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ACTUALIZATION OF SEMI-EMPIRICAL EQUATION FOR UV INDEX

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Abstract

UV radiation at ground level undergoes many variations in the present, due to the ozone column, aerosols, clouds, surface reflectivity, both positive and negative variations, depending on latitude.

This work reports on the updating of the semi-empirical equation proposed by Madronich in 2007 for estimating the UV index, by updating its coefficients, as they encapsulate the state of the atmosphere. Data for Bucharest in 2019-2021 was used for fitting the equation. It was found that the new equation improves the accuracy of the estimation of the UVI in Bucharest five times for 2021 (from nRMSE = 17.3% to nRMSE=3.3%). The validity of the obtained equation was assessed in various locations, showing a great improvement of the estimation accuracy in most of them (in 12 of the 14 chosen locations), regardless of latitude. The equation produces a negative bias for locations having Koppen climate types A and B, a positive bias for the investigated locations situated in climate type D and no definite bias for temperate climates (type C). More studies are needed for drawing a definite conclusion and further improving the applicability of the equation.

1. Introduction

Ultraviolet radiation (UV) is defined as electromagnetic radiation with wavelengths comprised in the 100-400 nm range and it is differentiated into three spectral bands [1]:

• Ultraviolet A (abbreviated UVA), also called long-wave UV light, with wavelengths ranging between 315–400 nm;

• Ultraviolet B radiation (UVB or medium wave UV) having wavelengths between 280-315 nm;

• Ultraviolet C radiation (UVC, shortwave UV, or germicidal UV) with wavelength less than 280 nm.

When radiation emitted by the Sun enters the Earth's atmosphere, it is modified by processes of absorption and scattering. The most important phenomenon influencing ultraviolet radiation at ground level is its absorption in the atmosphere due to photochemical reactions pertaining to the creation-destruction cycle of ozone. These reactions, which take place in the stratosphere, virtually absorb all radiation in the UVC band [2]. However, radiation in the UVA and UVB bands is not completely absorbed in the stratosphere and therefore reaches the Earth's surface in amounts depending on the total ozone content and the presence of other gases, aerosols or clouds [3, 4, 5].

The present work investigates the validity of a semi-empirical equation for determining the UVI in the present in Bucharest and proposes an up to date version of it. Then an assessment of its accuracy is performed in various locations.

1.1. Estimation of UV radiation at ground level

The ultraviolet radiation that reaches the ground presents a diurnal and annual variability governed by astronomical and geographical parameters, as well as atmospheric conditions. With the development of human activities that affect the atmosphere, new factors have appeared that influence the amount of UV reaching the ground, such as air pollution, new types of aerosols, and the ozone layer depletion. Consequently, solar ultraviolet radiation is a highly variable environmental parameter that changes greatly in time and space. Therefore, keeping the UV information up to date is an important issue.

Estimation of UV radiation at ground level cand be done, similarly to the case of the broadband radiation, in several ways:

- by employing parametrical models which are derived from spectral codes [6 - 9],
- using statistical models, such as polynomial regression analysis [10] or by using other types of models developed by statistical analysis of time series [11],
- by machine learning techniques [12, 13]
- or, by devising more simple and accessible empirical models, mainly obtained by fitting the data available by satellite or ground measurements. These empirically constructed models are to be used with caution because they are connected to the region and period of construction. Also, the changes in the local and global climate nowadays, might shade some doubt on the validity of the calibration of the empiric models.

Generally, to compute the total solar irradiance on ground level, either referring to broadband solar radiation or to a narrow band of the solar spectrum, the beam component E_b and the diffuse one E_d are firstly estimated, the global irradiance being the sum of these two.

They depend on the Sun-Earth distance, on the atmospheric transmittances $\bar{\tau}$ and on the Sun elevation angle h (Eq.1):

$$E_b = E_{SC}\varepsilon\overline{\tau_b}\sin h$$
$$E_d = \gamma E_{SC}\varepsilon\overline{\tau_d}\sin h \qquad (1)$$

where E_{SC} is the solar constant, ε is a correction for the Sun-Earth distance, γ is the downward fraction of scattered radiation, and $\bar{\tau}$ represent the average atmospheric transmittances, obtained by averaging the spectral transmittances over the spectral band of interest.

