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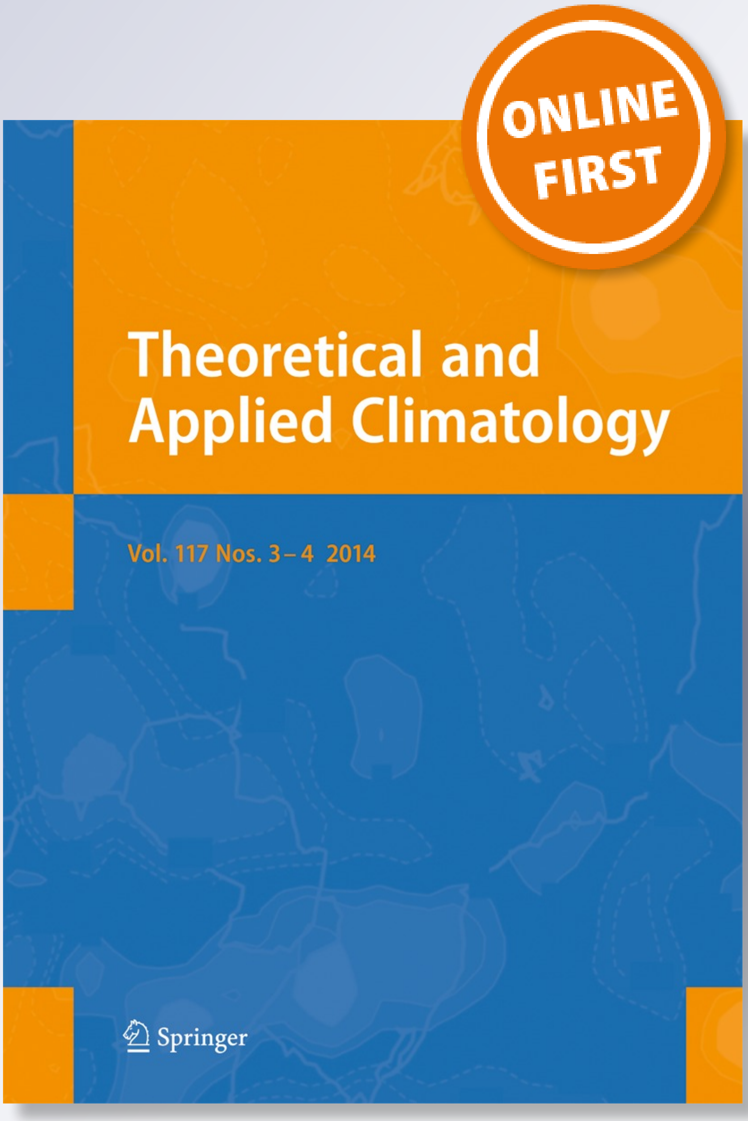

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ORIGINAL PAPER

Reconstruction of the erythemal UV radiation data in Novi Sad (Serbia) using the NEOPLANTA parametric model

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Abstract This paper focuses on the development and application of a technique for filling the daily erythemal UV dose data gaps and the reconstruction of the past daily erythemal UV doses in Novi Sad, Serbia. The technique implies developing the empirical equation for estimation of daily erythemal UV doses by means of relative daily sunshine duration under all sky conditions. A good agreement was found between modeled and measured values of erythemal UV doses. This technique was used for filling the short gaps in the erythemal UV dose measurement series (2003–2009) as well as for the reconstruction of the past time-series values (1981–2002). Statistically significant positive erythemal UV dose trend of 6.9 J m^{-2} per year was found during the period 1981–2009. In relation to the reference period 1981–1989, an increase in the erythemal UV dose of 6.92 % is visible in the period 1990–1999 and the increase of 9.67 % can be seen in the period 2000–2009. The strongest increase in erythemal UV doses has been found for winter and spring seasons.

