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INFLUENCE OF ATMOSPHERIC PARAMETERS ON BIOLOGICALLY EFFECTIVE SOLAR UV IRRADIANCE

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Article Info	Abstract
Received: 27.09.2025 *Accepted: 15.10.2025* **Keywords:** Ultraviolet radiation; atmospheric aerosol; effective solar UV irradiance; erythema; cataract.	Solar ultraviolet (UV) radiation has various effects on human beings, both positive and negative. Since solar UV spectral radiation is only rarely monitored, modeling of biologically effective solar UV spectral irradiance became a common practice in research. In this study, the influence of the main atmospheric parameters, ozone and aerosol, on the level of biologically effective solar irradiance is analyzed. The impact of UV radiation on the skin is compared with the action on the retina. The analysis was performed using synthetic solar UV spectra generated with SMARTS2, a high-quality spectral solar irradiance model. The native density of the extraterrestrial UV spectrum and, correspondingly, the density of the absorption coefficients were increased by linear interpolation. From the methodological perspective, a new continuous equation for the biological action function associated with cataract is reported. The results bring to light non-intuitive effects of different aerosol classes on biologically effective solar UV irradiance.

1. Introduction

Ultraviolet (UV) solar radiation designates the spectral range from 100 to 400 nm. Furthermore, the UV range is divided into three spectral bands: UV-C (0.10–0.28 μm), UV-B (0.28–0.32 μm) and UV-A (0.32–0.40 μm). Solar UV radiation affects many natural processes related to the environment and human activities, equally in positive and negative ways. UV-C radiation does not reach the Earth's surface, as it is entirely absorbed by atmospheric constituents. UV-A radiation does not have enough energy to cause a significative damage to the biosphere. Differently, any increase in the UV-B radiation level is of concern due to potential harmful effects on human beings, ranging from common skin burning to DNA damage.

The central part in photobiology is the correlation between spectral UV radiation and a particular biological response. This is quantified using the biological action function, which characterizes the efficiency with which UV radiation induces a specific biological effect as a function of wavelength. The effective UV spectral irradiance is defined by the product of solar UV spectral irradiance, measured or estimated using a spectral model, with the biological action function corresponding to a biological response. Modeling the biological effects of solar UV spectral radiation is carried out from various perspectives (e.g. [1]), being a current topic in research.

Since spectral solar irradiance is very rarely monitored, spectral models for estimating solar UV irradiance are frequently used in practice. Spectral solar irradiance modeling has been intensively studied since the 20th century. Researchers, such as Leckner [2], Bird [3] and Gueymard [4], have succeeded in developing spectral solar irradiance models recognized worldwide as high performing. These models can be applied to estimate the solar UV spectral irradiance too.

In this study we used the spectral solar irradiance model SMARTS2 [4] to estimate solar spectral UV irradiance. The choice is motivated by the high performance of SMARTS2 in UV and its flexibility in capturing aerosol properties, as this study is focused on the influence of aerosol properties on the effective solar UV irradiance.

The influence of atmospheric aerosols on biologically effective irradiance has been a subject of scientific inquiry for long. Pioneers, like Ångström [5], highlighted the role of scattering and absorption properties of aerosols in calculating the amount of radiation at Earth's surface. Advancements in radiative transfer modeling and satellite observation enabled researchers such as Madronich [6], to quantify how aerosols modulate solar UV radiation at the Earth's surface, directly impacting photobiological processes like DNA damage, photosynthesis, and vitamin D synthesis.

Many studies across Europe showed that changes in UV trends were often driven more by aerosol and cloud variability than ozone recovery (e.g. [7]). In urban Asia, Brewer and Dobson observations (2004–2008) from Seoul revealed that a 1% increase in aerosol optical depth reduced erythemal UV irradiance by about 0.29%, whereas equivalent ozone changes had about four times larger impact on UV irradiance [8]. In recent years, regional and global studies have deepened the quantitative understanding of aerosols. For example, Zhao et al. [9] found in their study that aerosol attenuation reduced UV irradiance by 30% under cloudless conditions and by 40% when clouds are included. In Europe, long-term measurements from 1990 to 2020 revealed divergent trends, with some sites experiencing increasing UV-B due to decreasing aerosols, while nearby stations saw declines associated with persistent aerosol loads [10].

