

AEROSOL IMPACT ON UV SOLAR IRRADIANCE AND DIFFUSE FRACTION

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Article Info	Abstract
<i>Received: 03.10.2024</i> <i>Accepted: 15.10.2024</i> Keywords: ultraviolet radiation; UV spectrum; aerosol; diffuse fraction; Ångström parameters	Aerosols modify the solar irradiance levels in the ultraviolet (UV) spectral band and, as a result, influence the magnitude of the biological effects of solar radiation. Also, aerosols contribute to the changes in nature (direct/diffuse) of the UV solar radiation received by a biological organism. This work quantitatively evaluates the aerosol effects on all components of solar UV irradiance (direct-normal, diffuse and global) under clear sky conditions. A note of originality is given by the wide perspective and the depth of detail in which the influence of aerosols in the UV band is captured. In addition to the common parameters, such as aerosol nature and the atmospheric aerosol loading, fine properties of aerosols, such as absorptivity and asymmetry factor, are considered. A distinctive feature of this study is given by the analysis of the effects of aerosols on the UV diffuse fraction. In general, changes in aerosol properties substantially change the direct-normal and diffuse components of UV solar irradiance and, to a lesser extent, the global component. The diffuse fraction in the UV band decreases notably with the increase of the Ångström turbidity coefficient and the Ångström exponent. Differently, the diffuse fraction is much less sensitive to the variation of the single scattering albedo and the asymmetry factor.

1. Introduction

The aerosol impact on solar irradiance is well documented today. There is a plethora of scientific reports dealing with the effect of the atmospheric aerosol on broadband solar irradiance [1-2]. Contrarily, the studies focused on the influence of aerosol in the ultraviolet (UV) spectral band (0.280–0.400 μm) are significantly fewer than those in the broadband. This happens although the aerosol considerably influences the solar radiation spectrum in the UV band. Generally, the research papers treat the effect of aerosol on the global UV solar irradiance, this component being taken into account when evaluating biological effects. Some

studies addressing the interaction of solar radiation with atmospheric aerosol from different perspectives, are acknowledged next.

The specific atmospheric transmittance related to the extinction of solar radiation by aerosols is almost always explicitly considered in the parametric modeling of the UV solar irradiance. A good example is FASTUV [3], a parametric model for estimating UV solar irradiance in all-sky conditions, based on Leckner's spectral model [4]. Considering the particular relationship of UV radiation with the biosphere, frequently the research aims directly at estimating the effective biological UV dose under clear sky [5]. The biological action spectrum, as a carrier of biological effects of UV radiation, is encapsulated into the atmospheric transmittance, leading to the calculation of the effective irradiance by simple algebra [5]. Both models, reported by [3] and [5], estimate the specific atmospheric transmittance associated to the aerosol extinction of the UV solar radiation passing through the atmosphere. Regional studies between UV radiation levels and aerosols are performed too. Reference [6] analyses the relationship between UV radiation and aerosol optical depth (AOD) in China, finding a negative linear correlation between UV irradiance and AOD. A negative linear correlation (stronger than that between UV irradiance and AOD) was also found between the UV fraction and AOD. Another regional study [7] deals with the short- and long-term variability of spectral UV irradiance at Thessaloniki, Greece, in association with changes in ozone column content, AOD and cloudiness. The authors report an increase in the annual mean of UV irradiance level during 1994 to 2006 followed by a relatively stable level thereafter. This behavior is assigned to the combined changes in the aerosol loading of the atmosphere and optical properties of aerosols [7].

In this paper, the effect of aerosol on all components of UV solar irradiance is evaluated. A note of originality is given by the wide perspective and the depth of detail in which the influence of aerosols in the UV band is captured. In addition to the common parameters, such as aerosol nature and the atmospheric aerosol loading, fine properties of aerosols, such as single scattering albedo and asymmetry factor, are considered. A distinctive feature of this study is given by the analysis of the effects of aerosols on the UV diffuse fraction.

The rest of the paper is organized as follows. Section 2 introduces the spectral solar irradiance model, describes the synthesis of UV spectra and presents the research methodology. The results are shown and analyzed in Sec. 3. The main conclusions are gathered in Sec. 4.

