lambda)$ at the top of the atmosphere. The procedure is based on the interpretation of photon-atmosphere interaction as a random process and the subsequent calculation of desired radiative characteristics. The fluxes measured at ground level as a function of wavelength are obtained as average values over a multiplicity of photon simulations.

The process of radiative transfer in the Monte-Carlo method is simulated as a multitude of photon movements. Coming from the top of atmosphere, the photon moves along a certain trajectory, which finishes either with a photon exiting the atmosphere, its absorption by the atmosphere, or its detection at the surface.

In our model we simulated the photon trajectories based on equation (2). A random number generator is used to provide random numbers $r$ between 0 and 1. These are used to calculate whether the photon reaches the surface, the nature of the interaction (absorption or scattering) and the scattering angle (deflection angle $\xi$ and azimuth $\psi$) [8]. And for each point new random number is generated.

In the first of these, if $r \leq T$, the photon passes through the atmosphere it becomes transmitted. On the other hand, if $r > T$ the photon is scattered or absorbed. The new generated random number ($r_1$) is compared with single scattering albedo ($\omega_0$) in order to simulate either scattering or absorption process. If $r_1 < \omega_0$, we simulate a scattered photon, otherwise absorbed. If the photon is scattered, it changes direction and the simulation continues from the scattering location. If the photon is absorbed, it is also annihilated, and therefore its trajectory ends [8].

Therefore, it is enough to simulate only three processes: the free path of a photon (i.e. the likelihood of interaction with the atmosphere), the interaction with the atmosphere (the absorption and scattering), and the scattering angle.

We computationally launched $10^4$ photons from the top of the atmosphere at four specific wavelengths and tracked the progress of each one through the atmosphere. We applied this to different aerosols types investigated in this study.

The aerosol optical depth $\tau_a$, single scattering albedo $\omega_0$ and asymmetry parameter $g$ used in this model are obtained from [6]. For $\tau_a$ we adopt typical values of $\alpha$ quoted for these aerosols by [6]. We investigate the scenario where $\tau_a(440\text{ nm}) = 1$, which corresponds to relatively high aerosol loading, and which therefore displays the effect of aerosols more clearly.

**Table 1**: Parameters associated with the aerosol types investigated

| **Wavelength** (nm) | **Biomass- Burning** | | | **Desert Dust** | | | **Urban –Mixed** | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\alpha = 2.0$ | | | $\alpha = 0.5$ | | | $\alpha = 1.8$ | | |
| | $g$ | $\omega_0$ | $\tau_a$ | $g$ | $\omega_0$ | $\tau_a$ | $g$ | $\omega_0$ | $\tau_a$ |
| **440** | 0.64 | 0.88 | 1.00 | 0.73 | 0.93 | 1.00 | 0.68 | 0.90 | 1.00 |
| **670** | 0.53 | 0.84 | 0.43 | 0.71 | 0.98 | 0.81 | 0.61 | 0.88 | 0.44 |
| **870** | 0.48 | 0.80 | 0.26 | 0.71 | 0.99 | 0.71 | 0.58 | 0.85 | 0.29 |
| **1020** | 0.47 | 0.78 | 0.18 | 0.71 | 0.99 | 0.66 | 0.57 | 0.83 | 0.21 |

In this paper, we only considered the case that the Sun is overhead. We furthermore only considered single scattering. Future work will incorporate other zenith angles and multiples scattering.

## 4. Results

We present the relationship between number of scattered photons and scattering angle from a simple Monte Carlo simulation. This is based on optical properties of biomass burning, desert dust and mixed urban aerosols. The dependence of scattered solar flux on wavelength is also presented. Scattering angle and scattering albedo together with AOD at different wavelength constitute a useful tool to determine the effect of aerosols on solar flux in our model.

### *4.1 The effect of biomass burning on solar flux*

Figure 1 shows the photons scattered by biomass burning aerosols, at different wavelengths as function of scattering angle. This confirms that our simulation produces forward scattering [7], and that this effect becomes more pronounced at shorter wavelengths.