1 Introduction

Ultraviolet (UV) radiation represents only 8 % of the solar radiation reaching the Earth's atmosphere, but it has a large impact on the whole living world. Its importance is explained by the high energy of the photons in this wavelength range (Gantner et al. 2000). The solar UV radiation is defined as the radiation between 100 and 400 nm, and is subdivided into three categories known as UV-C (100–280 nm), UV-B (280–315 nm), and UV-A (315–400 nm). These categories have been confirmed by the Commission Internationale de l'Eclairage (CIE 1987), although there is variation in usage. In the medical and biological fields, for example, 320 nm is used as the limit between UV-A and UV-B.

Human exposure to solar ultraviolet radiation has important public health implications. Evidence of harm associated with overexposure to UV has been demonstrated in many studies. It primarily causes detrimental health effects on skin and eyes and affects the immune system (Longstreth et al. 1998; Bachelor and Bowden 2004; Agar et al. 2004). Sunburn (erythema) is the best-known acute effect of the excessive UV radiation exposure. Over the longer term, the UV radiation induces degenerative changes in cells of the skin, fibrous tissue, and blood vessels leading to premature skin aging, photodermatoses, and actinic keratoses. Another long-term effect is an inflammatory reaction of the eye. In the most serious cases, skin cancer, and cataracts can occur (WHO 2006). Moreover, the UV radiation presents a large influence on many biological, ecological, and photochemical processes, being quite harmful for living organisms. In particular, the UV radiation increase can cause adverse effects on plant growth, photosynthesis, and aquatic ecosystems (Anton et al. 2008).

The amount of the UV radiation received at a location depends on many atmospheric factors such as total ozone amount, position of the sun, cloud cover, surface albedo, and atmospheric aerosols. The stratospheric ozone is especially important because it absorbs large amount of harmful UV-B radiation. Despite the fact that the decrease in stratospheric ozone was stopped in 1996 (WMO 2011), high levels of the UV radiation have still remained a significant problem. Since

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the UV radiation has a strong biological influence on human beings and other living organisms, measurements, prediction, and reconstruction of the UV radiation are crucial for the estimation of the long-term biological effects of this radiation (Reuder and Koepke 2005; Malinovic-Milicevic 2013).

Despite a considerable increase in the number of the UV monitoring sites in the last decade, the spatial density of meteorological stations which are equipped to observe the UV radiation is still low (Malinovic-Milicevic and Mihailovic 2011). The levels of the UV radiation could vary significantly in the past due to large long-term variations of the atmospheric parameters. The several UV dose reconstruction studies were performed during the last decade (Trepte and Winkler 2004; Lindfors and Vuilleumier 2005; Borkowski 2008; Hu et al. 2010; Paulescu et al. 2010 etc.). They are based on the radiative transfer model calculations, statistical modeling, and hybrid models, combining radiative transfer model calculations with the empirical estimates of the influence of various factors on the UV radiation (Borkowski 2008).

In spite of many general recommendations, the true UV monitoring in Serbia is still in its infancy. Practically, all of the pioneering steps made thus far, however, have been undertaken at the University of Novi Sad. The first step that started in 2003 was the measurement of the UV index, followed by model development (Mijatovic et al. 2010). The aim of this paper is to improve our understanding of variations in the surface UV radiation in the past in Novi Sad, Serbia by developing a technique for the UV reconstruction. The technique implies developing the empirical equation for estimation of the daily erythemal UV doses under all sky conditions, using the total ozone and sunshine duration data. The daily clear-sky erythemal UV doses were calculated by the NEOPLANTA model, using the daily values of total ozone as input data, while the effect of cloudiness is estimated from measured sunshine duration. An empirical relationship was found between daily data of the relative erythemal UV dose and relative sunshine duration. Based on this reconstruction method, a long-term data set of the UV radiation is developed and the variations in the UV characteristics of Novi Sad are investigated.

2 Data

Target parameter in this study is erythemal radiation because it is most commonly used in the public as the UV index (UVI). Daily doses of erythemal radiation can be used to derive monthly and annual doses, and are thus appropriate to study longer-term effects of the solar radiation on the environment (Feister et al. 2008). The data used in this study include the erythemal UV doses, sunshine duration as well as the total ozone column.