2. Data and methodology

2.1. Synthetic UV spectra

The study was conducted with synthetic UV spectra generated with SMARTS2 [8, 9], a worldwide used clear-sky spectral solar irradiance model. The original version [8] was implemented considering the particularities of the atmospheric transmittance in the UV band. The UV spectral irradiance components, direct-normal $G_{dn}(\lambda, m, \alpha, \beta)$, diffuse horizontal $G_d(\lambda, m, \alpha, \beta, SSA, g)$ and global horizontal $G(\lambda, m, \alpha, \beta, SSA, g)$, are expressed as functions of atmospheric parameters:

$$G_{dn}(\lambda, m, \alpha, \beta) = G_e(\lambda) \tau_o(\lambda, m) \tau_n(\lambda, m) \tau_R(\lambda, m) \tau_g(\lambda) \tau_a(\lambda, m, \alpha, \beta) \quad (1)$$

$$G_d(\lambda, m, \alpha, \beta, SSA, g) = G_{dR}(\lambda, m, \alpha, \beta, SSA) + G_{da}(\lambda, m, \alpha, \beta, SSA, g) \quad (2)$$

$$G_{dR} = \frac{1}{2} G_e(\lambda) \tau_o^*(\lambda, m) \tau_n(\lambda, m) \tau_g(\lambda, m) \tau_{aa}(\lambda, m, \alpha, \beta, SSA) (1 - \tau_R(\lambda, m)^{0.9}) \frac{1}{m} \quad (3)$$

$$G_{da} = \gamma(m, g) G_e(\lambda) \tau_o^*(\lambda, m) \tau_n(\lambda, m) \tau_g(\lambda, m) \tau_R(\lambda, m) \tau_{aa}(\lambda, m, \alpha, \beta, SSA) \cdot [1 - \tau_{as}(\lambda, m, \alpha, \beta, SSA)] \frac{1}{m} \quad (4)$$

$$G(\lambda, m, \alpha, \beta, SSA, g) = G_{dn}(\lambda, m, \alpha, \beta) \cdot \frac{1}{m} + G_d(\lambda, m, \alpha, \beta, SSA, g) \quad (5)$$

The equations are written underlining the dependence of the UV irradiance on the wavelength λ , atmospheric optical mass m and the physical parameters of the aerosols: the Ångström turbidity coefficient β (as a measure of the atmospheric aerosol loading), the Ångström exponent α (as a measure of the aerosol granularity), single scattering albedo SSA (as a measure of the aerosol absorptivity) and the asymmetry factor g . Aiming to highlight the influence of the atmospheric optical mass m , only the Sun elevation angles $h > 10^\circ$ were considered. In this case, m and h are related with a very good approximation as follows:

$$\sin h \cong \frac{1}{m} \quad (6)$$

Reference [8] provides a full description of the specific atmospheric transmittances τ .

2.2. Methodology

The methodology followed for evaluating the impact of the aerosol on UV solar irradiance is as follows. First, spectra of the solar UV radiation at the ground were generated with SMARTS2 by varying the aerosol specific parameters in the typical range: $0.01 \leq \beta \leq 0.3$, $0 \leq \alpha \leq 3$, $0.6 \leq SSA \leq 1$ and $0.4 \leq g \leq 0.8$. For each set of aerosol parameters the atmospheric optical mass was varied in the range $0.5 \leq m \leq 5.0$. The ozone column content and the nitrogen dioxide column content were prescribed at $l_{O_3} = 0.35 \text{ cm}\cdot\text{atm}$ and $l_{NO_2} = 0.0002 \text{ cm}\cdot\text{atm}$, respectively. In order to have a benchmark in the analysis, a reference spectrum was chosen. It is defined by the following atmospheric condition: $m = 1.5$, $l_{O_3} = 0.35 \text{ cm}\cdot\text{atm}$, $l_{NO_2} = 0.0002 \text{ cm}\cdot\text{atm}$, $w = 2.3 \text{ g/cm}^2$, $\beta = 0.079$, $\alpha = 1.3$, $SSA = 0.95$ and $g = 0.7$.