Our previous work [11] quantifies the aerosol influence on UV diffuse fraction. The results show that increasing the Ångström turbidity coefficient and the Ångström exponent significantly reduce the diffuse fraction. With this study we continue to investigate the impact of aerosols on solar UV radiation under various atmospheric conditions but taking into account the biological response. Thus, the aim of this study is to explore the effect of the atmospheric parameters, ozone and aerosol, on the biologically effective solar irradiance. The paper focuses on the UV radiation action on the human skin and on the retina of the eye. Regarding the last item, we propose a continuous equation for the action spectrum associated with cataract.

The rest of the paper is structured as follows. In Sec. 2 the biological action functions, erythema and cataract, are introduced. Section 3 explains the generation of synthetic UV data. The results are presented and commented on Sec. 4. The main conclusions are gathered in Sec. 5.

2. Biologically effective solar irradiance

2.1. Biological action functions

The erythemal action function was standardized by the Commission Internationale de l'Éclairage (CIE) in 1987 [12].

$$B_e(\lambda) = \begin{cases} 1, & \lambda \in [0.250, 0.298]\ \mu\text{m} \\ 10^{94(0.298-\lambda)}, & \lambda \in (0.298, 0.328)\ \mu\text{m} \\ 10^{15(0.139-\lambda)}, & \lambda \in (0.328, 0.400)\ \mu\text{m} \end{cases} \quad (1)$$

where: λ [μm] – broadband wavelength. Equation (1) was used in this study for calculating erythemal effective UV irradiance. Figure 1a displays $B_e(\lambda)$, showing that the erythemal action function reaches its maximum value in the UV-B range. $B_e(\lambda)$ decreases sharply when wavelength exceeds 315 nm. The biological action can be summarized as follows: in the UV-B range, the impact of UV radiation on the skin is very high while in the UV-A range the erythemal effect significantly decreases.

The biological action function associated with cataract $B_c(\lambda)$ is graphically presented in Fig. 1b (after [13]). $B_c(\lambda)$ shows similar tendency as $B_e(\lambda)$, roughly constant values in the UV-B range and a sharp decrease in the UV-A range. It varies by four orders of magnitude in the UV spectral range.