The beam transmittance E_b takes into consideration the most important attenuators in the atmosphere, by their specific transmittances: O_3, NO_2, water vapours, other mixed gases, Rayleigh scattering and the extinction due to the aerosols. The diffuse transmittance appears as a sum of two components, corresponding to the Rayleigh scattering and the scattering processes on aerosols. These transmittances are generally difficult to equate, hence the difficulty of constructing an accurate parametric model.

The sun elevation angle may be substituted by the zenith angle θ_z:

$$\sin h = \sin\left(\frac{\pi}{2} - \theta_z\right) = cos\theta_z \qquad (2)$$

Other factors that influence UV radiation reaching the surface of the Earth, besides Sun-Earth distance and sun elevation angle are ozone, clouds, albedo, aerosols, latitude, time of day, the season of the year, and altitude [14].

Ozone is a very important atmospheric component that greatly influences UV radiation at ground level. The stratospheric ozone shows substantial daily, seasonal, and annual fluctuations, but it is well known that a gradual downward trend in the amount of stratospheric ozone occurred in the last decades of the last century, mostly over Antarctica, but also in temperate zones. Although the problem of the “ozone Hole” has been addressed internationally by the Montreal Protocol and the Antarctic ozone hole is recovering, while still occurring every year, no significant trend has been detected in global (60°S–60°N) total column ozone over the 1997–2016 period with average values remaining roughly 2% below the 1964–1980 average [15]. The change in the ozone layer in the second half of this century is projected to be complex, with increases and decreases in different regions. At mid latitudes, a decreasing trend in the total ozone column might still occur [16], resulting in an increased flux of UV radiation at the earth's surface and in the top layers of the ocean.

Clouds also influence greatly the level of UV radiation on ground, leading to both an increase and a decrease in UV radiation on the surface of the Earth [4, 17]. Attenuation depends on various cloud properties such as cloud fraction, cloud optical thickness, relative position to the Sun, cloud type, number of cloud layers, etc.

Aerosols affect solar radiation both by scattering and absorption. Krzyscin and Puchalski [18] state that daily variation in aerosol optical depth can be responsible for up to 20 – 30% changes in erythemal UV. Erlick and Frederick [19] model the effect of aerosols relative to an aerosol-free atmosphere, finding a transmission reduction of 15.2% for continental aerosol and 40.0% for urban aerosol, both for 310 nm and average summer humidity conditions. Seckmeyer [20] studied transmission reduction due to AOD and obtained a 20% reduction at 355 nm when AOD increases from 0.1 to 1. Krotkov et al. [21] found that aerosol absorption can produce a very large reduction in UV flux (50%) in some parts of the world.

As far as altitude is concerned, UVB increases with 2 – 23% km^{-1} [22, 23], UVA increases with cu 7 –15% km^{-1} [23], erythemal UV increases with 6– 18% km^{-1} [24 -26].

All these are cumulative factors, hence the daily UV dose may vary with 24% in a place, from which the ozone variation counts for 3% and the rest may be due to the clouds [27].

1.2. Biological effects of UV radiation

UV radiation, even if it constitutes only a mere 8% of the solar spectrum, plays an important role in many biological processes. On one hand, it can have beneficial effects, such as the production of Vitamin D, but on the other hand it can be harmful to living organisms [28]. Bearing in mind that the energy of a photon is inversely proportional to its wavelength, electromagnetic radiation in the UV range can have severe physiological consequences because the photon's energy reaches the value of an average chemical bond.

Of particular biological interest is the rate at which an object receives radiative energy capable of initiating a certain biological process. The received radiation is weighted with a specific spectral function $A(\lambda)$ called action spectrum. A biological action spectrum describes the wavelength dependent response of a particular biological system to the electromagnetic radiation.