The UV monitoring in Novi Sad has been in operation by broadband Yankee UVB-1 biometer at the campus of the University of Novi Sad (45.33° N, 19.85° E, 84 m above sea level) since 2003. Its output is a voltage signal that is then converted to the erythemally weighted UV irradiance and the UVI using a multiplication constant. The main sources of errors in the UVI measurements are: (i) uncertainties in the determination of the instrumental calibration constant, (ii) the conversion of the instrument output analog signal to a digital one (error of quantization), and (iii) the conversion of the raw signal to the erythemally weighted UV irradiance. The Yankee UVB-1 biometer was calibrated in 2002 at the factory (Yankee Environmental Systems Inc. 2002) using the National Institute of Standards and Technology traceable reference detector and appropriate equipment. Time stability test of the instrument is made every year and it does not show major deflexion. The upper limit of error for the calibration constant is 8 %. The quantization error can be neglected, because the precise 12-bit analog-to-digital converters used to convert the analog signal (0–4 V) from the instrument into digital form. In our case, the conversion of the raw signal to the erythemally weighted UV irradiance is nonstandard because the calibration matrix which takes account of the dependence of calibration factors on the solar zenith angle (SZA) and ozone has not been used (Webb et al. 2007). The conversion was done by multiplying the output voltage by conversion function given by the manufacturer, for the SZA at the time the sample was taken. The conversion done in such way introduces an error of about 4 % for the SZA lower than 65°, and 6 % for the SZA greater than 65° (Yankee Environmental Systems Inc. 2002). However, according to Anton et al. (2011a, b), the conversion of the erythemally weighted UV irradiance signal using the manufacturer's factors overestimates the real values (the mean bias error=14 %). This bias is lower for small erythemal weighted UV irradiance values (9 % for SZA greater than 50°) than for high values (16 % for SZA smaller than 30°). The biometer detects the UV radiation every 10 s, but our measurements were collected with a temporal resolution of 10 min. The results are then recorded on the internet (www.cmep.rs) in 10-min intervals together with several meteorological data (temperature, humidity, wind velocity, etc.), which are measured by the automatic weather station and stored at the same time intervals. In this study, measured data of daily erythemal UV doses for the period 2003–2009 were used.

The global irradiance and sunshine duration data are commonly used to describe cloud effects on the solar UV radiation. Since records of global irradiance in Novi Sad were not available, we have used daily sum sunshine duration to describe the impact of clouds on the solar UV radiation. The daily sunshine duration is measured by using Campbell–Stokes sunshine recorder (burn method) and provided by the Serbian Meteorological Service.

The total ozone content, given in Dobson Units (DU), is one of the most important parameters affecting the UV radiation on the ground (Rieder et al. 2008). In general, the length of the reconstructed UV time series of sunshine-based methods is limited due to availability of historical records of total ozone. The daily total column ozone data (1981–2009) for Novi Sad, used in the reconstruction model runs, were taken by Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI) on satellites (Nimbus-7, Meteor-3, Earth Probe, and Aura) (NASA 2010).

3 Methods

In this study, the reconstruction technique implies the empirical equation for the estimation of daily erythemal UV doses (ERY) by using relative daily sunshine duration (S/S_0) under all sky conditions. The data of the erythemally weighted UV irradiance and sunshine duration (S) measured in Novi Sad during the 7-year period (2003–2009) were used. The daily erythemal UV doses (ERY) were calculated by integrating the measured values of the erythemally weighted UV irradiance during daylight. Therefore, ERY relates to the potential maximum daily erythemal exposure to the actual weather conditions of the day. Through the same period, we estimated the values of the daily erythemal UV doses in cloudless sky (ERY_0) and sunshine duration in cloudless sky (S_0). In order to quantify the relationship between ERY and S, we performed a linear regression analysis between the relative daily erythemal UV dose (ERY/ERY_0) and relative daily sunshine duration (S/S_0).