For each generated spectrum, the direct-normal, diffuse and global spectral irradiances were integrated with respect to the wavelength in the UV spectral range $[0.28\mu\text{m}, 0.4 \mu\text{m}]$. The obtained values represent the solar irradiance components in the UV band. The changes induced in the direct-normal, diffuse and global solar irradiances by the aerosol parameters (β , α , SSA and g) variations were evaluated and analyzed. Under the reference spectrum the solar irradiance components in UV are estimated as follows: $G_{dn} = 23.4 \text{ W/m}^2$, $G_d = 20.8 \text{ W/m}^2$ and $G = 36.5 \text{ W/m}^2$.

At the last step, the diffuse fraction in the UV spectral band was calculated according to its definition, the ratio between diffuse and global solar irradiances at the ground level:

$$k_d \equiv \frac{G_d}{G} \quad (7)$$

The diffuse fraction is a broadband radiometric parameter routinely used in solar energy modeling under all-sky conditions [10]. Under clear sky conditions, k_d mostly depends on the atmospheric aerosol loading and the atmospheric optical mass m [11]. Thus, the diffuse fraction under clear sky appears naturally as a quantifier for the way in which the atmosphere separates the global solar irradiance into beam and diffuse components through aerosol absorption and scattering, and Rayleigh scattering. In this study, the dependence of k_d to the aerosol properties in the UV spectral band was investigated.

3. Results and discussions

3.1. Direct-normal UV irradiance

From the aerosol's perspective, the direct-normal spectral irradiance G_{dn} depends on the Ångström turbidity coefficient β and the Ångström exponent α (Eq. 1). Figure 1 illustrates the effect of the two parameters on G_{dn} . Figure 1a) shows four UV spectra emulated with the reference set of atmospheric parameters, with one exception, β . It takes a different value for each curve. Figure 1b) is like Fig. 1a), but this time the parameter of the curves is α . Extraterrestrial solar radiation (ETR) spectrum is also displayed. Even with an insignificant presence of aerosols in the atmosphere ($\beta = 0.01$), G_{dn} is significantly reduced in magnitude by ozone absorption and Rayleigh scattering. As α and β increase, more and more photons are removed from the direct-normal radiation beam. In other words, G_{dn} notably decreases with the increasing of the atmospheric aerosol loading. Figure 1b) shows that at a moderate loading of the atmosphere with aerosols ($\beta = 0.079$), the decrease of the solar spectral irradiance through the atmosphere is more pronounced as the aerosols are more absorbent. Since the scattering process by aerosols is continuous with respect to wavelength, the contour of the spectrum is largely preserved. However, as α and β increase, a smoothing of the curves occurs.

Figure 1 overall shows the significant magnitude of the effect of aerosols on direct-normal spectral irradiance, and once again argues this study. For instance, at a wavelength $\lambda = 0.35 \mu\text{m}$, spectral solar irradiance at the top of the atmosphere is $G_e(\lambda = 0.35\mu\text{m}) = 1018.3 \text{ W/m}^2\mu\text{m}$. In the reference atmosphere condition, without aerosols, this value is reduced at the ground to $G_{dn}(\lambda = 0.35\mu\text{m}, \beta = 0.01) = 373.7 \text{ W/m}^2\mu\text{m}$ (a percentage decrease of 63.3%). If the atmosphere is heavily loaded with aerosols ($\beta = 0.3$), the spectral direct-normal irradiance decreases to $G_{dn}(\lambda = 0.35\mu\text{m}, \beta = 0.3) = 68.0 \text{ W/m}^2\mu\text{m}$ (-93.3%). This means that, when passing from a clean atmosphere to an atmosphere polluted with aerosols, the direct-normal beam of solar radiation in the UV range is reduced by roughly 81% at the wavelength $\lambda = 0.35 \mu\text{m}$.

Figure 2 shows the variation of G_{dn} with respect to the atmospheric optical mass m for different levels of atmospheric aerosol loading (Fig. 2a) and for different aerosol types (Fig. 2b). As expected, G_{dn} decreases when both coefficients increase. The strong aerosol loading of the atmosphere and/or the fine aerosol (for example smoke-absorbing particles) reduce the UV radiation at the ground to almost zero. In the atmospheric conditions defining the reference spectrum, changing β to 0.01 (a clean atmosphere, loaded with a small amount of aerosol) leads

to an increase in G_{dn} by 46.7 % while changing β to 0.3 leads to a decrease in G_{dn} by 70.5%. The coarse mode of aerosol ($\alpha = 0$, characteristic to desert dust) leads to an increase in G_{dn} by 37.8 %, while the fine mode ($\alpha = 3$, characteristic to aerosol resulted from biomass burning) leads to a decrease in G_{dn} by 85.4%.

