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Abstract: A major consequence of decreasing stratospheric ozone is the increase of solar ultraviolet radiation (UV) passing through the atmosphere. Ultraviolet radiation is very harmful to the entire ecosystem, including health of the human population and for that reason, in the last few decades, scientists have placed a large emphasis on monitoring UV radiation and development and use of estimation procedures. Model NEOPLANTA estimates UV irradiance under cloudless conditions on a horizontal surface and computes the UV index. Model includes effects of the absorption of UV radiation by ozone, SO_2 and NO_2 and absorption and scattering by aerosol and air molecules in the atmosphere. Aerosols are incorporated in model using the model OPAC that provides optical properties for ten different aerosol types. Surface influence on UV irradiance was taken into account using spectral albedo values for nine different surface types. Model can use standard atmosphere meteorological profiles but it is possible to include real time meteorological data coming from the high-level resolution mesoscale models. The capability of the model to reproduce correctly processes in atmosphere is tested by changing input parameters. The performance of the model has been tested in relation to its predictive capability of global solar irradiance in the UV range (290-400 nm). For this test we have used data recorded by the radiometer YANKEE UVB-1 biometer located on the Novi Sad University campus (45.33^o N, 19.85^o E, 84 m a.s.l).

Keywords*:* Modeling; Irradiance; UV index; Ozone; Aerosol

1. INTRODUCTION

Ultraviolet (UV) radiation is a small part of solar spectrum, but it has a large impact on human health. It is defined as radiation between 100 and 400 nm, and can be divided into three categories: UV-C (100-280 nm) that is not reach the ground, UV-B (280-320 nm) which is very small but very harmful part of terrestrial UV spectrum and UV-A (320-400 nm) which is major part of terrestrial UV spectrum but much less erythmogenic than UV-B radiation [Diffey, 1991]. A major consequence of decreasing stratospheric ozone in last several decades is the increase of solar UV radiation passing through the atmosphere, especially the most harmful UV-B part. Although ozone is one of the major factors in determining the UV-B irradiance, the UV flux reaching the ground depends on many other factors such as aerosols and other UV absorbing gases. Understanding the processes affecting UV radiation allows scientists to estimate UV levels when measurements are not available. UV exposure of the skin depends very strongly on the behavior of the human being. It can be reduced to quite a small extent in many cases by providing daily information about current values and expected values for the next day(s). The easily understood parameter that describes potential detrimental effects on health from UV radiation is UV index. For that reason UV index is recommended by several international institutions and widely used to inform public.

This paper describes the NEOPLANTA model, which computes the UV index under cloudless conditions on a horizontal surface. Model simulates the effects of the absorption of UV radiation by ozone, SO_2 and NO_2 and absorption and scattering by aerosol and air molecules in the atmosphere. In order to investigate the performance of the model, we have tested model by changing input parameters and compared the computed results with clear sky solar UV index measured in Novi Sad.

2. MODEL DESCRIPTION

The numerical model NEOPLANTA computes the solar direct and diffuse UV irradiances under cloud-free conditions for the wavelength range 280-400 nm, and computes UV index. The UV irradiances can be computed at any location at different altitudes and times of day.

The global irradiance is the sum of the direct and the diffuse components. The values of the direct and diffuse irradiances can be calculated separately and can be integrated over any wavelength range with resolution of 1 nm. Model divides atmosphere into maximum 40 layers and takes into account its curvature. The vertical resolution of the model is one kilometre for altitudes less than 25 kilometres, and 5 kilometres above this height. Direct and diffuse intensity are computed at lower limit of each layer. Calculation of the direct part of radiation is carried out by the Beer-Lambert law. The starting point for calculation of diffuse part of radiation is the set of equations from Bird and Riordan spectral model [1986], which represents equations from previous parametric models [Leckner, 1978; Brine and Iqbal, 1983; Justus and Paris, 1985] improved after comparisons with rigorous radiative transfer model and with measured spectra. In contrast to mentioned models our model ignores the absorption by O_2, CO_2 and H_2O since they not absorb in the relevant wavelength range. However the absorption by SO_2, NO_2 was added for both the direct and diffuse components.

The required input parameters are the local geographic coordinates and time or solar zenith angle, altitude and the amount of gases. Aerosols are incorporated in model using the model OPAC that provides optical properties for ten different aerosol types [Hess at al., 1998]. Surface influence on UV irradiance was taken into account using spectral albedo values for nine different surface types. The model includes its own vertical gas profiles and extinction cross-sections, extraterrestrial solar irradiance, aerosol optical properties and spectral surface reflectivity. The model uses standard atmosphere meteorological profiles but it has possibility of including real time meteorological data coming from the high-level resolution mesoscale models.