The weighted UV dose rate (on a flat horizontal surface) is calculated as:

$$\frac{dD}{dt} = \int_{\lambda min}^{\lambda max} A\,(\lambda) \cdot E(\lambda)\; d\lambda \tag{3}$$

where E(λ) is the spectral irradiance, A(λ) is the action spectrum for the specific biological process, and λ_{min} and λ_{max} delimit the spectral range of interest. The radiation dose D is obtained by integration over a time interval.

1.3. UV Index

As UV radiation can also have effects on humans, a parameter that is easy to understand by the general public has been created to be used in the field of public health. This parameter is called the UV index (UVI) and is closely related to the known erythematous effects of solar ultraviolet radiation on human skin. Humans need low levels of UVB radiation to produce vitamin D, but overexposure may lead to adverse effects, such as immunosuppression and skin cancer. It was found that the wavelength dependence of squamous cell carcinoma induction in humans is similar to the one of sunburn - between 290 and 300 nm (figure 1) [2, 29].

To provide UV related information in a way that is easy to understand and useful for sun protection and health care, a dimensionless index for erythemal irradiance has been introduced, the UV index [30]. UV index (UVI) is defined based on the spectral irradiance of sunlight that is known as ultraviolet erythemal radiation (UVER) using a weighted function related to the occurrence of skin erythema [31], and it represents the instantaneous sunburn potential of UVER [14]. In 2002, WHO also defined a colour code to visualize the UVI [1].

The erythemal action spectrum used to define UVI is defined by equation (4) according to McKinlay and Diffey [32], and its graphical representation is the one presented in figure 1:

$$A_{ERY}(\lambda) = \begin{cases} 1, & \lambda \in [250,\ 298]\ nm \\ 10^{0.094(298-\lambda)}, & \lambda \in (298,\ 328)\ nm \\ 10^{0.015(139-\lambda)}, & \lambda \in (328,\ 400)\ nm \end{cases} \tag{4}$$

UVI is a dimensionless quantity defined as the erythemal irradiance multiplied by 40:

$$UVI = 40m^2W^{-1}E_{ery} = 40m^2W^{-1}\int_{\lambda=250nm}^{\lambda=400nm} E(\lambda,t)A_{ery}(\lambda)d\lambda \tag{5}$$

UVI is usually presented to the public as the value computed for the maximum UVER in a day, usually at noon, and rounded to the nearest integer. In Europe, for most meteorological conditions, UVI remains lower than 10.

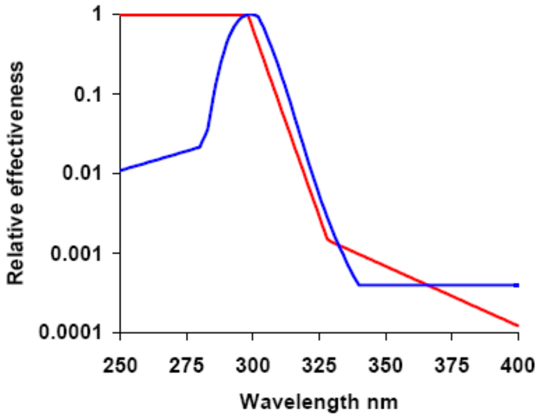


Figure 1. The CIE (1987) reference action spectrum for erythema in human skin (red) and the estimated CIE (2000) action spectrum for human squamous cell carcinoma (blue) based on mouse studies [29]

UV related risk factors for humans depend heavily on skin type, with skin phototype I being the one of people with fair skin, and skin phototype VI of people with darker skin [33]. The minimum erythemal dose (MED) is defined as the threshold above which erythema starts to develop (perceptible redness of human skin), and it depends on skin type (colour and thickness). For Caucasian population, the definition of 1 MED can vary from 200 to 450J·m^{-2}, depending on the skin type. To avoid ambiguities, the standard erythemal dose (SED) has recently been defined as 100 J·m^{-2} of erythemally weighted UV radiation. A sunburn duration for each skin type can be defined as the maximum time to stay unprotected in the sun without developing a sunburn UVER [31].