The UV reconstruction model used in this study is described in details in Malinovic et al. (2006), Malinovic-Milicevic and Mihailovic (2011) and Malinovic-Milicevic et al. (2013) The NEOPLANTA parametric model computes the solar direct and diffuse UV irradiances on a horizontal surface under cloud free conditions for the wavelength range 280–400 nm with 1-nm resolution as well as the UVI. The effects of O_3, SO_2 and NO_2, aerosols and nine different ground surface types on the UV radiation are included. The atmosphere in the model is divided into 40 parallel layers with constant values of meteorological parameters. The required input parameters are the following: the local geographic coordinates and time or SZA, altitude, spectral albedo, and the total amount of gasses. The NEOPLANTA model includes its own 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). The model uses standard atmosphere meteorological profiles although it is possible to include assimilation of real-time meteorological data assimilated from the high level resolution atmospheric mesoscale models. The output data are spectral, direct, diffuse, and global irradiance divided into the UV-A (320–400 nm) and UV-B (280–320 nm) parts of the spectrum, the erythemally weighted UV irradiance calculated by using the erythemal action spectrum by McKinley and Diffey (1987), the UVI, the spectral optical depth, and the spectral transmittance for each atmospheric component. Accuracy of the NEOPLANTA model was tested by comparison of the calculated and measured UVI. A simple inspection of the data indicates that absolute difference between the model outputs and measurements (cloudiness$\leq$0.2) was in the interval of ±0.5 UVI for 95 % of the data (Malinovic et al. 2006). Under all amounts of cloudiness, we found a strong Pearson correlation of 0.85 between the measured data and the NEOPLANTA outputs (Malinovic-Milicevic and Mihailovic 2011).

The erythemally weighted UV irradiance was calculated every half hour from sunrise to sunset by means of variation in SZA. Standard atmosphere meteorological profiles were used throughout all the simulations. Because of a large portion of soil particles and soot presence in the air of the town, continental averaged aerosol type was assumed. The total column ozone data were taken from the online NASA database (NASA 2010). The surface is asphalt. All input parameters were assumed to be constant during the day. Daily erythemal UV doses in cloudless sky (ERY_0) were calculated by integration of the half hour's erythemally weighted UV irradiance values.

The daily values of sunshine duration in cloudless sky (S_0) were estimated from the following equation (Akpabio 1992; Duffie and Beckman 1994)

$$S_0 = \left(\frac{2}{15}\right)\cos^{-1}(-\tan\phi\tan\delta), \tag{1}$$

where ϕ is the latitude of the location and δ is the declination angle given as (Allen et al. 1998)

$$\delta = 0.409\sin\left(\frac{2J\pi}{365}-1.39\right). \tag{2}$$

The parameter J is the Julian day number.

We divided the 7-year period in two data sets: 6-year development period (2003–2008) and 1 year testing period (2009). A linear regression by means of the least-squares technique was performed in the development period to carry out the best fit between $\mathrm{ERY}/\mathrm{ERY}_0$ and S/S_0. The regression equation found through calculation is

$$\mathrm{ERY}_{\mathrm{estimated}} = \mathrm{ERY}_0\left(0.5343\frac{S}{S_0}+0.3589\right). \tag{3}$$

However, it should be mentioned that the UV radiation time series has gaps. In total, 62 % of the measured data was available in the developmental period, and 82 % in the testing period.

The performance of the reconstruction technique was evaluated using the root mean square error (RMSE) and mean bias error (MBE) expressed as a percentage of the mean measured value (Batlles et al. 2008):

$$\mathrm{RMSE}(\%) = 100\frac{\left(\sqrt{\frac{\sum\left(X_{\text{estimated}}-X_{\text{measured}}\right)^2}{N}}\right)}{\overline{X}_{\text{measured}}}, \tag{4}$$

$$\mathrm{MBE}(\%) = 100\frac{\left(\frac{\sum X_{\text{estimated}}-X_{\text{measured}}}{N}\right)}{\overline{X}_{\text{measured}}}. \tag{5}$$

The *MBE* gives information about possible underestimation or overestimation performed by reconstruction technique, and the RMSE is linked to data dispersion. The correlation coefficient *R* between estimated and measured radiation values was defined by

$$R = \frac{\sum\left(X_{\text{estimated}}-\overline{X}_{\text{estimated}}\right)\left(X_{\text{measured}}-\overline{X}_{\text{measured}}\right)}{\sqrt{\sum\left(X_{\text{estimated}}-\overline{X}_{\text{estimated}}\right)^2\sum\left(X_{\text{measured}}-\overline{X}_{\text{measured}}\right)^2}}. \tag{6}$$

Here, *X* is the ERY, and *N* is the total number of data while overbar indicates an arithmetic average.