Output data are UV-A and UV-B intensity, biologically active UV irradiance at the surface, UV index, spectral direct, diffuse and global irradiance, total spectral optical depth and values for each component and spectral transmitivity. All values can be obtained at the surface and at the lower limit of each layer.

2.1 Extraterrestrial Source Spectra

The model uses the extraterrestrial spectral irradiance from the solar flux atlas of Kurucz et al. [1984]. The ellipticity of the Earth's orbit about the sun is considered, as a correction to the extraterrestrial solar spectrum.

2.2 Sun's Position and Optical Masses

The model NEOPLANTA calculates instantaneous spectral irradiance for a given solar zenith angle. There is also possibility of calculation of the UV index for the whole day at half-hour intervals from sunrise to sunset. Solar zenith angle depends on latitude, longitude, day of the year and time of day. The zenith angle is derived using spherical trigonometry [Spencer, 1971]. Model has possibility taking into account daylight saving time.

A single optical mass, the optical mass for air molecules or "air mass", is used to estimate the total slant path for all the extinction processes in the atmosphere, except ozone. Optical mass that is taking into account Earth curvature and refraction is calculated using formula proposed by Hardie in Hiltner [1962]. Different expressions for ozone optical mass is considered here because ozone extinction process corresponds to a different vertical concentration profile [Komhyr, 1980].

2.3 Gas Absorption

Extinction of UV radiation by gases is calculated by the product of the cross-sectional area and the particle concentration for each atmospheric layer:
Ozone is the most important gas in the atmosphere that absorbs UV radiation. Ozone extinction cross-section values as a function of wavelength and temperature were obtained from Burrows at al. [1999] for the wavelength range 280-400 nm. Values are given for five temperatures, from 202 K to 293 K, and for particular layer estimated by a linear interpolation. Particle concentration is calculated by combining vertical profiles and total gases amount. Model uses four ozone profiles that are representative for seasons in mid-latitudes. Forecasted total ozone amounts for 24, 48 and 72 hours are provided by German National Service.

Extinction cross section SO_2 and NO_2 as a function of wavelength and temperature were obtained from

SCIAMACHY spectrometer measurements for the 280-400 nm wavelength range [Bogumil at al., 2000]. SO_2 and NO_2 profiles are used from Nakajima and Tanaka [1986]. The model uses the total dioxides content of the day before under the assumption of persistency. In the case of unavailability of actual measurements long-term mean values are used instead.

2.4 Aerosols Extinction

As mentioned before ten different aerosol mixtures that are representative of a boundary layer of certain origin from OPAC aerosol model are available in the NEOPLANTA model. These types differ from one another in the way their scattering efficiency, single scattering albedo and asymmetry factors vary with wavelength. The software package OPAC also gives optical properties of upper atmosphere aerosol, which are representative of free troposphere (boundary layer-12 km) and stratospheric aerosol properties (12-36 km). OPAC also describes the vertical distribution of aerosol particles by exponential profile [Hess at al., 1998]. To estimate amount of aerosols in layer at the ground model NEOPLANTA permits different possibilities. The user can choose the averaged conditions provided by OPAC aerosol model, Angstrom's turbidity coefficient [Angstrom, 1961], visibility [Koschmieder, 1924; Gueymard, 1995] or aerosol optical depth on 550 nm.

2.5 UV index

To provide the public with easily understood information about UV radiation and its harmful effects, scientists are defined UV index (UVI). UV index is related with erythemal effects of UV radiation on human skin and it is standardised under the umbrella of several international institutions [Vanicek, 1999]. A unit of UV index corresponds to 25 mWm^{-2} biologically active UV radiation (UV_{bio}) and it is defined as:

$$UVI = UV_{bio} \times 40 .$$

To estimate biologically active UV radiation, spectral irradiance at the surface must be weighted with an action spectrum. An action spectrum describes the relative efficiency of UV radiation at a particular wavelength in producing a particular biological response.

Figure 1 shows normalized erythemal action spectrum by McKinley and Diffey [1987], spectral UV irradiance, and its spectral overlap. The solid lines are for a total ozone column of 348 DU and the thin lines for 250 DU. It can be seen that the overlap is greatest in the 300-320 nm range and is very sensitive to ozone amounts [Madronich at al., 1998]. The potential biologically active UV irradiance (UV_{bio}) at the surface is found by a multiplication of the UV spectrum and the action spectrum, and integration between 290 and 400 nm:

$$UV_{bio} = \int B_\lambda I_\lambda d\lambda$$

where B_λ is normalized erythemal action spectrum, I_λ is spectral UV irradiance and λ is wavelength.

