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Estimation of biologically effective UV radiation in Croatia

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Abstract

Background and Purpose: *Solar UV radiation is harmful to plants: it reduces photosynthesis, stunts growth, and causes a variety of damage to a plant. The purpose of this study was to estimate solar UV exposure and harmful biologically effective irradiance during the vegetative growth period in Croatia. Biologically effective irradiances were calculated for several action spectra. Data were analyzed in order to establish the relationship between UV exposure, time of a day and week of the year. Simplified formulas were developed that mimic complex radiative transfer models.*

Methods: *UV radiation in Croatia was estimated using the Tropospheric Ultraviolet-Visible (TUV) model, version 4.2. Dose rates harmful to plants (UV-B, UV-A) and also useful photosynthetically active radiation dose rate (PAR) were calculated at 13 h (CEST) at fifty sites during the vegetative growth period (April-October). Daily and monthly variations of UV-B dose rate (irradiance) were calculated (and some approximate formulas were developed) for one representative location. Biologically effective UV daily doses were calculated using data on four different action spectra.*

Results*: In July, at some elevated locations, UV-B irradiance was higher than 2 Wm*$^{-2}$ *at 13 h (CEST). The biologically effective UV daily doses ranged from 29 kJ m*$^{-2}$ *in October to 72 kJ m*$^{-2}$ *in July. The daily doses calculated in this study are the maximum values; all calculations refer to clear-sky conditions and to the total ozone column value 300 DU, which approximately corresponds to the lowest total ozone value measured during the vegetative growth period.*

Conclusions: *UV exposure in Croatia was estimated at one location chosen as representative. Simplified formulas that describe daily and monthly variations of UV-B irradiance may be used instead of the TUV model and produce a relative error of less than 10 %. Corrections for the total ozone column and cloudiness are also possible.*

INTRODUCTION

Solar ultraviolet (UV) radiation reaching the Earth's surface is an important factor for the equilibrium of ecosystems. Although UV-B radiation is necessary for biological processes it also causes acute and chronic damage to the cell, tissue and whole body. Photosynthesis of plants requires sunlight, yet UV radiation can reduce photosynthesis, stunt growth and induce a variety of damage *(1-3)*.

The effect of UV radiation on a biological specimen is determined by spectral irradiance, I_λ (W m^{-2} nm^{-1}) delivered to the surface of a biological body and the duration of exposure, T. Total exposure, F (J m^{-2}), is defined as a time integral of spectral irradiance between 280 and 400 nm, namely

$$F = \int_0^T \int_{280}^{400} I_\lambda d\lambda dt \qquad [1]$$

F provides information about the total photon energy in the UV waveband that falls onto unit area of the body surface. However, the response of the biological body varies with radiation wavelength. For a given photobiological process, the wavelength dependence of the relative spectral effectiveness *(4)*, S_λ, is called action spectrum. To express biological effectiveness of UV radiation at various wavelengths for a particular biological process, it is necessary to weigh spectral irradiance with the action spectrum. Thus, for a selected biological process, the biologically effective UV irradiance, I_{eff} (W m^{-2}) is

$$I_{eff} = \int_{280}^{400} S_\lambda I_\lambda d\lambda \qquad [2]$$

and its time integral is called radiant exposure or radiant dose *(5)*, F_{eff} (J m^{-2}).

Although harmful effects of UV radiation are well established and described in literature *(1–3),* few measurements exist for Croatia *(4, 5)*. Instruments for measuring spectral irradiance are complex and difficult to maintain. Due to high cost and calibration problems, UV measurements are still relatively sparse *(6, 7)*. Instead, UV exposure is frequently estimated using different models. Surface UV radiation is a function of the extraterrestrial solar flux, solar zenith angle, ozone amount, cloud characteristics, aerosols and surface albedo. Models for UV-index forecasting usually include in calculation the following parameters: geographic position (longitude, latitude and altitude), date, time of the day, total ozone data and cloud data, and, when available, aerosol data. There are several models that accurately calculate the passage of sunlight through the atmosphere *(8, 9, 10)*. Some approximate formulas have also been developed *(11, 12)*. Such formulas are usually simple and easy to use. Forecasts of the UV index using Model DM4 are available on the web pages of the Meteorological and Hydrological Service of Croatia *(13)*. The UV index is associated with the influence of sunlight on human skin (erythemal action spectra). However, other effects on humans and plants are less known.