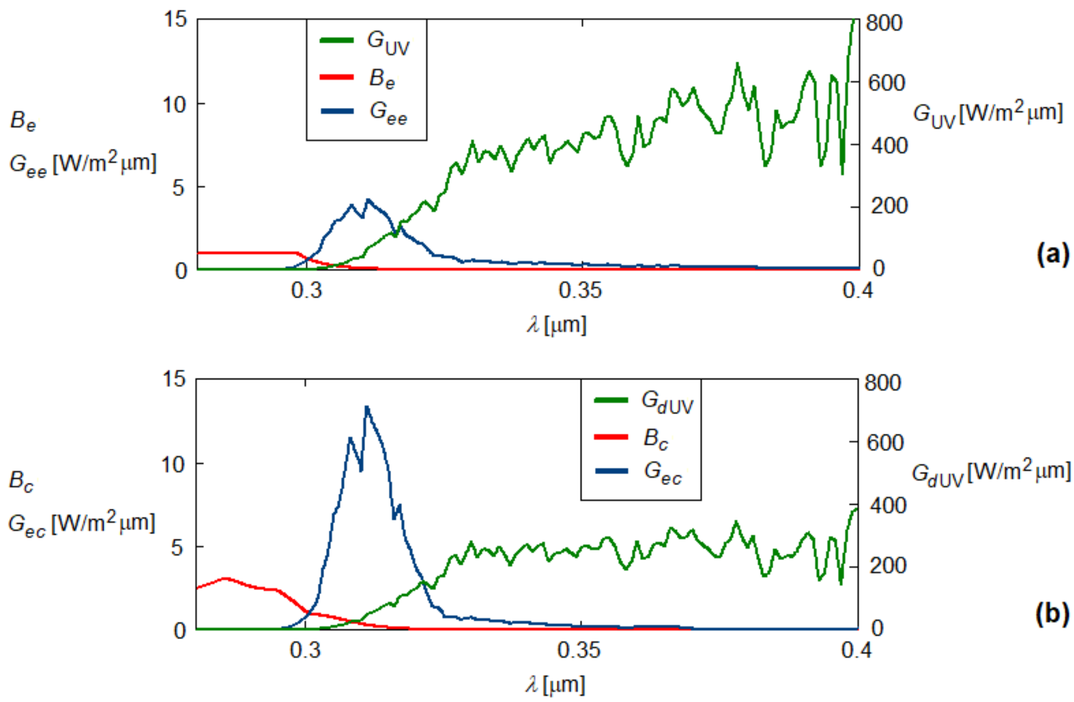

Figure 1. (a) Erythemal action function B_e and effective solar UV irradiance G_{ee}. Spectral solar UV irradiance G_{UV} is plotted in the background. (b) Biological action function B_c and effective solar UV irradiance G_{ec} associated with cataract. Spectral diffuse solar UV irradiance G_{dUV} is plotted in the background. The G_{UV} and G_{dUV} spectra are simulated for an atmosphere characterized by the following parameters l_{o3}=0.35 cm·atm, l_{No2}=0.0002 cm·atm, β=0.079, α=1.3, SSA=0.95, g=0.7, and the optical mass fixed at m=1.5

The biologically effective UV irradiance associated with cataract is simply calculated by integrating $B_c(\lambda)$ multiplied with solar UV spectral irradiance. Despite all the efforts made in searching scientific literature, we were unable to identify an equation for $B_c(\lambda)$. Aiming to fill this gap, we have developed for $B_c(\lambda)$ a continuous equation with respect to wavelength:

$$B_c(\lambda) = \begin{cases} \frac{a1+c1\cdot\lambda+e1\cdot\lambda^2}{1+b1\cdot\lambda+d1\cdot\lambda^2}, & \lambda \in [0.280, 0.295)\ \mu m \\ \frac{a2+c2\cdot\lambda^{0.5}+e2\cdot\lambda+g2\cdot\lambda^{1.5}}{1+b2\cdot\lambda^{0.5}+d2\cdot\lambda+f2\cdot\lambda^{1.5}}, & \lambda \in [0.295, 0.310)\ \mu m \\ (a3+b3\cdot\lambda+c3\cdot\lambda^2+d3\cdot\lambda^3+e3\cdot\lambda^4)^2, & \lambda \in [0.310, 0.325)\ \mu m \\ \frac{a4+c4\cdot\lambda^{0.5}+e4\cdot\lambda+g4\cdot\lambda^{1.5}+i4\cdot\lambda^2}{1+b4\cdot\lambda^{0.5}+d4\cdot\lambda+f4\cdot\lambda^{1.5}+h4\cdot\lambda^2+j4\cdot\lambda^{2.5}}, & \lambda \in [0.325, 0.370]\ \mu m \end{cases} \quad (2)$$

Specifically, $B_c(\lambda)$ was fitted on data from [13] with a determination coefficient R^2 = 0.999. The wavelength range that is relevant for effective UV irradiance associated with cataract is between 0.28 μm and 370 μm. Due to the very large gradient of $B_c(\lambda)$, it was necessary to divide the 0.28 - 370 μm spectral range into four intervals. The fitting coefficients are listed in Table 1. The high quality of $B_c(\lambda)$ fitting can be seen by bare eye in Fig. 2.