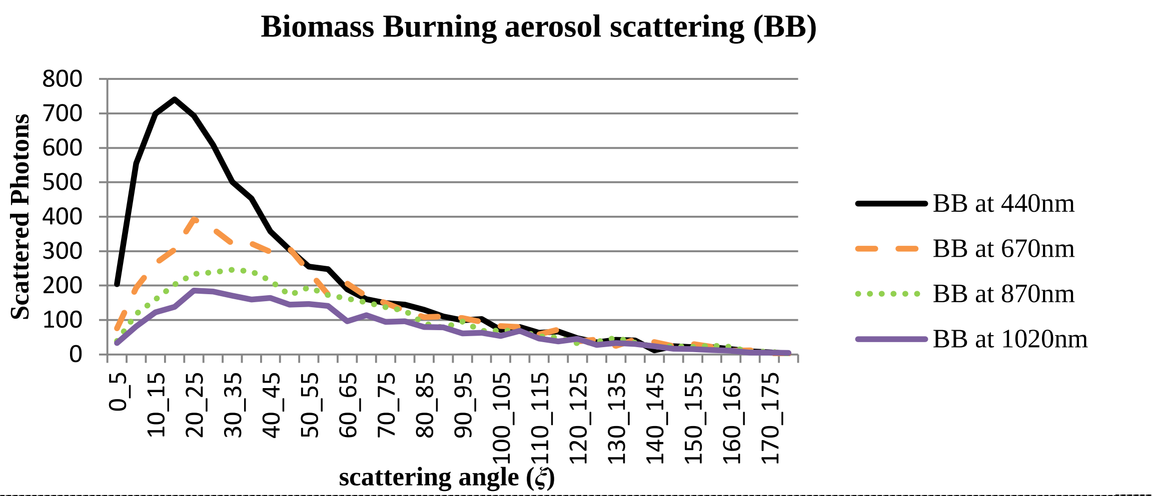


**Figure 1.** Distribution of scattered photons as a function of scattering angle for biomass burning aerosols.

*4.2 The effect of desert dust on solar flux*

Figure 2 shows the angular distribution of scattered photons at different wavelengths for desert dust aerosols. We note that our simulation correctly reproduces the strong forward scattering associated with this aerosol type.

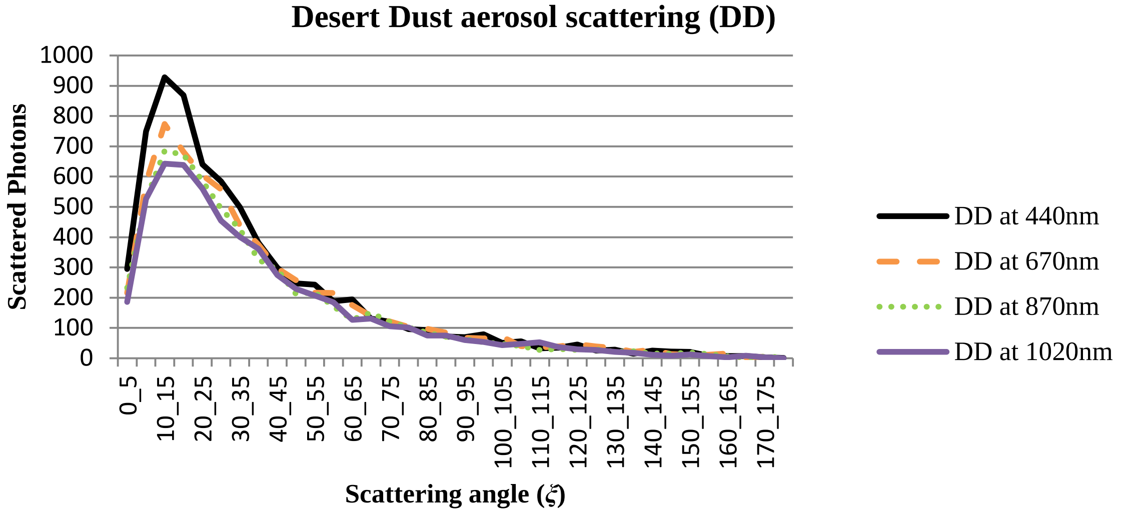


**Figure 2.** Distribution of scattered photons as a function of scattering angle for desert dust aerosols.

*4.3 The effect of urban –mixed on solar flux*

Figure 3 shows the angular distribution of scattered photons at different wavelengths for urban-mixed aerosols. As expected, the distribution here closely resembles the BB case.