In this study, we calculated UV dose rates for 50 sites in Croatia using the Tropospheric Ultraviolet-Visible (TUV) model. On the basis of spectral irradiance data obtained by the TUV model, we then calculated biologically effective UV dose rates for several plant-damaging action spectra. The purpose of this study was to estimate maximum plant UV dose rates between April and October (vegetative growth period) in Croatia. Some simplified relations were found between UV dose rates, time of a day and week of the year. These simplified formulas may be used instead of the TUV model.

METHODS

To evaluate UV exposure, we used the Tropospheric Ultraviolet-Visible (TUV) Model, version 4.2 (developed by Sasha Madronich; released May 2003) *(8, 9, 14, 15)*. TUV is a multistream radiative transfer model able to quantify the transfer of radiation in a scattering and absorbing atmosphere. Atmospheric curvature is modelled using a pseudo-spherical approximation. It is a one-dimensional FORTRAN 77 model suitable to compute various radiative quantities over a broad range of environmental conditions. It can be used in the wavelength range 121–750 nm for calculating spectral irradiance, spectral actinic flux, photodissociation coefficients, and biologically effective irradiances. Output parameters are presented as functions of wavelength and altitude. Many papers describe good agreement between the measured values of UV radiation and those calculated by the TUV model *(16–18)*.

In our first approximation, the following constants and atmospheric conditions were assumed:

– US standard atmosphere *(19)*

– surface albedo 0.1 at all wavelengths

– aerosol vertical optical depth $\tau_{aer} = 0.235$ at 550 nm from surface to space [for aerosols, vertical profile typical for continental regions from Elterman *(20)* was assumed]

– total ozone column 300 DU (DU – Dobson Unit, one DU is 2.69×10^{20} ozone molecules per square meter)

– to calculate the dose rate, the UV spectrum on the ground was integrated with a 1 nm step over the 280–420 nm band

– mean solar noon time

Dose rates of UV-B (280–315 nm), UV-A (315–400 nm), and photosynthetically active radiation, PAR (0.4–0.7 μm) were calculated for 50 sites in Croatia with corresponding data on longitude, latitude and altitude (Table 1) for 1 April, 1 July, and 1 October. UV dose rates were calculated at 13 h local time (daylight saving time/summer time- Central European Summer Time, CEST) which represents the mean solar noon and it roughly corresponds to the true local noon. PAR was calculated in a separate subroutine by integrating the spectrum on the ground with a 1 nm step over the 421–750 nm band. Cloudless sky was assumed in all calculations. For one representative location, daily UV doses were determined for different months over the vegetative growth period (the first day of a month was used as a representative). Data on spectral irradiance calculated with the model were weighted with different action spectra *(21–24)* to obtain harmful biologically effective UV irradiation.

RESULTS

Table 1 shows both (harmful and useful) dose rates (UV-B, UV-A and PAR) calculated with the TUV model for 50 sites in Croatia for 1 April, 1 July, and 1 October (at 13 h, CEST). The differences between the lowest and the highest dose rates were not high: the relative standard deviations were usually lower than 5% for each of the

TABLE 1

Dose rates (W m^{-2}) calculated for 50 sites in Croatia using the TUV model.