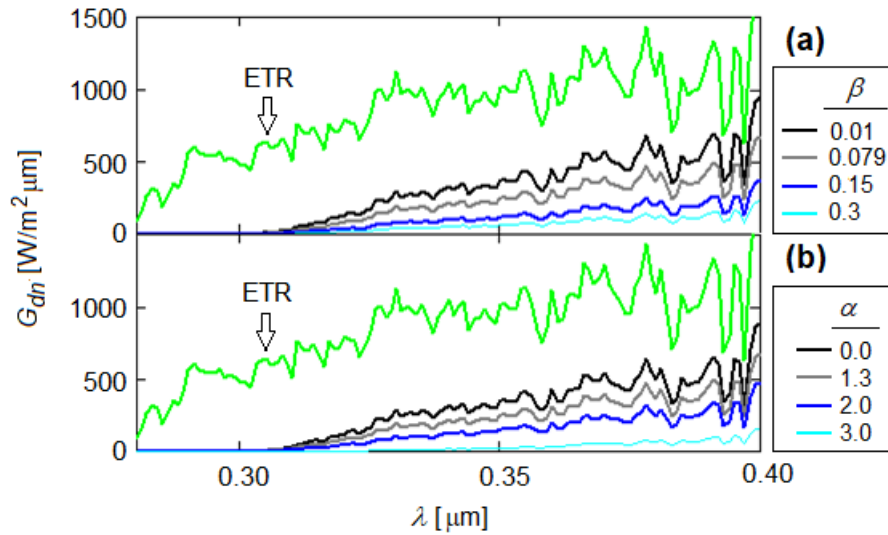


Figure 1. Spectral direct-normal irradiance $G_{dn}(\lambda)$ as function of wavelength λ . The curves parameter is: (a) the Ångström turbidity coefficient β and (b) the Ångström exponent α . The other atmospheric parameters in Eq. (1) are kept at the reference values. The UV extraterrestrial spectrum (ETR) is mapped in green.

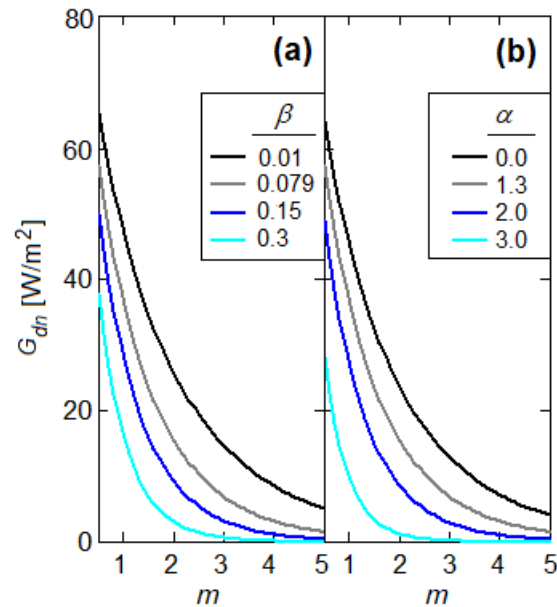


Figure 2. Direct-normal irradiance G_{dn} as function of atmospheric mass m . The curves parameter is: (a) the Ångström turbidity coefficient β and (b) the Ångström exponent α . The other atmospheric parameters in Eq. (1) are kept at the reference values: $l_{O_3} = 0.35 \text{ cm}\cdot\text{atm}$, $l_{NO_2} = 0.0002 \text{ cm}\cdot\text{atm}$, $w = 2.3 \text{ g/cm}^2$.

3.2. Diffuse UV irradiance

In addition to the Ångström parameters β and α , the spectral diffuse irradiance (Eq. 2) is a function of the single scattering albedo SSA and the aerosol asymmetry factor g . Thus, UV diffuse irradiance, depends on the same four aerosol's parameters.

