Clear-sky spectral UV radiation modeling

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Abstract

The parametric model NEOPLANTA was used to study the effects of various atmospheric conditions on terrestrial spectral UV irradiance. The capability of the model to correctly reproduce processes in the atmosphere is tested by changing input parameters such as ozone content, solar zenith angle, amount and type of aerosols, and altitude. The results of the model testing on input parameter change were satisfactory. As is expected, the amount of UV radiation reaching the surface is the most dependable on ozone layer thickness and solar zenith angle. Erythemal irradiance is more dependent on changes in the amount of ozone in the atmosphere than spectral UV irradiance, showing a significantly greater impact of UV-B radiation on human skin than radiation in the UV-A part of the spectrum.

Introduction

Although ultraviolet (UV) radiation (UVR) is a small part of the solar spectrum, its effect on the living world is very important because it is highly energetic and biologically very active. UVR is divided into the UV-C range (100–280 nm), UV-B range (280–315 nm), and UV-A range (315–400 nm). Surface UVR is predominantly within the UV-A range, while the UV-B wavelengths are largely filtered out by stratospheric ozone and make less than 5% of surface UVR. The UV-C radiation does not reach the earth's surface because it is completely absorbed in the upper atmosphere by ozone and oxygen. Besides ozone content, the ambient UVR depends on many other variables such as the position of the Sun, cloud cover, atmospheric aerosols type and content, surface albedo, and altitude. Processes are very complex since factors that control attenuation vary as a function of time and location.

The detection of the large depletion of stratospheric ozone in the last three decades of the 20th century (Molina and Rowland, 1974; Kaurola et al., 2000; etc) initiated increased public and scientific interest in the state of stratospheric ozone levels and variability of UV radiation and led to the establishment of the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987. However, although mitigation activities over the past three decades significantly limited the production of ozone-depleting substances and stabilized the ozone levels, UV radiation levels are still high (EEAP, 2019).

Although the ground-based UV monitoring network constantly growing since its formation in the 1980s, the measuring sites are still sparsely located, while UV data are, in most cases, limited to the period up to 25 years. Most of the stations are equipped with broadband meters (75% in Europe) that measures irradiance over a certain wavelength range and convert it into UV index, while the spectral measurement is even rarer (Schmalwieser, 2017). Due to lack of the long-term measurements different modeling techniques based on radiative transfer, and empirical method has been established (Diffey, 1977; Ruggaber et al., 1994, Mayer and Kylling, 2005, Lindfors and Vuilleumier, 2005; Rieder *et al.*, 2008; Paulescu *et al.*, 2010; etc). Radiative transfer models use available atmospheric parameters and estimate the UV radiation considering the scattering and absorption processes that take place in the radiation path through the atmosphere. In general, those models are more accurate than empirical, although their accuracy depends on the availability and reliability of input parameters.

This paper aims to improve our understanding of variations in the surface UVR using the parametric model NEOPLANTA which was developed at the University of Novi Sad (Malinović, 2003) as the first original model in Serbia.

Analysis and results

Description of the model

The numerical model NEOPLANTA calculates the intensity of clear sky direct and diffuse solar UVR, the corresponding erythemal UVR, and the UV index on the horizontal surface. The calculation of direct and diffuse UVR was performed with a wavelength resolution of 1 nm in the range of 280-400 nm. The model simulates the effects of the absorption of the UVR by O_3, SO_2, and NO_2, and absorption and scattering by aerosol and air molecules in the atmosphere. It calculates the spectral irradiance for a given solar zenith angle (SZA), but there is also the possibility of calculating the UV index for the whole day at intervals of half an hour from sunrise to sunset. It is designed so that it can be used in any location in the world at any time.

In the model, the atmosphere is divided into parallel layers (maximum 40), and it is assumed that each layer is a homogeneous medium with constant meteorological parameters. The vertical resolution of the model is 1 km for altitudes less than 25 km and 5 km for altitudes between 25 km and100 km, while the thickness of the last layer varies depending on the altitude. The values of the meteorological elements in each layer are determined using vertical profiles. The model contains data on the vertical profile of meteorological parameters of the standard atmosphere (Kurucz et al.,1984), but it is possible to use measured or modeled values. The influence of the surface on the intensity of UVR was calculated using the spectral albedo values for nine different types of surfaces.

The required input parameters are the local geographic coordinates and time or SZA, altitude, spectral albedo, and the total amount of gases. The model includes its vertical gas profiles (Ruggaber et al. 1994) and extinction cross-sections (Burrows et al. 1999; Bogumil et al. 2000), extraterrestrial solar irradiance shifted to terrestrial wavelength (Koepke et al. 1998), aerosol optical properties for 10 different aerosol types (Hess et al. 1998), and spectral albedo for nine different ground surface types (Ruggaber et al. 1994). Output data are spectral direct, diffuse, and global irradiance divided into the UV-A and UV-B part of the spectrum, erythemal irradiance, UV index (UVI), spectral optical depth, and spectral transmittance for each atmospheric component. All outputs are computed at the lower boundary of each layer.