4 Results and discussion

Using the Eq. (3), we estimated the daily erythemal UV doses for the period 1981–2002, and filled data gaps between 2003 and 2009. The following analysis refers to 29-year data set consisting of (1) the estimated (1981–2002) and (2) the measured and the filled (2003–2009) erythemal UV doses (ERY) in Novi Sad.

The Figs. 1 (development period) and 2 (testing period) depict the relationship between the measured (ERY_M) and estimated (ERY_E) daily erythemal UV doses using the Eq. (3) for different seasons (December–February for winter, March–May for spring, June–August for summer, and

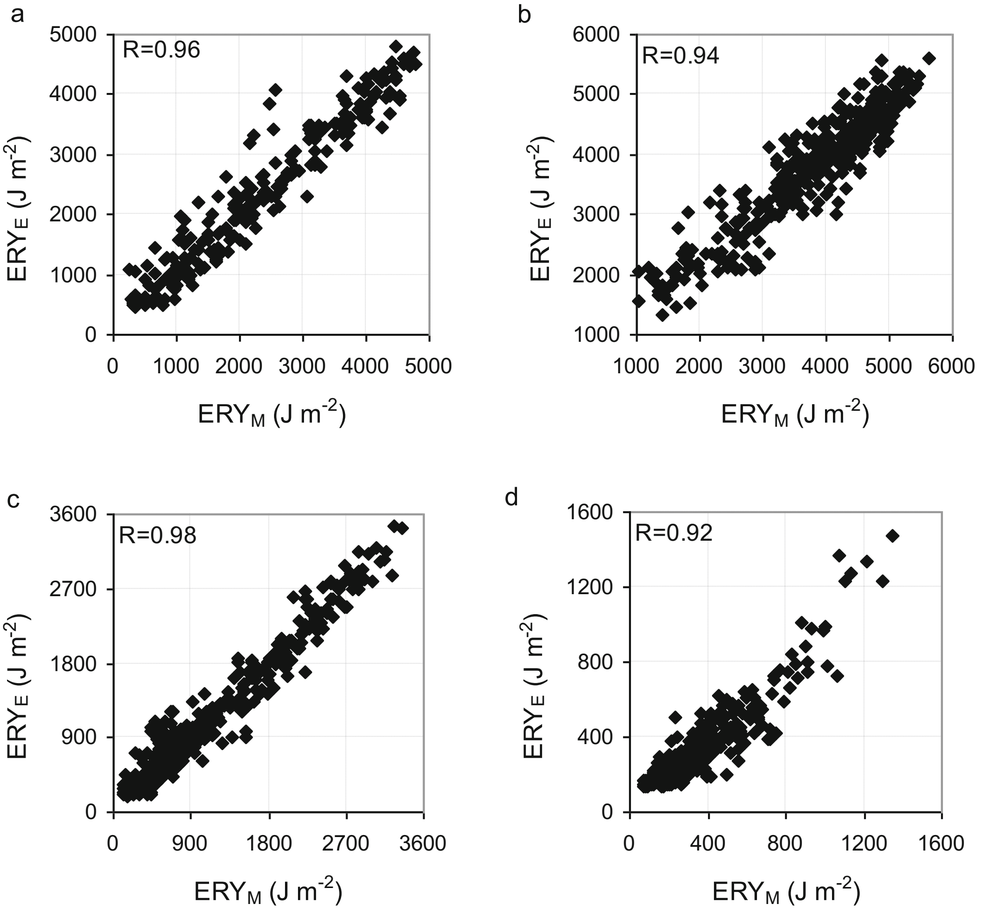

Fig. 1 Measured (ERY_M) versus estimated (ERY_E) daily erythemal UV doses for the development period (2003–2008) in Novi Sad for **a** spring, **b** summer, **c** autumn, and **d** winter seasons