Some authors analyse how damage from sun exposure depends on cumulative daily doses and not only on UVI [10, 34] and how exposure in the middle of the day to low levels of UV (UVI=2) poses a significant risk of erythema for people with lighter skin phototypes, even for a duration of 3 h [35].

In Romania, the algorithm used for calculating UV index under clear sky conditions is the one developed by the international consortium of research institutes called "Satellite Application Facility on Ozone and Atmospheric Chemistry Monitoring" (O3M-SAF) under the auspices of the European Organization for the Exploitation Meteorological Satellites (EUMETSAT) [36].

2. Method and data

All the UVI and ozone data used in this paper for all investigated locations were collected using the archives provided by TEMIS (Tropospheric Emission Monitoring Internet Service) [37] for the years 2003 - 2021. These UVI values will be referred to hereafter as "measured values". The geographic coordinates of the weather stations in all locations are presented in Table 1.

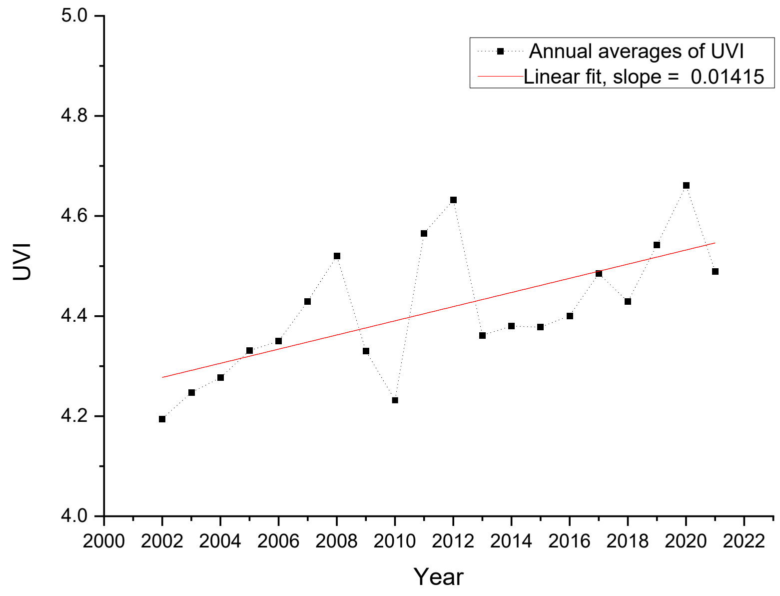


Figure 2. Annual averages of UVI in Bucharest between 2003 - 2021

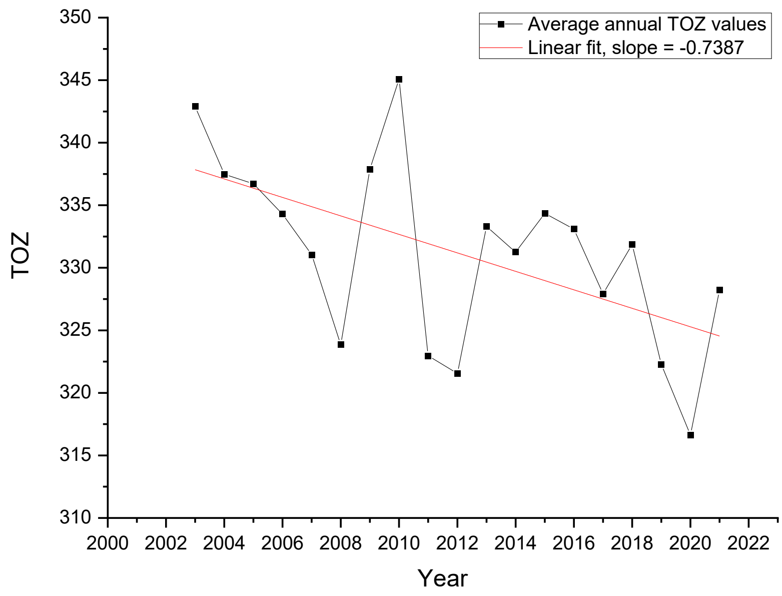


Figure 3. Evolution of annual averages of TOZ values in Bucharest between 2003-2021