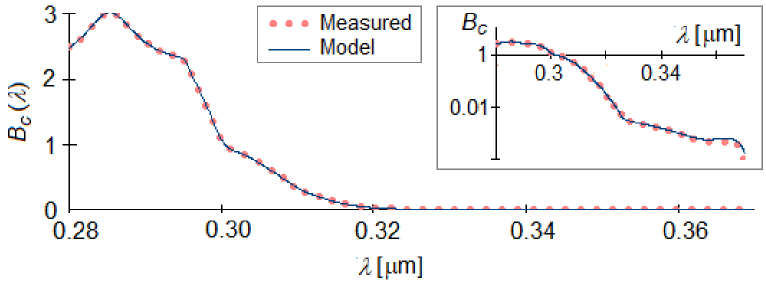

Figure 2. Measured and modeled of the biological action function associated with cataract, $B_c(\lambda)$, plotted with respect to wavelength λ

2.2. Biologically effective solar irradiance

Biologically effective solar irradiance is defined as the solar UV irradiance weighted with a specific biological action function. Therefore, erythema effective UV irradiance is defined as:

$$G_{ee} = \int_{0.28\ \mu m}^{0.4\ \mu m} G_{UV}(\lambda) \cdot B_e(\lambda) d\lambda \tag{3}$$

Similarly, cataract effective UV irradiance is defined by the equation:

$$G_{ec} = \int_{0.28\ \mu m}^{0.4\ \mu m} G_{dUV}(\lambda) \cdot B_c(\lambda) d\lambda \tag{4}$$

Table 1. The fitted coefficients in Eq. (2)

Equation / Spectral range [μm]	1 / [0.280, 0.295)	2 / [0.295, 0.310)	3 / [0.310, 0.325)	4 / [0.325, 0.370]
a	2.1719295	- 2.73926381	- 20232.2268	- 0.00057324128
b	- 7.0101811	- 5.56347765	253478.1315	- 8.5439236
c	- 15.226581	14.87627459	-1188987.7	0.0038670782
d	12.288302	10.31494044	2475088.6	29.170416
e	26.694919	- 26.9281748	- 1929471.1	- 0.0097808954
f	0	6.37330414	0	-49.748259
g	0	16.24693734	0	0.010992914
h	0	0	0	42.3813223
i	0	0	0	- 0.0046323506
j	0	0	0	- 14.4288951

3. Synthetic UV data

This study was conducted with synthetic data generated with the spectral model SMARTS2 [4]. For different atmospheric conditions, the spectral solar irradiance components, direct-normal G_{dnUV}, diffuse G_{dUV}, and global G_{UV}, were estimated in the wavelength range 0.28-0.40 µm

$$G_{UV}(\lambda) = G_{dnUV}(\lambda) \cdot \frac{1}{m} + G_d(\lambda) \quad (3)$$

$$G_{dnUV(\lambda)} = G_{eUV(\lambda)} \cdot \tau_{R(\lambda)} \cdot \tau_{O3(\lambda)} \cdot \tau_{NO2(\lambda)} \cdot \tau_g(\lambda) \cdot \tau_{w(\lambda)} \cdot \tau_a(\lambda) \quad (4)$$

$$G_{dUV(\lambda)} = G_{eUV}(\lambda) \cdot \frac{1}{m}(\gamma R \cdot \tau_{dR}(\lambda) + \gamma a \cdot \tau_{da}(\lambda)) \quad (5)$$

G_{eUV} denotes the extraterrestrial spectral solar irradiance corrected with the Earth - Sun distance. $\tau_{O3}, \tau_{NO2}, \tau_g, \tau_w, \tau_R, \tau_a$ represent the spectral atmospheric transmittances associated with the following processes: ozone absorption, nitrogen dioxide absorption, uniformly mixed gas absorption, water vapor absorption, Rayleigh scattering and aerosol extinction, respectively. γR and γa denote the ground-scattered fraction of solar radiation by gas molecules and aerosols, respectively. Due to their large transmittance in the UV range, the absorption of water vapor and uniformly mixed gas was ignored. Thus, the specific atmospheric transmittances associated with these two attenuation processes were assumed to be equal to one: $\tau_w = \tau_g = 1$.

Because we considered only the Sun elevation angles h higher than 11.2°, the approximation $\sin(h) \cong 1/m$ was applied, where m denotes the optical atmospheric mass.