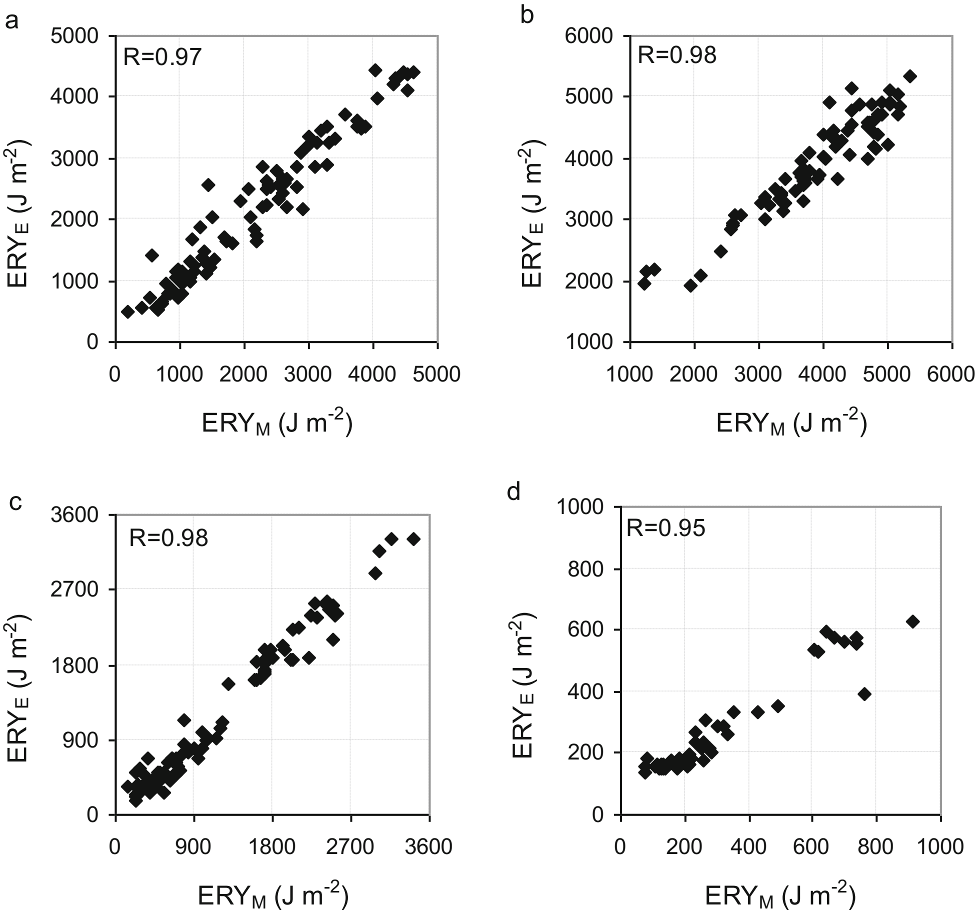

Fig. 2 Measured (ERY_M) versus estimated (ERY_E) daily erythemal UV doses for the testing period (2009) in Novi Sad for **a** spring, **b** summer, **c** autumn, and **d** winter seasons

September–November for autumn). The statistical parameters for the ERY values are listed in the Table 1. The results show a good agreement between the estimated and measured data during spring, summer, and autumn, while the reconstructed values have lower quality during the winter season.

To test the performance of our method, we have compared it with two other similar methods. Lindfors and Vuilleumier (2005) used the method based on sunshine duration and snow depth as input, while Rieder et al. (2008) used the method based on global radiation measurements for reconstructing the past UV levels. The values of R that found Lindfors and Vuilleumier (2005) and Rieder et al. (2008) were in the range of 0.96–0.99 and 0.95–0.98, respectively, which is similar to our method. Lindfors and Vuilleumier (2005) found the RMSE between 18 % (spring) and 30 % (autumn), while the RMSE by Rieder et al. (2008) was between 13 % (spring) and 26 % (winter). When we compared the MBE by our method to the MBE by two other methods, we found better results for all seasons, except for winter. A larger disagreement during the winter, in comparison to method developed by Lindfors and Vuilleumier (2005), can be attributed to the fact that we did not take into account the influence of higher surface albedo during days with the snow cover. The above inspection depicts that our method is comparable to two aforementioned studies, and that overall performance of our method is very good for spring, summer, and autumn seasons. Accuracy for winter season is less, but also satisfactory.