By analysing the data corresponding to Bucharest station for this time period, one can observe a positive trend in the values of the UVI (figure 2) with an yearly increase of 0.014

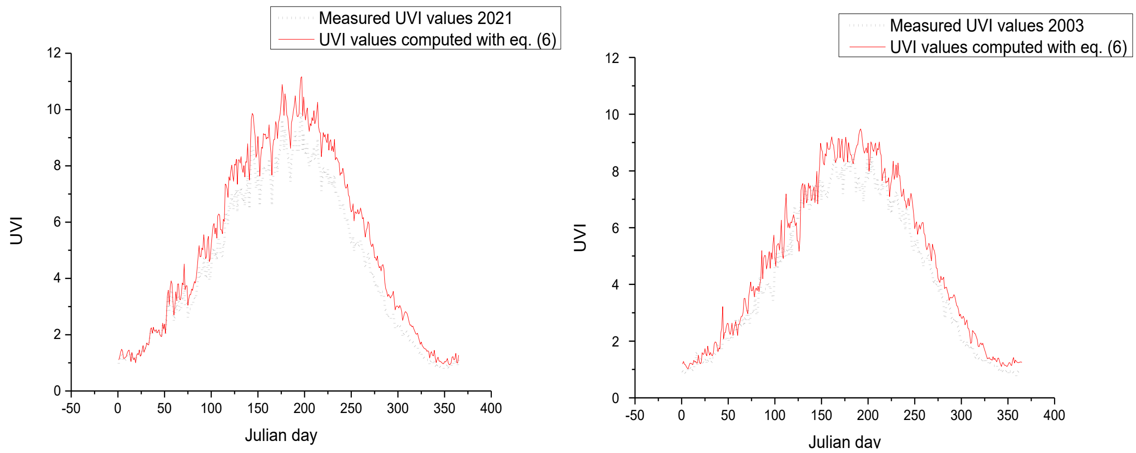
and a decrease of the TOZ, with an annual rate of 0.73DU/year (figure 3). These observations prove the dynamics of the UVI and the ozone over the time, and motivate the necessity of checking the validity and, eventually, the updating of the empirical models.

As seen in equation (5), the computation of the UVI requires the spectral irradiance (not easily available) and the erythemal action spectrum. Hence, in this work, a simpler equation was employed to compute the UVI, namely the semi-empirical equation proposed by Madronich in 2007 [38]:

$$UVI = 12.5 \cdot (\cos\theta_z)^{2.42} \, (TOZ/300)^{-1.23} \tag{6}$$

where $\cos\theta_z$ represents the cosine of the zenith angle and TOZ is the total ozone column.

First, we analysed the validity of equation (6) in the present atmospheric conditions, by computing the UVI for years 2003 and 2021 for Bucharest, by inputting the values of the zenith angle and TOZ from the database in equation (6). Figures 4. A) and B) display the measured values for UVI [TEMIS] and the computed values, for the years 2003 and 2021, respectively.



A) B)

Figure 4. UVI values computed for Bucharest with equation (6) (red line) and measured values (dots): A) year 2003; B) year 2021

Visual inspection of figure 4 leads to the observation that there is a significant discrepancy between the measured values of the UVI and the ones estimated with equation (6).

To quantify the relative error in estimating the UVI with equation (6), nRMSE (normalized Root Mean Square Error) was used:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(UVIcomputed_i - UVImeasured_i)^2}{N}}$$

$$nRMSE = \frac{RMSE}{UVImeasured} = \frac{\sqrt{\frac{\sum_{i=1}^{N}(UVIcomputed_i - UVImeasured_i)^2}{N}}}{\frac{\sum_{i=1}^{N}(UVImeasured_i)}{N}} \quad (7)$$

The relative errors are $nRMSE_{2003}$=0.177 (17.7%), for 2003 and $nRMSE_{2021}$= 0.173 (17.3%) for year 2021, which show quite a low precision of the estimation.