				April, 1			July, 1			October, 1		
Site	Latitude	Longitude	Altitude (m)	UVB	UVA	PAR	UVB	UVA	PAR	UVB	UVA	PAR
Bjelovar	45.900	16.867	135	1.20	48.66	76.78	1.89	61.85	95.62	0.82	39.56	63.30
Cres	45.050	14.383	40	1.23	49.38	77.78	1.91	62.19	96.17	0.86	40.55	64.84
Daruvar	45.589	16.250	161	1.21	49.02	77.29	1.90	62.08	95.93	0.84	39.99	63.95
Delnice	45.403	14.808	696	1.26	49.96	78.32	1.96	63.04	96.90	0.88	40.95	65.09
Drniš	43.858	16.153	278	1.30	50.92	79.99	1.97	63.49	97.54	0.92	42.08	66.98
Dubrovnik	42.642	18.100	40	1.34	51.78	81.05	1.98	63.57	97.73	0.96	43.22	68.83
Gospić	44.540	15.743	656	1.29	50.79	79.55	1.98	63.49	97.58	0.91	41.83	66.40
Hvar	43.004	16.442	40	1.32	51.47	80.62	1.97	63.38	97.51	0.95	42.96	68.44
Imotski	43.450	17.225	440	1.33	51.57	80.75	1.99	63.79	98.00	0.95	42.86	68.28
Karlovac	45.492	15.558	112	1.21	49.05	77.37	1.90	62.06	95.94	0.84	40.09	64.12
Knin	44.034	16.191	220	1.29	50.67	79.65	1.96	63.08	97.31	0.91	41.81	66.61
Komiža	43.050	16.067	40	1.32	51.42	80.55	1.97	63.38	97.51	0.95	42.93	68.40
Koprivnica	46.157	16.833	149	1.19	48.42	76.42	1.88	61.71	95.42	0.81	39.29	62.92
Krapina	46.167	15.883	203	1.19	48.50	76.56	1.88	61.80	95.60	0.82	39.44	63.16
Kutina	45.483	16.783	149	1.22	49.11	77.43	1.90	62.12	96.00	0.89	40.06	64.06
Lastovo	42.767	16.900	26	1.33	51.62	81.16	1.97	63.45	97.98	0.96	42.90	68.33
Lipik	45.417	17.167	154	1.22	49.18	77.52	1.91	62.16	96.05	0.85	40.10	64.12
M. Lošinj	44.567	14.383	40	1.25	49.88	78.44	1.92	62.48	96.42	0.89	41.21	65.81
Makarska	43.292	17.017	40	1.31	51.17	80.21	1.96	63.23	97.32	0.94	42.56	67.83
Našice	45.500	18.167	157	1.22	49.06	77.35	1.90	62.09	95.94	0.84	39.92	63.84
Nova Gradiška	45.268	17.374	129	1.23	49.29	77.69	1.91	62.21	96.13	0.85	40.22	64.31
Ogulin	45.267	15.224	323	1.24	49.57	78.00	1.93	62.59	96.45	0.86	40.62	64.79
Osijek	45.550	18.717	90	1.21	48.90	77.15	1.89	61.93	95.77	0.83	39.72	63.59
Otočac	45.868	15.242	459	1.22	49.16	77.30	1.92	62.39	96.15	0.84	40.11	63.96
Pag	44.442	15.050	40	1.26	50.02	78.63	1.93	62.57	96.53	0.89	41.33	65.99
Pakrac	45.436	17.200	178	1.22	49.19	77.52	1.91	62.19	96.07	0.85	40.11	64.12
Pazin	45.242	13.942	361	1.24	49.61	78.07	1.93	62.57	96.53	0.87	40.81	65.21
Ploče	43.033	17.433	40	1.32	51.42	80.55	1.97	63.35	97.47	0.95	42.83	68.24
Poreč	45.226	13.593	29	1.22	49.16	77.57	1.90	62.04	95.97	0.86	40.36	64.57
Požega	45.337	17.683	164	1.22	49.26	77.63	1.91	62.21	96.12	0.85	40.16	64.20
Pula	44.867	13.850	30	1.22	49.26	77.60	1.91	62.26	96.16	0.87	40.86	65.29
Puntijarka	45.910	15.970	980	1.25	49.87	78.00	1.96	63.21	96.93	0.86	40.67	64.52
Rab	44.750	14.767	40	1.24	49.70	78.20	1.92	62.39	96.31	0.88	40.97	65.46
Ravni Kotari	44.033	16.200	233	1.29	50.69	79.67	1.96	63.10	97.33	0.91	41.82	66.63
Rijeka	45.333	14.417	40	1.22	49.11	77.39	1.90	62.04	95.90	0.85	40.30	64.45
Senj	44.983	14.900	40	1.23	49.47	77.89	1.91	62.26	96.16	0.87	40.69	65.04
Sinj	43.700	16.641	326	1.31	51.14	80.28	1.98	63.43	97.73	0.93	42.28	67.25
Sisak	45.483	16.270	98	1.21	49.05	77.36	1.90	62.05	95.93	0.84	40.03	64.05
Slavonski Brod	45.152	18.018	96	1.23	49.35	77.71	1.91	62.20	96.09	0.85	40.31	64.47
Split	43.517	16.450	40	1.30	50.95	79.91	1.96	63.10	97.17	0.93	42.34	67.50
Srđ	42.650	18.133	412	1.36	52.25	81.83	2.01	64.09	98.62	0.98	43.39	68.85
Supetar	43.371	16.330	40	1.31	51.06	80.34	1.96	63.16	97.55	0.93	42.30	67.44
Šibenik	43.733	15.917	40	1.29	50.74	79.61	1.95	62.98	97.02	0.92	42.12	67.18