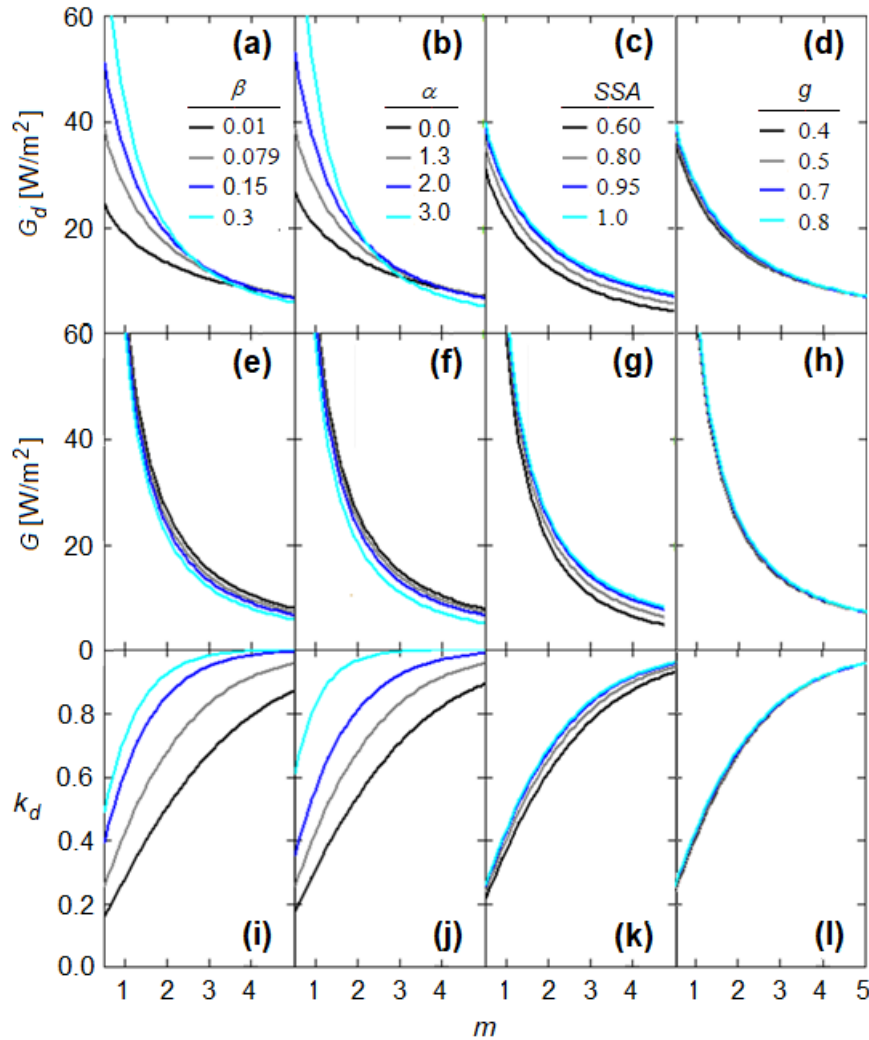


Figure 3. UV irradiance components: (a, b, c, d) diffuse G_d , (e, f, g, h) global G and (i, j, k, l) the diffuse fraction k_d with respect to the atmospheric optical mass m . The curves parameter is: (a, e, i) the Ångström turbidity coefficient β and (b, f, j) the Ångström exponent α , (c, g, k) single scattering albedo SSA and (d, h, l) asymmetry factor g . The other atmospheric parameters in Eqs. (2-5) are kept at the reference values: $l_{O_3} = 0.35 \text{ cm}\cdot\text{atm}$, $l_{NO_2} = 0.0002 \text{ cm}\cdot\text{atm}$, $w = 2.3 \text{ g/cm}^2$.