SMARTS2 [4] generates different UV spectra allowing control over the main atmospheric parameters: atmospheric optical mass m, ozone column content l_{O3}, nitrogen dioxide absorption l_{No2}, aerosol nature (Ångström exponent α and the single scattering albedo SSA) and the atmospheric aerosol loading (Ångström turbidity coefficient β). To have a benchmark in the analyses, a reference spectrum was defined for parameter values commonly accepted as typical in temperate zones: m = 1.5, l_{o3} = 0.35 cm·atm, l_{No2} = 0.0002 cm·atm, α = 1.3, β = 0.079, SSA = 0.95 and g = 0.7.

The extraterrestrial solar irradiance spectrum and the absorption coefficients in SMARTS2 are tabulated at 121 wavelengths, from 0.28 to 0.4 µm. Aiming a better accuracy, we increased the spectral density by 10 times by applying linear interpolation. Figure 3 illustrates the extraterrestrial UV spectrum G_{eUV} and the normalized ozone absorption coefficient k_{O3} at native resolution and ten times higher.

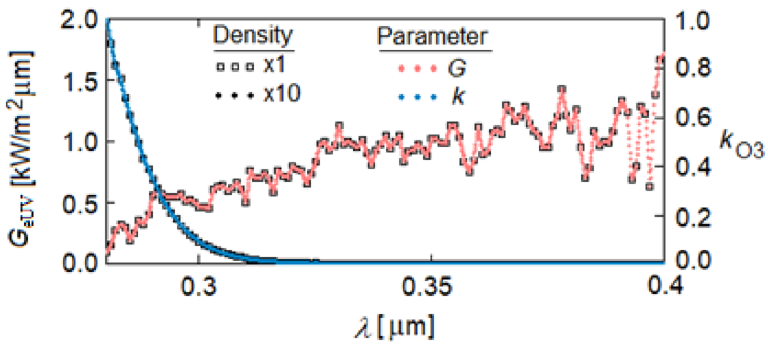

Figure 3. Extraterrestrial spectrum G_{eUV} and the normalized ozone absorption coefficient k_{O3} at the native resolution and at a ten times higher resolution.

4. Results and discussions

4.1 Influence of ozone and aerosol quantities on effective solar UV irradiance

As expected, the effective solar UV irradiance depends on atmospheric parameters. Its value changes more or less with the variation of a specific atmospheric parameter. Figures 4a,c illustrate the influence of atmospheric ozone absorption on erythemal G_{ee} (Fig. 4a) and cataract G_{ec} (Fig. 4c) effective spectral irradiances. Figures 4b,d illustrate the impact of aerosol amount on erythemal (Fig. 4b) and cataract (Fig. 4d) effective spectral irradiances. In all graphs, spectral UV solar irradiances are displayed in the background. At first glance, Fig. 4 shows that the UV-B spectrum is strongly influenced by variations in the atmospheric ozone content (Fig. 4a,c), while the atmospheric aerosol loading primarily influences the UV-A spectrum (Fig. 4b, d).

The strong ozone absorption in the UV-B band dominantly influences the effective solar UV irradiance. Figures 4a,c show that the G_{ec} magnitude is higher than G_{ee}., but the variation around a given wavelength is roughly similar. Both, erythemal and cataract effects, are strongly dependent on the ozone column content l_{o3}. For example, at wavelength $\lambda = 0.3112$ µm, when the ozone column increases from the reference value l_{o3} = 0.35 cm·atm to l_{o3} = 0.55 cm·atm, G_{ee} and G_{ec} decrease by half. At the same wavelength, when ozone column content decreases to a critical value l_{o3} = 0.2 cm·atm, G_{ee} and G_{ec} increase by 1.7 times.