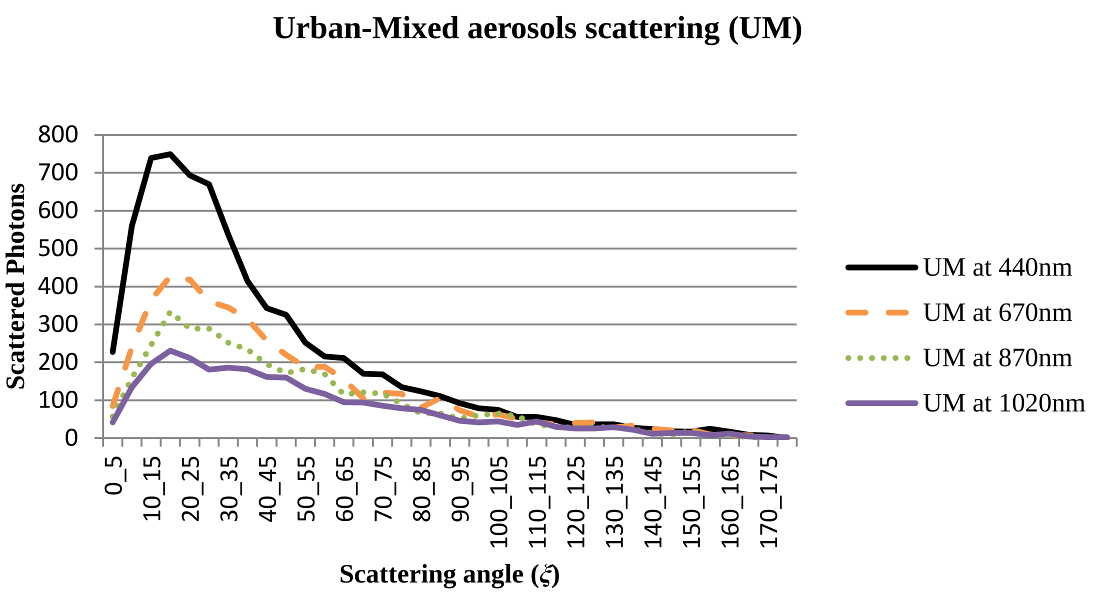


**Figure 3.** Distribution of scattered photons as a function of scattering angle for urban-mixed aerosols.

*4.4 The wavelength dependence of aerosols optical depth*

Figure 4 shows the wavelength dependence of the aerosol optical depth for aerosol types investigated here. In all cases the graph was calculated for an assumed value of $\tau_a(440\text{ nm}) = 1$. Our simulations therefore confirm the stronger wavelength dependence of the scattered portion for the BB and UM cases.

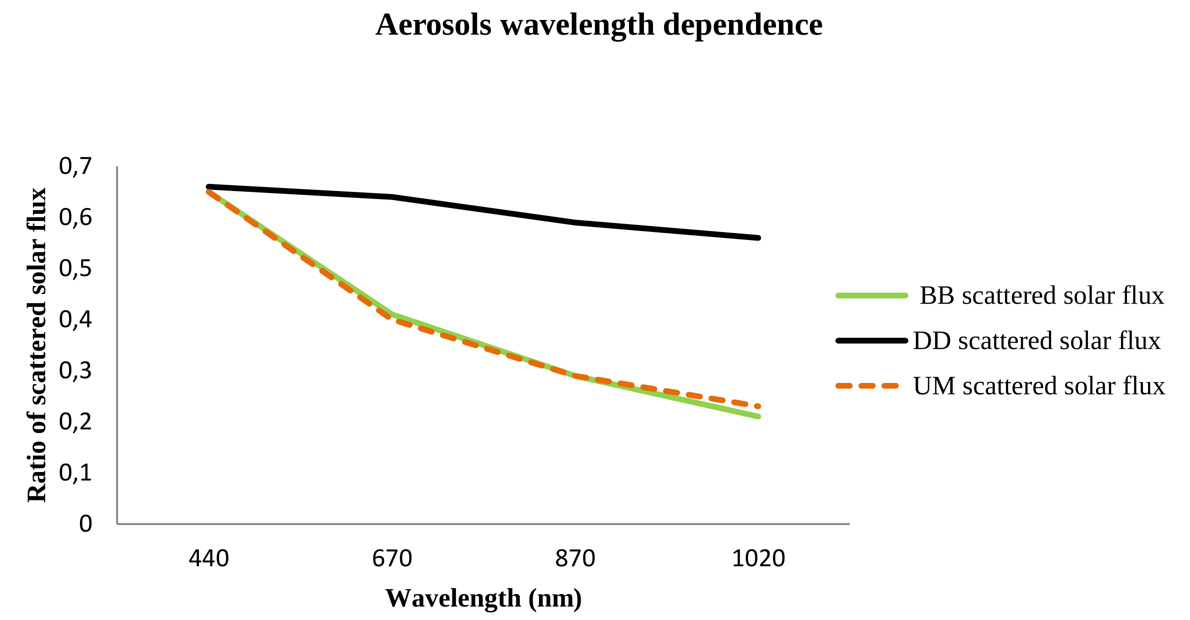


**Figure 4.** Relation between scattered solar flux and wavelength for $\tau_a(440\text{nm}) = 1$.

## 5. Conclusion and future work

We have presented the results of aerosol single scattering stochastic simulations on solar irradiance, and the scattered photon distribution as a function of scattering angle. The simulations were carried out at four wavelengths and for three aerosol types commonly present in the atmosphere over Africa. This distribution determines the aerosol contribution to the sky brightness and colour. Despite using the simplifying assumption that secondary scattering is small and the limited number of photons used in each simulation, we obtain scattering distributions that present a good reproduction of the true sky for the aerosol types tested, which can then be combined with the Rayleigh scattered components to construct the spectrum of the total skylight as a function of zenith angle. We are therefore able to confirm that the methodology used is suitable for further development to also model the sky colour for more complex arrangements such as off-zenith solar position and the consideration of multiple scattering events. The only minor scatter (i.e. distribution function plots) in our plots shows that good approximations can be achieved without prohibitively long computation time usage.

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