2.1. Actualization of the model coefficients

The amount of UV radiation reaching the ground level, and therefore UVI, also depends on other factors besides the total ozone concentration (TOZ) and the cosine of the zenith angle: the concentration and nature of aerosols, other atmospheric pollutants, the albedo of the surface [39], parameters that have changed in recent years. These parameters are embedded in the values of the coefficients in equation (6). Changes in the ozone layer, in climate and in the interaction of UV radiation with the atmosphere have caused seasonal and local changes in UVI [40].

To obtain a more accurate estimate with the semi-empirical equation (6) an adjustment of the coefficients of the equation is needed, to reflect the present atmospheric conditions. For this purpose, we chose the 2019-2021 interval for determining the new coefficients. The updated form of the Madronich-type function was obtained by fitting the data for Bucharest from the database from the period 2019-2021 (UVI, $\cos(\theta_z)$, TOZ) with a two-variable function of the form proposed in [38]:

$$UVI = A \cdot y^B \cdot (x/300)^C \quad (8)$$

With y= $\cos(\theta_z)$, and x=TOZ (in DU).

The surface obtained by 2D fitting with equation (8) of the measured values of UVI (coefficient of determination R^2=0.99745) is presented in figure 5.

The values of the fitting parameters to be used in equation (8) are:

A=10.94461 (9)

B=2.46536

C= -1.15055

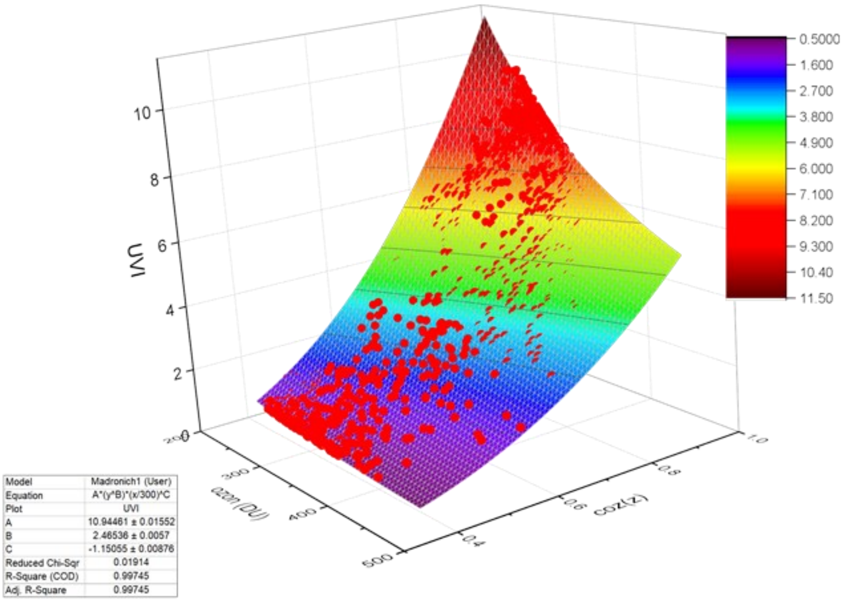
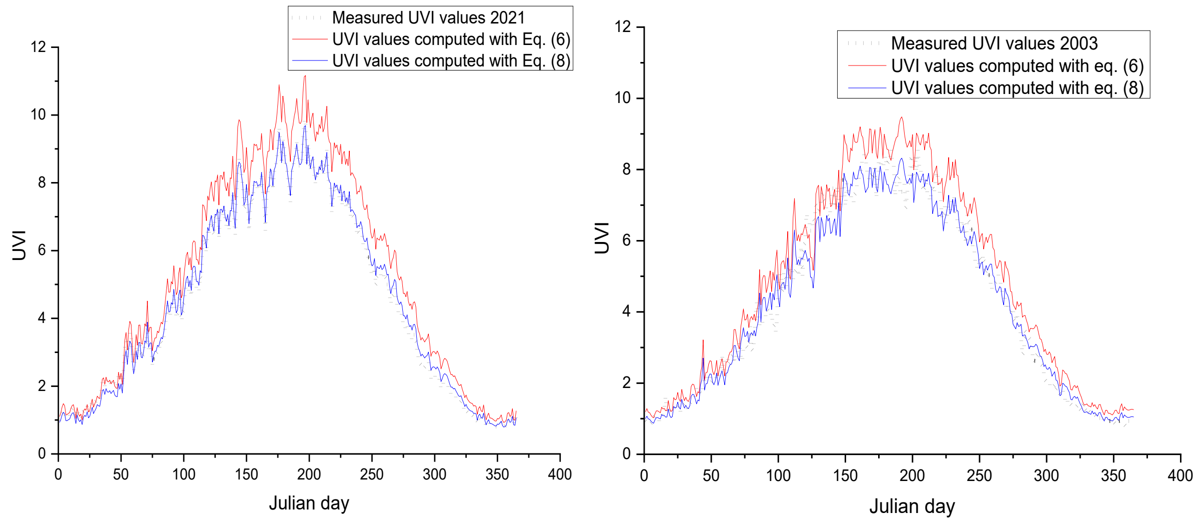