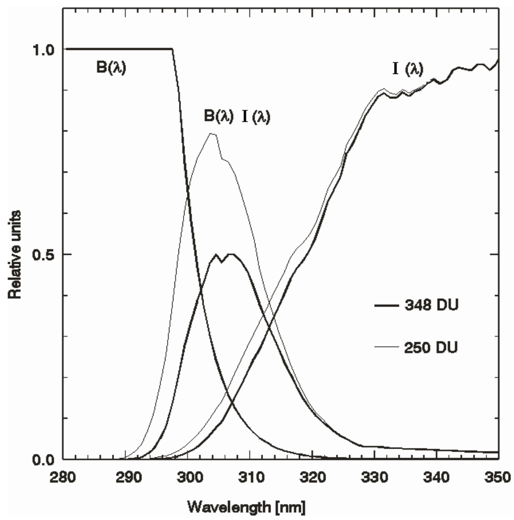

Figure 1. Biologically active UV radiation. The overlap between the spectral irradiance I(λ) and the erythemal action spectrum B(λ) given by McKinlay and Diffey shows the spectrum of biologically active radiation I(λ) B(λ) [Madronich at al., 1998].

3. RESULTS AND DISCUSSION

3.1 Sensitivity Studies

The capability of the model to reproduce correctly processes in atmosphere is tested by changing input parameters such as ozone and dioxides content, solar zenith angle, amount and type of aerosols and altitude.

Under cloud-free skies UV index depends largely on solar zenith angle and ozone content. Model results show decreasing UV index with increasing solar zenith angle and increasing of diffuse component of radiation. The response of UV-B radiation to ozone changes is strongly dependent on wavelength because of the rapid increase of the ozone absorption cross section toward shorter wavelengths, with greater sensitivity at short wavelengths and low sun, where the slant ozone optical depth is greater [Madronich at al., 1998]. As can be seen on Figure 2, biologically weighted radiation calculated by model NEOPLANTA shows the theoretically expected dependence on ozone and it is in accordance with measured values showed in Madronich at al. [1998].

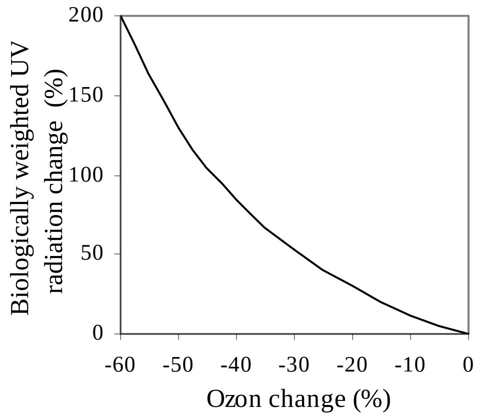

Figure 2. Dependence of erythemal ultraviolet radiation calculated by NEOPLANTA model at fixed solar zenith angles on atmospheric ozone

SO_2 absorbs predominantly in the UV-B region while NO_2 except UV-B region has also noticeable absorption in UV-A part of spectrum. Model is estimating only a minor effect of SO_2 on decreasing global UV irradiance (about 2% for wavelengths below 300nm for 1 DU gas increasing). At UV-A part of spectrum model estimates less than 1% influence NO_2 on global UV irradiance.

Atmospheric aerosols are characterized by their amounts and chemical composition. Model results showed decreasing direct and increasing diffuse UV component with aerosol amounts. Diffuse component increases with relative humidity, that is result of increasing aerosol radius. Aerosol influence on UV irradiance is equalized in whole UV spectrum.

Elevation of the surface above sea level has a small effect, but it becomes considerable in mountainous areas. The enhancement of the UV index according to model results can be about 3 % to 10 % per kilometer.

3.2 Comparison with Measurements

The accuracy of the model was tested by comparing model output to clear sky measured data recorded by the radiometer YANKEE UVB-1 biometer. The biometer measures direct and scattered broadband ultraviolet irradiance from the hemisphere of the sky and calculates UV index. The spectral sensitivity of the device is similar to the human skin. The measurement technique employs colored glass filters in combination with fluorescing ultraviolet-sensitive phosphorus. Measurement errors introduced by changes in ambient temperature are significantly reduced [Dichter at al., 1992]. The used device is located on the Novi Sad University campus (45.33^o N, 19.85^o E, 84 m a.s.l). The measurements are collected with a temporal resolution of 10 minute.