Although the European Union's Action COST 726 identified global irradiance as best to describe cloud effects on the solar

Table 1 The statistical parameters for development (2003–2008) and testing (2009) period

	RMSE (%)		MBE (%)		R	
	2003–2008	2009	2003–2008	2009	2003–2008	2009
Spring	15.08	13.08	0.89	0.65	0.96	0.97
Summer	11.27	9.41	1.37	0.91	0.94	0.98
Autumn	15.61	12.21	1.71	0.18	0.98	0.98
Winter	26.3	30.89	−4.20	−12.14	0.92	0.95

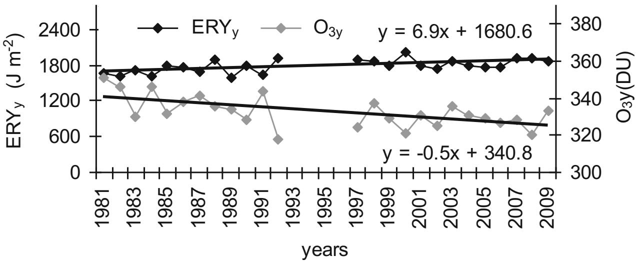

Fig. 3 Annual average of daily erythemal UV dose (ERY$_y$) and total ozone (O_{3y}) trends in Novi Sad for the period 1981–2009

UV (Koepke et al. 2006), the data availability of the global radiation is much lower than the availability of the sunshine duration. Therefore, it is important to develop and verify the techniques that estimate the impact of clear-sky and cloudy conditions on UV radiation using sunshine duration, especially in Eastern Europe where ground measurements are rare. The above analysis has shown that the NEOPLANTA model, together with the sunshine duration data, can be useful for the estimation in seasons when the UV values are high. The reconstructed data obtained in that way can be highly significant for institutions dealing with their implications on human health and plant development.

In order to illustrate the long-term trend of erythemal UV doses in Novi Sad, we calculated the yearly averages of daily erythemal UV dose (ERY$_y$) and the total ozone (O_{3y}) for the period 1981–2009. They are shown in Fig. 3. The linear long-term trends were obtained as the least squares fits of the annual mean values. To determine the significance level (p) of each trend, we used the Mann-Kendall nonparametric test (Yue and Pilon 2004; Helsel and Frans 2006). This figure shows (i) decreasing trend in the total ozone since 1981 (0.5 DU per year and p=0.001) and (ii) an increasing trend in daily erythemal UV dose (6.9 J m^{-2} per year and p=0.007).

Variability of the erythemal UV doses over the year is shown in Fig. 4 using monthly averaged daily erythemal UV dose, ERY$_{aver}$, (solid line) and absolute maximum of daily erythemal UV dose recorded and then monthly averaged, ERY$_{max}$, (circle). The monthly averaged daily erythemal UV dose is between 219.3 J m^{-2} (December) and 3 744.9 J m^{-2} (July). Half of the annual erythemal UV dose (50.2 %) occurs between June and August. The highest absolute maxima are recorded in June and July and have similar values in May and August.

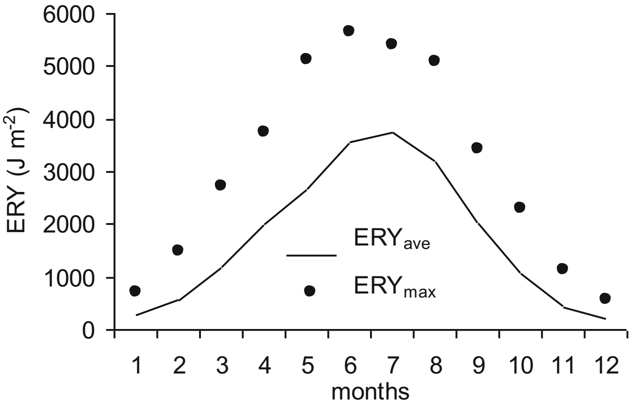

Fig. 4 Monthly averaged daily erythemal UV dose (ERY$_{aver}$) and monthly averaged absolute daily maximum (ERY$_{max}$) in Novi Sad for the period 1981–2009