The variation of G_d with β , α , SSA and g is illustrated in Figs. 3a, 3b, 3c and 3d, respectively. While β and α strongly influence the diffuse irradiance, g has a negligible influence. At low atmospheric mass, the increase in β and α leads to a sharp increase in G_d . As m increases, the effect is getting weaker, disappearing completely at approximately $m = 4$. At constant β and α , the decrease in SSA causes a moderate decrease in G_d regardless of the atmospheric optical mass, as an effect of the intensification of the absorption of solar radiation

by aerosols. In concrete figures, under the atmospheric conditions defining the reference spectrum, changing β to 0.01 leads to a decrease in G_d of 26.0 % while changing β to 0.3 leads to an increase in G_d by 34.3%. The coarse mode of aerosol ($\alpha = 0$) leads to a decrease in G_d by 21.7 %, while the fine mode ($\alpha = 3$) leads to an increase in G_d by 37.3%. A more absorbing aerosol ($SSA = 0.6$) decreases G_d with 25.1 % while a perfect diffusive aerosol ($SSA = 1$) increases G_d with 3.6 %. It was already shown a low influence of g on G_d , the extreme values of g changing compared to the reference with -6.7% when $g = 0.4$ and +2.1% when $g = 0.8$.

Aiming to provide the reader with a broader perspective on the solar irradiance, Fig. 4 shows the spectral diffuse UV irradiance at ground. Each spectrum was generated under the reference conditions with only one aerosol parameter changed. These spectra correspond to the instances used in the previous numerical illustrations.

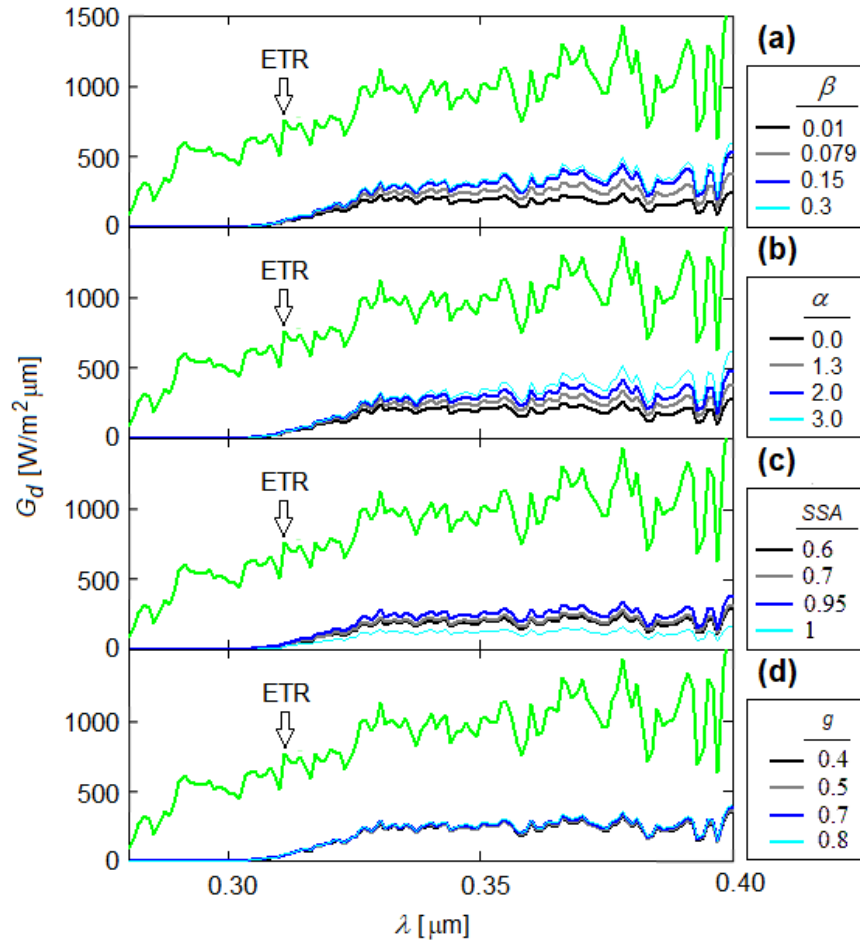


Figure 4. Spectral diffuse irradiance G_d as function of wavelength λ . The curves parameter is: (a) the Ångström turbidity coefficient β , (b) the Ångström exponent α , (c) the single scattering albedo SSA and (d) the asymmetry factor g . The other atmospheric parameters in Eq. (1) are kept at the reference values. The UV extraterrestrial spectrum (ETR) is mapped in green.