Nearly clear sky conditions were observed on several days during the summer of year 2003. UV index is calculated every half hour from sunrise to sunset by means of variation in solar zenith angle. Standard atmosphere meteorological profiles are employed with summer humidity profile. All input parameters were assumed to be constant over the day. On Figure 3 measured values are presented by solid line and forecasted by rhombus.

In the presented comparison, total ozone content of the atmosphere is the input parameter that has to be known, so therefore we consider that ozone does not represent a great source of uncertainty. Total column ozone over the Novi Sad coordinates for these days was taken from the on-line database of TOMS Meteor-3 observations. There exist no aerosol chemical composition and amount measurements in Novi Sad so we consider aerosol to be main source of difference between measured and calculated values. Due to a large portion of soil particles and soot presence in the air of the town, continental averaged aerosol type is assumed. Aerosol extinction is calculated using visibility data for previous day by Koschmieder equation [1924]. Overestimation partly results from extinction of UV radiation by clouds because the sky was not completely cloud free and, as mentioned above, cloudiness is not an input parameter of the model.

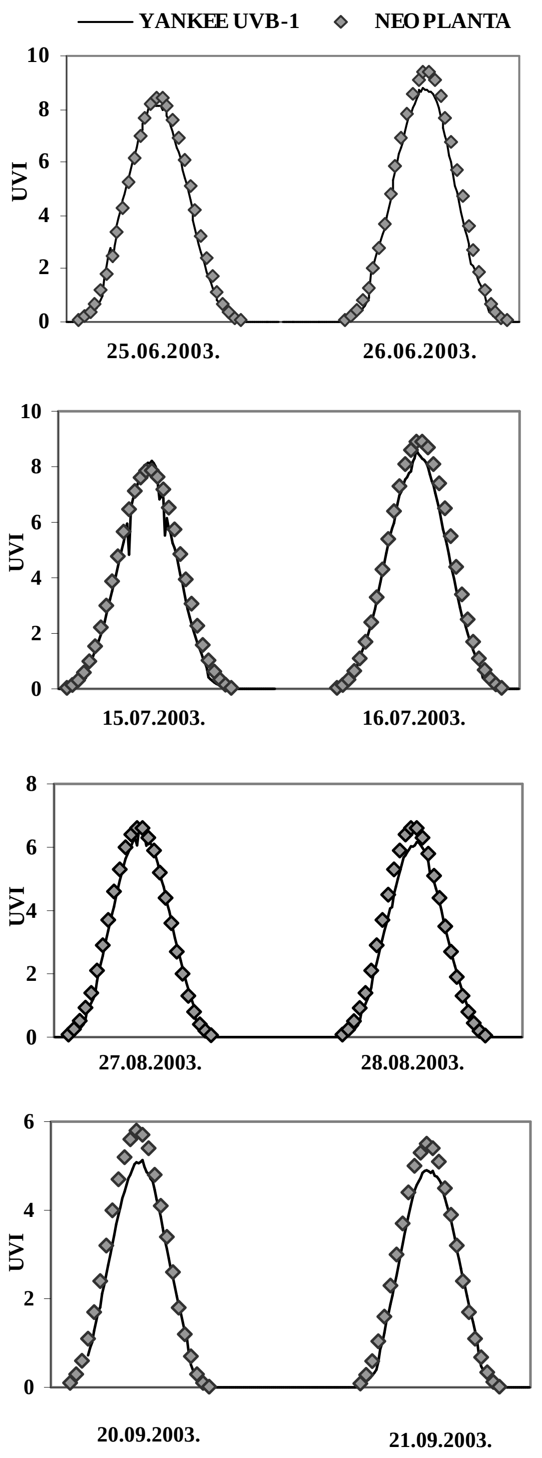

Figure 3. Comparison model calculations and clear sky measurements

UV Index indicates the highest possible UV irradiance reaching down to the earth's surface. Therefore forecasted UV index should be higher than the measured one, so results from model calculation are called unsatisfactory if the forecast value is lower than the observation. As can be seen in Figure 3, model calculations are only slightly higher than the measurements. This gives confidence that this model provides a satisfactory representation of the UV intensity at the surface.

3. CONCLUSIONS

A numerical model for computing clear sky UV index at surface was constructed. The model results were satisfactorily tested on input parameters change. The performance of the model has been tested in relation to its predictive capability of global solar irradiance in the UV range using data recorded by the radiometer YANKEE UVB-1 biometer. It was found that model calculations are slightly higher than the measurements. The main source of difference is lack of necessary measurement that can provide better input atmospheric conditions.

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