To better understand the change of the erythemal UV radiation and factors affecting that radiation, the 10-year averages of daily erythemal UV dose, total ozone, and sunshine duration for the periods 1990–1999 and 2000–2009 are compared with averages for the reference period 1981–1989. In order to precisely establish differences during the year, the percentage of change for different seasons was calculated and listed in the Table 2. Simple inspection of values shows the reduction of yearly averages of total ozone of 3.44 % for the period 1990–1999 and 3.21 % for the period 2000–2009 in comparison to the reference period. The decreasing of yearly averages of total ozone was larger during the period 1990–1999 which indicates its recovery in the last 10-year period. However, the growth is the result of recovery during the winter season, while the values in other seasons continue to decrease. The sunshine duration was increased in both 10-year periods compared to the reference period during spring, summer, and winter, while the dataset for autumn shows a decrease. The increase in sunshine duration during summer and autumn was higher during the period 2000–2009 than during the period 1990–1999, while during winter, the increase was greater in the 1990–1999 period. In comparison to the reference period, we found an increase in the yearly averages of the erythemal UV dose of 6.92 % for the period 1990–1999 and 9.67 % for the period 2000–2009. The larger increase in the yearly averages of the erythemal UV dose during 2000–2009 is primarily due to the increased sunshine duration in this period compared to the period 1990–1999. On a seasonal scale, we have found an increase in the erythemal UV dose in spring, summer, and winter and decrease in autumn. The decline in the erythemal UV dose during autumn is the result of the reduction of duration of sunshine and the smallest loss

Table 2 Changes (%) in mean values of the estimated erythemal UV dose (ERY), total ozone (O_3), and relative sunshine duration (S) for the periods 1990–1999 and 2000–2009 in comparison to the reference period 1981–1989

	ERY		O_3		S	
	1990–1999	2000–2009	1990–1999	2000–2009	1990–1999	2000–2009
Spring	+8.82	+14.37	−3.52	−3.73	+12.82	+23.74
Summer	+6.96	+11.06	−3.38	−4.01	+7.70	+13.10
Autumn	−0.19	−2.98	−0.95	−1.03	−2.73	−1.95
Winter	+21.75	+14.44	−5.56	−3.74	+30.28	+16.06
Year	+6.92	+9.67	−3.44	−3.21	+8.86	+12.67

of total ozone. A higher increase in the erythemal UV dose was calculated for the winter season, and this is explained by the largest decrease in total ozone in combination with the highest increase in sunshine duration, especially in the period 1990–1999. Analysing the changes of the erythemal UV dose during spring and summer, when the radiation levels are more dangerous for the living world, and comparing the two 10-year periods with the reference period, a larger growth can be seen in the period 2000–2009 than in the period 1990–1999.

5 Conclusions

Assessment of the UV radiation variability and trend is of a great interest because of (i) the environmental and health risks caused by an increase in this radiation, (ii) low spatial density of meteorological stations which are equipped to observe the UV radiation, and (iii) short UV data series. Thus, the reconstruction methods should be used.

In this study, the reconstruction technique for the estimation of daily erythemal UV doses under all sky conditions by means of daily sunshine duration was developed. The application and use of the reconstruction technique have shown that this method is capable for modeling the complex relationship between the solar UV radiation and meteorological input data. The technique was used for filling short gaps in the erythemal UV dose measured series (2003–2009) as well as for the reconstruction of the past time-series values (1981–2002). The reconstructed daily totals of erythemal UV doses were used to derive monthly and annual averages that show annual and long-term UV variations together with the variations of the input parameter, ozone, and sunshine duration. Statistically significant positive erythemal UV dose trend was found (6.9 J m^{-2} per year and p=0.007) during the period 1981–2009. The strongest increase in the erythemal UV doses has been found for winter and spring seasons.

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