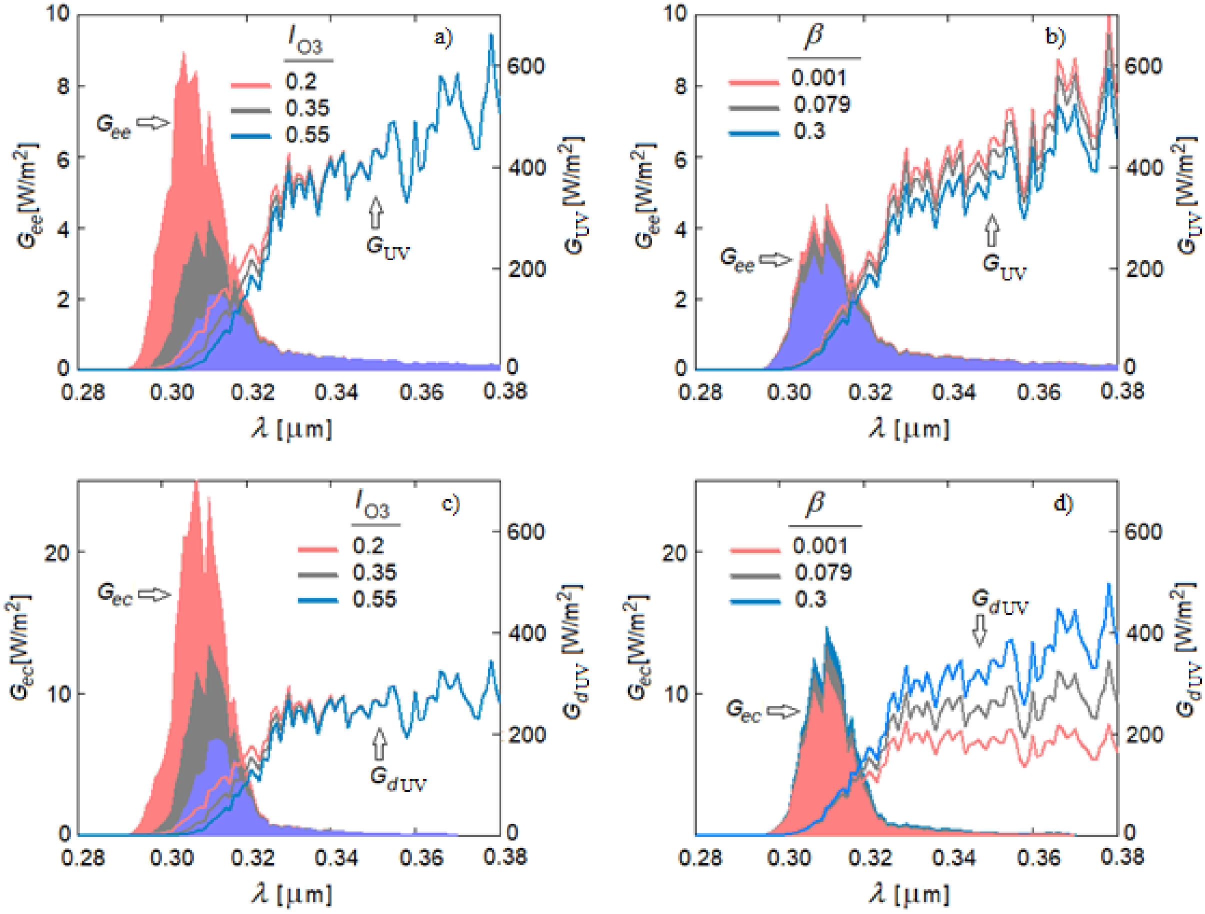

Figure 4. (a, c) Influence of the ozone column content l_{o3} and (b, d) Ångström turbidity coefficient β influence on the effective UV irradiance, (a, b) erythemal G_{ee} and (c, d) cataract G_{ec}. Spectral solar irradiance is displayed in each graph.

A notable difference in the G_{ee} and G_{ec} behavior is caused by the atmospheric aerosol loading. When β increases, G_{ee} decreases and G_{ec} increases (Fig 4b,d). This behavior is caused by the different components of solar irradiance that enter in the calculation of the two effective irradiances. G_{ee} is calculated based on the global solar irradiance which decreases with increasing aerosol content in the atmosphere. G_{ec} is calculated based on the diffuse component of solar irradiance, which increases with increasing aerosol content in the atmosphere due to the intensification of the scattering process. Somewhat non-intuitively, the results in Fig. 4b,d show that the impact of turbidity on G_{ee} and G_{ec} is quite small. The last part of the study focused on the influence of the aerosol nature on effective solar UV irradiance, erythema, and cataract.