3.3. Global UV irradiance

The variation of global solar irradiance G with β , α , SSA and g is illustrated in Figs. 3e, 3f, 3g and 3h, respectively. Global solar irradiance is the sum in the horizontal plane of direct-normal and diffuse components (Eq. 5). Since aerosols influence the two components, G_{dn} and G_d , in opposite directions, the effect of aerosols on G is much lower than on each component taken separately. Again, in concrete figures, under the atmospheric conditions defining the reference spectrum, changing β to 0.01 leads to an increase in G by 5.1% while changing β to 0.3 leads to a decrease in G by 10.5%. The coarse mode of aerosol ($\alpha = 0$) leads to an increase in G 4.3 %, while the fine mode ($\alpha = 3$) leads to a decrease in G by 15.2%. A more absorbing aerosol ($SSA = 0.6$) decreases G by 13.2 % while a perfect diffusive aerosol ($SSA = 1$) increases G by 2.0 %. In absolute terms, these percentages are significantly lower than in the case of the diffuse UV component, analyzed in the previous section. The asymmetry factor g is a low influential parameter of G . Compared to the reference, the extreme values of g change G by -3.4% when $g = 0.4$ and +1.2% when $g = 0.8$, half values compared to the amplitudes of G_d variation.

If we think about the UV index, which is calculated based on the global UV spectral irradiance [12], we can draw the conclusion that it is also rather weakly influenced by the change in the properties of aerosols. This statement is well argued by Fig. 5, where the UV spectrum at different values of β (Fig. 5a) and α (Fig. 5b) are plotted.

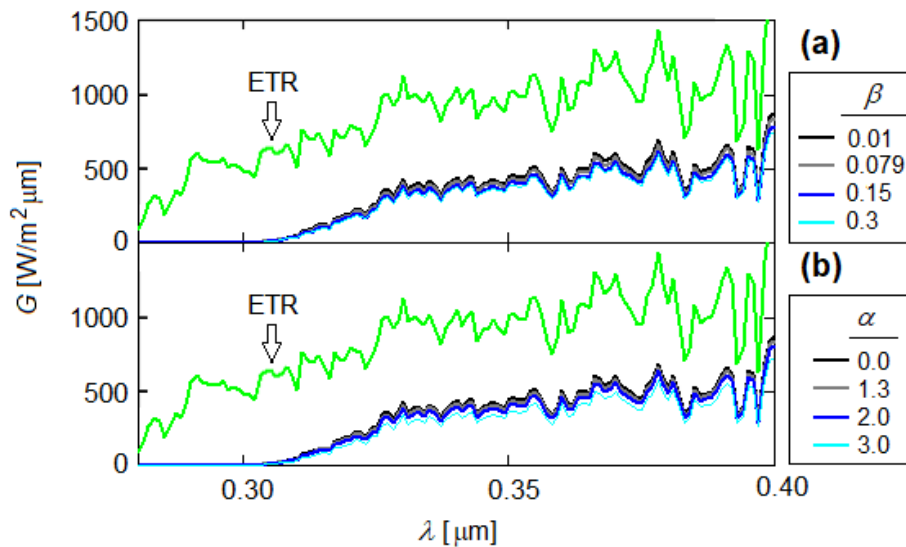


Figure 5. Spectral global irradiance G as function of wavelength λ . The curves parameter is: (a) the Ångström turbidity coefficient β and (b) the Ångström exponent α . The other atmospheric parameters in Eq. (1) are kept at the reference values. The UV extraterrestrial spectrum (ETR) is mapped in green.

3.4. UV diffuse fraction

The diffuse fraction under clear sky has been investigated in the broadband spectrum but rarely in narrow spectral bands, such as the UV band. However, diffuse UV radiation generates biological effects similar to direct UV radiation. Over the course of a year, we are exposed to significantly more diffuse UV radiation than direct. If we think about the effect on the eye, since diffuse radiation comes from all parts of the sky, it can be even more harmful than direct radiation [13-14], which we know to avoid. As we have seen in Sec. 3.2, under clear sky conditions, a significant amount of UV radiation is diffuse. From the perspective of monitoring the UV radiation level on the ground, global UV solar irradiance is often measured. As a result, the development of models for the UV diffuse fraction gains a practical importance. In this general context, the current study reports concerning the influence of aerosol properties on the diffuse fraction.