Varaždin	46.308	16.342	173	1.18	48.34	76.28	1.88	61.67	95.33	0.81	39.19	62.75
Vinkovci	45.292	18.817	90	1.22	49.16	77.46	1.90	62.08	95.94	0.84	40.05	64.08
Virovitica	45.833	17.385	122	1.20	48.70	76.85	1.89	61.86	95.64	0.83	39.58	63.36
Vukovar	45.350	19.007	108	1.22	49.10	77.44	1.90	62.06	95.94	0.84	39.93	63.89
Zadar	44.100	15.200	40	1.27	50.36	79.11	1.94	62.76	96.76	0.91	41.72	66.58
Zagreb	45.824	15.990	180	1.20	48.81	76.97	1.90	61.97	95.76	0.83	39.77	63.61
Zavižan	44.800	15.000	1670	1.34	51.94	80.58	2.06	64.92	98.87	0.95	42.83	67.33
			minimum	1.18	48.34	76.28	1.88	61.67	95.33	0.81	39.19	62.75
			maximum	1.36	52.25	81.83	2.06	64.92	98.87	0.98	43.39	68.85
			median	1.24	49.52	77.94	1.92	62.39	96.24	0.87	40.68	64.94
			average	1.25	49.93	78.51	1.93	62.64	96.62	0.88	41.03	65.48
			STD	0.0486	1.0790	1.4821	0.039	0.7137	0.8629	0.0458	1.2207	1.8011

three analyzed days. Locations Pag, Pazin, Mali Lošinj, and Rab exhibit values close to the average. This is why we selected Pag as a representative location for subsequent calculations (Table 1). Figure 1 shows the spectral irradiance wavelength dependence for Pag on 1 April, 1 July, and 1 October, at 13 h CEST. Figure 2 shows the variation of UV-B dose rates over the day, calculated using the TUV model and simplified equation, as was done previously by Pehnec *et al.* *(25)* for the UV index estimation:

$$I_{UVB} = 2 - \left| \frac{t-13}{3} \right| \qquad [3]$$

where t is local time (CEST).

Figure 3 presents the relative difference D of these two methods.

$$D = \frac{I_{UVB}(TUV) - I_{UVB}(eq)}{I_{UVB}(TUV)} \times 100 \qquad [4]$$

Variations of UV-B dose rates over the vegetative growth period are shown in Figure 4. Simplified equation that replaced the TUV model was:

$$I_{UVB} = 2 - \left| \frac{w-25}{15} \right| \qquad [5]$$

where w is the week of the year. The relative difference between the TUV and equation [5] results is shown in Figure 5.

Table 2 and Figure 6 show different biologically effective UV irradiances (daily doses and maximum daily value at 13 h, CEST) calculated using the TUV-obtained data from Figure 1 and action spectra data from literature. Four action spectra were used: generalized plant damage spectrum *(21),* plant damage in higher plants *(22),* inhibition of photosynthesis *(23)* and photoinhibition of chloroplast reactions *(24).*

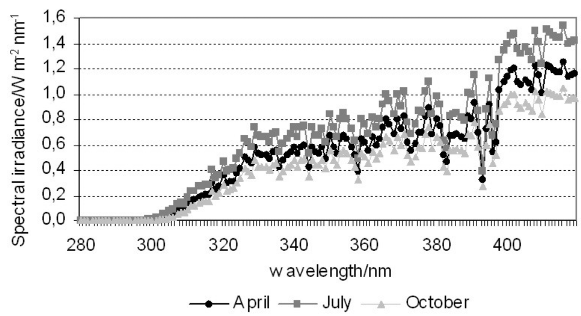

Figure 1. *Spectral irradiance calculated using the TUV model for Pag at 13 h, CEST (cloudless conditions).*