4.2 Aerosol nature influence on effective solar irradiance

Many researchers have attempted to catalogue aerosols according to their optical properties. In this study, according to [14], five major aerosol classes are considered: desert dust (DD), urban-industrial (UI), biomass burning products (BB), marine aerosol (MA) and mixed (MX). These classes are defined by two aerosol-specific parameters, namely Ångström exponent α (as a measure of the aerosol size) and the single scattering albedo *SSA* (as a measure of the aerosol absorptivity). The last frame in Fig.5 roughly shows the geometric locus in the plane (α, SSA) of aerosol classes.

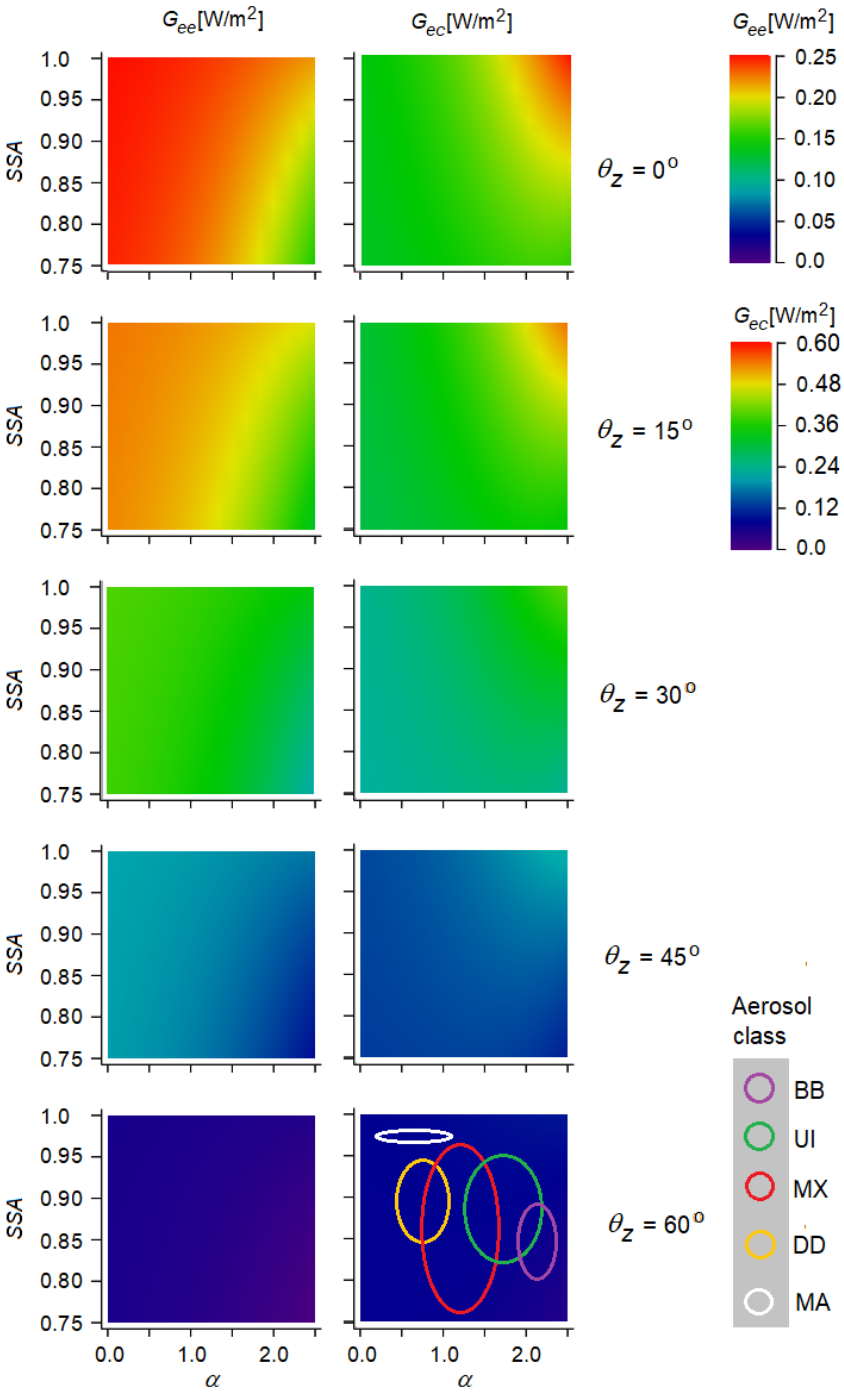

Figure 5. Effective spectral solar irradiance associated with erythema G_{ee} (left) and cataract G_{ec} (right) with respect to the Ångström exponent α and the single scattering albedo *SSA*. The geometrical locus of the aerosol classes in the plane (α, *SSA*) is indicated in the last frame: desert dust (DD), urban-industrial (UI), biomass burning products (BB), marine (MA) and mixed (MX).

Overall, Fig. 5 presents the effective solar UV irradiances G_{ee} and G_{ec} with respect to α, *SSA,* estimated at five values of the zenith angle θ_Z. 21 values for SSA, ranging from 0.75 to 1, and 16 values for α, with a ranging from 0 to 2.5, were considered for build each frame in Fig. 5. All other atmospheric parameters were kept at reference values.

Visual inspection of Fig. 5 shows that an increase of the zenithal angle θ_Z causes a sharp decrease of effective solar UV irradiance. This was expected because the UV solar irradiance decreases when the Sun descends in the sky. The two effective solar UV irradiances experience opposite behavior when the size of aerosol changes. As the atmosphere is loaded with coarser aerosols (small α) an increase in the erythemal effect and a decrease in the cataract effect are noticed. As the atmosphere is loaded with finer aerosols (large α), a decrease in the erythemal effect and an increase in the cataract effective irradiance are noticed. When *SSA* is changed, the two effective irradiances have similar behavior: the more reflective the aerosol (larger *SSA*), the more intense the erythema and cataract effects.