The UV irradiance is calculated as the sum of the direct and the diffuse components. Calculation of the direct part of UVR is carried out by Beer-Lambert law. The direct irradiance $E_{dir}(\lambda)$ at wavelength λ received at ground level by unit area is given by:

$$E_{dir}(\lambda) = E_0(\lambda)T(\lambda), \quad (1)$$

where $E_0(\lambda)$ is the extraterrestrial irradiance corrected for the actual Sun-Earth distance and $T(\lambda)$ is the total transmittance that includes O_3, NO_2, SO_2, aerosol, and air transmittances. Each transmittance is calculated using optical depth $\tau(\lambda)$ is the product of extinction coefficient $\beta(\lambda)$ and ray path through the atmosphere s:

$$\mathrm{T}(\lambda) = exp[-\tau(\lambda)] = exp[-\beta(\lambda)s]. \quad (2)$$

The extinction coefficient of UV radiation, $\beta(\lambda)$, is calculated by the product of the cross-sectional area, $\sigma(\lambda)$, and layer particle concentration, N.

The diffuse UVR, $E_{dif}(\lambda)$, is divided into three components: (i) the Rayleigh scattering component, $E_{ray}(\lambda)$ (ii) the aerosol scattering component, $E_{aer}(\lambda)$ and (iii) the component that accounts for multiple reflections of irradiance between the ground and the air, $E_{rf}(\lambda)$. Calculation of $E_{dif}(\lambda)$ is made using an improved set of the equation described by Bird and Riordan (1986) and Blattner (1983) that were modified to include the wavelength range calculated by the NEOPLANTA model. The downward fraction is calculated from the same transmittance functions used to determine the direct UV irradiance. Calculation procedure of $E_{dif}(\lambda)$ is described in more detail in Malinović (2003) and Malinovic et al. (2006).

Evidence of an increasing number of skin cancer cases (IARC, 1992) has made it necessary to inform the public about the risk of solar radiation. Therefore, to take into account the potential erythemal effects of UVR on human skin calculated UV spectrum (in $Wm^{-2}nm^{-1}$) was multiplied by the erythema spectral weighting function ($s_{er}(\lambda)$) adopted by the CIE (CIE, 2019) thus providing the erythemal irradiance ($E_{er}(\lambda)$, in Wm^{-2}):

$$E_{er}(\lambda) = \int E(\lambda)s_{er}(\lambda)d\lambda, \quad (3)$$

where $E(\lambda)$ is spectral UV irradiance ($E_{dir}(\lambda) + E_{dif}(\lambda)$). $E_{er}(\lambda)$ assesses the potential of UV radiation to induce erythema (sunburn) and it is usually expressed as UVI ($UVI = E_{er} \times 40$). The erythemal irradiance accumulated over time gives the erythemal radiant exposure (H_{er}, in $\mathrm{Jm^{-2}}$) (CIE, 2019).

Sensitivity of the model to input atmospheric parameters

Similar to measurements, models are subject to uncertainties that can be divided into two groups, numerical errors and uncertainties due to input parameters. Numerical errors can be avoided by programming and testing, while the uncertainties due to input parameters can be examined by sensitivity analysis and comparison with measured data.

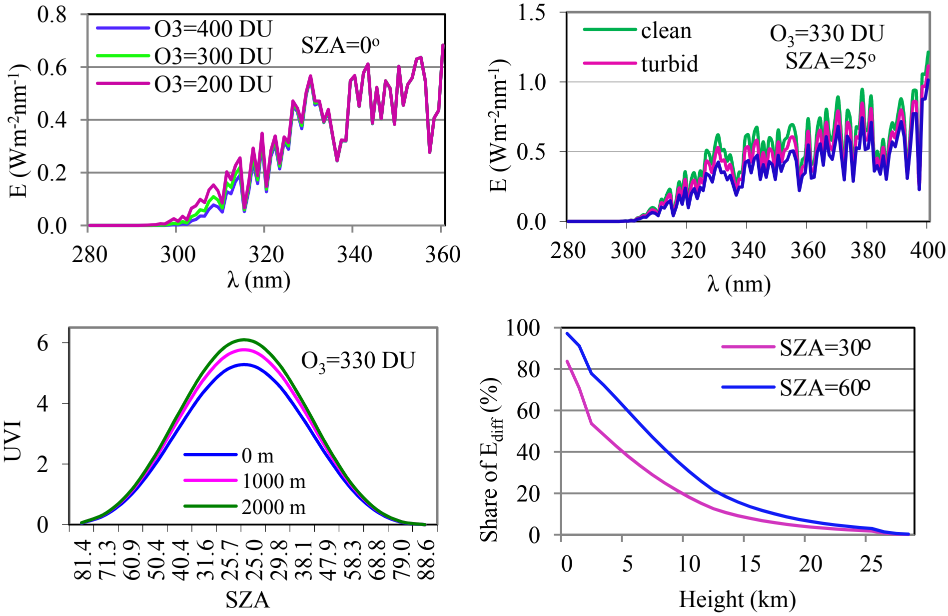

Fig. 1. Dependence of spectral UV irradiance on (a) ozone thickness and (b) air pollution levels; (c) dependence of UVI on altitude, and (d) dependence of share of diffuse UV irradiance on SZA.