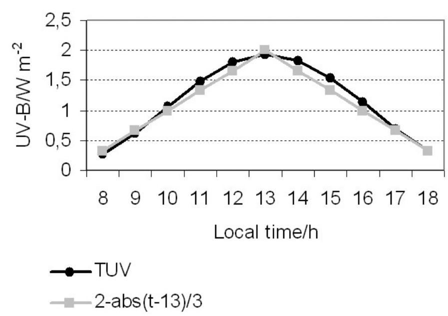

Figure 2. *Variations of UV-B dose rates during the daytime, calculated for Pag on July,1 (cloudless conditions).*

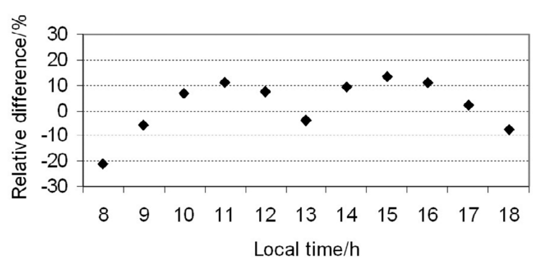

Figure 3. *Relative difference between UV-B dose rates calculated using the TUV model and simplified equation [3], daytime variations.*

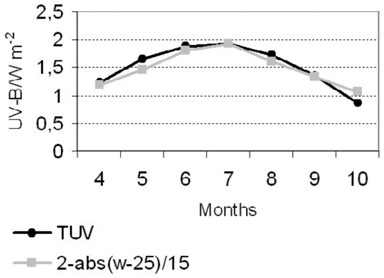

Figure 4. *Variations of UV-B dose rates over the vegetative growth period, calculated for Pag at 13 h, CEST (cloudless conditions). The first day of the month was taken as a representative.*

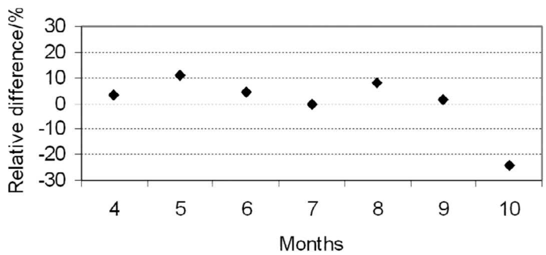

Figure 5. *Relative difference between UV-B dose rates calculated using the TUV model and simplified equation [5], monthly variations*

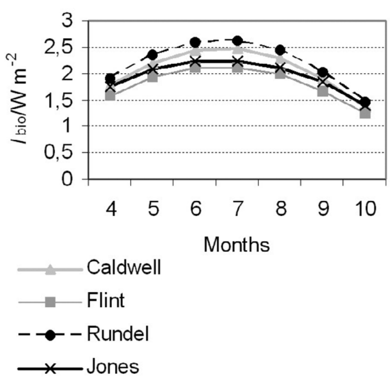

Figure 6. *Variations of biologically effective UV dose rates over the vegetative growth period, calculated for Pag at 13 h, CEST (cloudless conditions). The first day of the month was taken as a representative.*

Caldwell *et al.* *(21)* – Generalized plant damage spectrum
Flint and Caldwell *(22)* – Plant damage in higher plants
Rundel *(23)* – Inhibition of photosynthesis
Jones and Kok *(24)* – Photoinhibition of chloroplast reactions

DISCUSSION

In this study we found that UV-B dose rates in Croatia varied from 1.18 W m^{-2} (Varaždin) to 1.36 W m^{-2} (Srđ) in April, from 1.88 W m^{-2} (Varaždin, Koprivnica, Krapina) to 2.06 W m^{-2} (Zavižan) in July, and from 0.81 W m^{-2} (Varaždin, Koprivnica) to 0.98 W m^{-2} (Srđ) in October. Daytime variations of UV-B dose rates can be described by the simplified equation [3]. The relative difference between this equation and the TUV model is less than 15% for hours 9–18 (Figure 3). Variations of mean solar noon UV-B dose rates during April-September can be estimated by equation [5], with an error of less than 10% (Figure 5). These results show that both simple equations may be used to estimate UV-B exposure in Croatia instead of using complex radiative transfer models.