Figure 5, as a whole, shows that the nature of the aerosol has a complex influence on effective solar irradiances, erythema and cataract. On a given day, at the same time (given by θ_Z) and an atmosphere characterized by the same reference parameters (including aerosol loading), the nature of aerosol can dramatically influence the level of effective irradiance. For example, when the atmosphere is loaded with aerosol from desert dust (DD) class the erythemal effective irradiance G_{ee} is higher than for a similar atmosphere but loaded with smoke resulted from biomass burning (BB) class. When the Sun is near to zenith, in the case of DD aerosol G_{ee} can be even 50% higher than in the case of aerosol from BB class.

5. Conclusions

Based on the SMARTS2 model, a versatile and accurate application for estimating biologically effective solar irradiance was developed. The general equations capture the dependence of the biologically effective solar irradiance on the main influential atmospheric parameters in the UV spectral band (ozone absorption, aerosol amount and nature). The model allows estimating the biological dose accumulated by a human exposed to solar UV radiation by simply summing the effective irradiances over time. A new continuous equation for the biological action function associated with cataract is reported. As case study, the impact of atmospheric aerosol loading and nature on the biologically effective solar UV irradiances is analyzed. Non-intuitive effects are revealed. For example, the results show that the atmospheric turbidity is a less influential parameter, while aerosol nature is a stronger influential parameter.

Higher values of the erythemal effective solar UV irradiance are observed when the atmosphere is loaded with coarse and absorbing aerosol. Differently, fine and reflective aerosol determine high levels of cataract effective solar UV irradiance. The work in progress is focused on estimating the effective solar UV irradiance on surfaces with different spatial orientations, with the aim of estimating the biological dose accumulated by a human with a certain behavior outdoors.

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