All the input parameters of the model have an impact on the intensity of UVR reaching the surface, but not to the same extent. The capability of the model to correctly reproduce processes in the atmosphere is tested by changing input parameters. The tests have shown that the model can properly simulate changes in the intensity of UVR as well as the ratio of direct and diffuse UVR with the change in input parameters. The simulations qualitatively agree with the existing knowledge: (i) the intensity of UVR decreases with increasing the thickness of the ozone layer (Fig. 1a), the amount of aerosol (Fig. 1b), altitude, and the increase in

SZA (Fig. 1c), (ii) the contribution of diffuse UVR increases with increasing SZA (Fig. 1 d), the amount of aerosols, the presence of aerosols with a higher amount of water-soluble particles, air humidity, and more reflecting surface. Elevation of the surface above sea level has a small effect, but it becomes considerable in mountainous areas. Simulations have shown that ozone absorbs the largest amount of radiation while SO_2 and NO_2 have little impact, except in heavily polluted areas. It has been shown that aerosols can also greatly affect the amount and composition of UVR on the surface, while the effect on the surface reflection is small, except in the case of snow-covered areas. It has also been shown that the contribution of diffuse radiation in clear-sky UVR reaching the surface is large and that its amount depends mostly on SZA.

While extraterrestrial radiation $E_0(\lambda)$ is almost constant over time in UV-B and UV-A range $T(\lambda)$ transmittance is highly dependent on the composition of the Earth's atmosphere and is therefore very variable over time. However, as Fig. 1a shows, while $E_0(\lambda)$ is highly variable on the wavelength scale, the $T(\lambda)$ forms a relatively smooth curve. The processes in the Earth's atmosphere, mainly ozone absorption and Rayleigh scattering, vary smoothly with wavelength, define the transmittance $T(\lambda)$ and form the UV-B cutoff. The resulting spectrum $E(\lambda)$ in Fig. 2b is the product of graphs in Fig. 1a. Erythemal irradiance $E_{er}(\lambda)$ has a maximum in the wavelength range of 300 to 320 nm. $E_{er}(\lambda)$ and therefore it is more dependent on changes in the amount of ozone in the atmosphere than $E(\lambda)$, showing a significantly greater impact of UV-B radiation on human skin than radiation in the UV-A part of the spectrum (Fig. 2c).

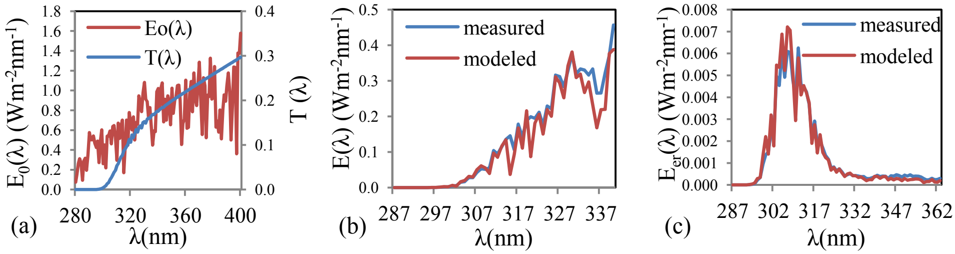

Fig.2. (a) Extraterrestrial UV spectrum$E_0(\lambda)$, and transmittance of the atmosphere $T(\lambda)$, (b) measured and modeled spectral UV irradiance $E(\lambda)$, and measured and modeled erythemal UV irradiance at 12:10 CET, 1 July 2021, Uccle, Belgium.

Conclusions

The parametric model NEOPLANTA was used to study the effects of various atmospheric conditions on terrestrial spectral UV irradiance. The capability of the model to correctly reproduce processes in the atmosphere is tested by changing input parameters such as ozone content, SZA, amount and type of aerosols, and altitude. Tests showed that the intensity of UVR decreases with increasing the thickness of the ozone layer, the amount of aerosol, altitude, and the increase in

SZA. It has been also confirmed that the contribution of diffuse UVR increases with increasing SZA, the amount of aerosols, the presence of aerosols with a higher amount of water-soluble particles, air humidity, and more reflecting surface. Elevation of the surface above sea level has a small effect, but it becomes considerable in mountainous areas. Erythemal irradiance is more dependent on changes in the amount of ozone in the atmosphere than spectral UVR, showing a significantly greater impact of UV-B radiation on human skin than radiation in the UV-A range. The results are in accordance with the existing knowledge.

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