The variation of the UV diffuse fraction k_d with β , α , SSA and g is illustrated in Figs. 3i, 3j, 3k and 3l, respectively. As expected, the k_d increases with the increase of atmospheric optical mass m , the Ångström turbidity coefficient β and the Ångström exponent α . What is interesting and non-intuitive in Figs. 3i)-l) is the amplitude of the k_d variation with respect to the aerosol parameters. At low values of the atmospheric optical mass (about $m < 2$) the diffuse UV component is relatively small. k_d increases as the aerosol loading increases. In an atmosphere moderately loaded to polluted with aerosols, the diffuse component becomes predominant, k_d increasing over 0.5. For example, in an atmosphere polluted with mixed aerosol ($\beta = 0.3$), k_d exceeds 0.6 even at low values of the atmospheric optical mass, indicating that more than 2/3 of the global UV solar irradiance is diffuse. A similar behavior is observed in the variation of k_d with α . In conditions of aerosols pollution or in the case of moderate loading of the atmosphere with fine aerosol, at higher values of m , k_d saturates, the UV radiation being predominantly of diffuse nature. SSA has a much smaller influence (Fig. 3k), even at large values of m . Regardless of m , a shift of SSA change k_d by approximately the same proportion. The asymmetry factor has a low influence on k_d (Fig. 3l) in the entire range of m .

The variation of UV diffuse fraction with aerosol properties is illustrated next in concrete figures. Under the atmospheric conditions defining the reference spectrum, changing β to 0.01 leads to a decrease in k_d of 29.6 % (from 0.57 to 0.37) while changing β to 0.3 leads to an increase in k_d of 50.2% (from 0.57 to 0.85). The coarse mode of aerosol ($\alpha = 0$) leads to a decrease in k_d of 24.1 % (from 0.57 to 0.43), while the fine mode ($\alpha = 3$) leads to an increase in k_d by 62.0% (from 0.57 to 0.92). A more absorbing aerosol ($SSA = 0.6$) decreases k_d of 11.6 % (from 0.57 to 0.50) while a perfect diffusive aerosol ($SSA = 1$) increases k_d by 1.5 % (from

0.57 to 0.58). For aerosols, the asymmetry factor g ranges between approximative 0.4 and 0.8. The more the particles scatter in the forward direction, the higher is the asymmetry factor. For isotropic scattering $g = 0$. In this example, under the atmospheric conditions defining the reference spectrum, changing from 0.7 to 0.4 leads to a decrease in k_d of 2.7% while changing g to 0.8 leads to an increase in k_d of 0.91%.

4. Conclusions

Aerosols are atmospheric constituents whose concentration and properties are volatile. The aerosol influences the UV radiation levels, and the biological doses associated with various harmful effects on human health (erythema, cataracts, etc.). This study evaluated the influence of different properties of aerosols on all components of solar UV irradiance and diffuse fraction under clear sky conditions.

The increase in the atmospheric aerosol loading (measured by Ångström turbidity coefficient) significantly decreases the direct-normal UV solar irradiance and increases the diffuse component. The transition from a coarse aerosol to a fine aerosol (measured by Ångström exponent) also causes a significant decrease of the direct-normal component and an increase of the diffuse component. The two tendencies are compensated when evaluating the global UV solar irradiance, determining its weaker dependence on the properties of aerosols. The increase in the aerosol absorptivity (measured by the single scattering albedo) causes a moderate decrease of the diffuse component, regardless of the atmospheric optical mass.

A distinctive feature of this study is given by the analysis of the effects of aerosols on the UV diffuse fraction. The diffuse fraction in the UV band decreases notably with the increase of the Ångström turbidity coefficient and the Ångström exponent. Differently, the diffuse fraction is much less sensitive to the variation of the single scattering albedo and the asymmetry factor.

These results can be regarded as a basis for integrating the aerosols properties in the parametric models for estimation solar irradiance within the UV spectral band. The results can be used further for understanding much deeper the aerosol influence on the biological effects of the UV radiation. Thus, our future work will be focused on evaluating the complex effect of aerosols on the effective erythema irradiance and UV index.

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