TABLE 2

Daily biologically effective UV doses (kJ m^{-2}) calculated using the spectral irradiances obtained by the TUV model.

Date	F_{bio} Caldwell	F_{bio} Flint	F_{bio} Rundel	F_{bio} Jones
1 April	42.8	39.2	45.3	44.8
1 May	57.7	51.9	61.3	58.0
1 June	67.0	59.8	71.2	66.1
1 July	67.9	60.6	72.2	66.9
1 August	60.7	54.5	64.5	60.6
1 September	46.9	42.6	49.6	48.4
1 October	31.0	29.0	32.7	33.8

Caldwell *et al.* *(21)* – Generalized plant damage spectrum
Flint and Caldwell *(22)* – Plant damage in higher plants
Rundel *(23)* – Inhibition of photosynthesis
Jones and Kok *(24)* – Photoinhibition of chloroplast reactions

Biologically effective UV daily doses ranged from 29 kJ m^{-2} in October to 72 kJ m^{-2} in July. Biologically effective UV dose rate in July, at 13 h CEST, was between 2.1 W m^{-2} for photoinhibition of chloroplast reactions and 2.5 W m^{-2} for generalized plant damage spectrum.

The values calculated in this paper are higher than those obtained by measurements at similar locations *(26–29)*. However, doses and dose rates calculated in this study are the maximum values; all values were obtained assuming clear-sky conditions and the total ozone column value 300 DU which roughly corresponds to the lowest total ozone value measured during vegetative growth period (Figure 7). The influence of clouds on UV exposure was not analyzed in this paper although TUV model allows cloud correction using the parameter τ – cloud optical depth (uniform cloud coverage of the sky is assumed).

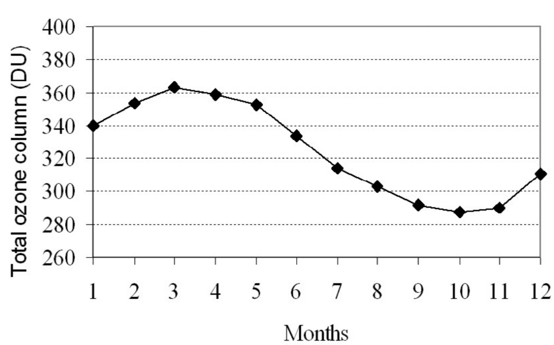

Figure 7. *Annual variations of total ozone column over the year 2001 (data on total ozone column values from the NASA/TOMS web site were used).*

Clouds significantly reduce UV radiation reaching the Earth's surface. There is a linear relationship between UV dose rates calculated during cloudless conditions and in cloudy weather, according to the expression UV dose rate (cloudy weather) = UV dose rate (cloudless condition) × C, where C is cloud transmission factor with values 0–1. However, C and τ are not available from standard ground-based measurements. This expression also does not account for a case of partially cloudy sky. In this study, cloud correction was not included in calculations, because plant exposure depends not only on cloud conditions, but also on the position of a plant in the field (for example, if it is in the shadow or not).

Changes in ozone were found to contribute significantly to UV exposure. Over the last few decades, the decrease in stratospheric ozone caused an increase in UV radiation on the surface *(30, 31, 32)*. Total ozone column used in our study was 300 DU for all calculations. It corresponds to one of the lowest values over the year, which is usually measured over Croatia in September and October (the end of vegetative growth period). Figure 7 shows average annual variations of total ozone column over Croatia for the year 2001. The figure was created using data on total ozone column values from the NASA/TOMS web site *(33)*. New data on annual variation of total ozone in the region of Croatia can be found in Vujnović *at al. (34)*.

The influence of changes in total ozone column on UV exposure was discussed in detail by several authors, for example Madronich *et al. (31)* and Micheletti *et al. (32)*. Using the TUV model, they calculated radiation amplification factor (RAF) for different action spectra, including those used in this study. RAF is a measure of the sensitivity of biologically active irradiance, I_{bio}, to changes in ozone vertical column amount. A simple relationship describes the dependence of UV dose rates on ozone *(32)* and makes it possible to correct our data additionally.

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