Figure 5. The measured values of UVI (2019-2021) with dots and the surface obtained by 2D fitting with equation (8)



A) B)

Figure 6. Measured values for UVI for **Bucharest** (black dots), UVI computed with equation (6) (red line), and values computed with equation (8) (blue line) for year 2021 (A) and 2003 (B)

3. Results and discussions

3.1. Assessment of the accuracy of estimation of UVI in Bucharest

The assessment of the accuracy of estimation of UVI, with equation (8) with coefficients (9) for the data of year 2021 for Bucharest, led to the value of $nRMSE_{2021'} = 0.033 = 3.3$ %. Therefore, changing the coefficients as proposed in this paper leads to a more than 5-fold improvement in the accuracy of UV index estimation (Figure 6 A). Equation (8) was also checked for year 2003, and the accuracy of the estimation for this period was obtained to be $nRMSE_{2003'}$ = 0.109 =10,9 %. Thus, changing the coefficients in those proposed in this paper leads to an almost 2-fold improvement in the accuracy of the UV index estimation for year 2003 (Figure 6B).

3.2. Assessment of the accuracy of estimation of UVI in other locations

Equation (8) with parameters (9) was used to estimate UVI in various location at different latitudes, to investigate its generality. The results are graphically presented in figures 7 and the corresponding nRMSE and Mean Bias Error (MBE) (eq. 10) values are synthesised in Table 1. MBE was chosen to capture an eventual bias of the equation.

$$MBE = \frac{\frac{\sum_{i=1}^{N}(UVIcomputed_i - UVImeasured_i)}{N}}{\frac{\sum_{i=1}^{N}(UVImeasured_i)}{N}} \quad (10)$$

The results presented in Table 1 show that the model proposed in this paper produces in most locations UVI values much closer to the measured ones than the original version of the equation, both in mid-latitude and in more northern locations, bringing improvements in accuracy even more than 5-fold. For lower latitudes, it seems that the accuracy is not improved so much, even being worse in some situations (Bangkok and Andorra la Vella). The best estimation was obtained for Adana (2.9% for 2021) followed by Madrid, Poprad-Ganovce, Bucharest, and Budapest. The lowest accuracy is obtained for Stockholm and Anchorage, but even in these situations the accuracy is three times better than by using eq. (6).

By analysing the graphs in figure 7, one can see that, in some locations, equation (8) overestimates the UVI (Anchorage, Poprad-Ganovce, MalinHead, and Stokholm), in other locations it underestimates UVI (Ahmedabad, Basra, Bangkok, Andorra la Vella) and in the remainder locations it estimates correctly the UVI. By analysing the geographic characteristics of these locations, it can be noticed that most locations where the model overestimates UVI are situated at latitudes higher than 49°N (between 49-61°N), and the climate is subarctic; the locations where the model underestimates UVI are situated at latitudes between 13-42 °N and the climate is tropical or hot semi-arid.

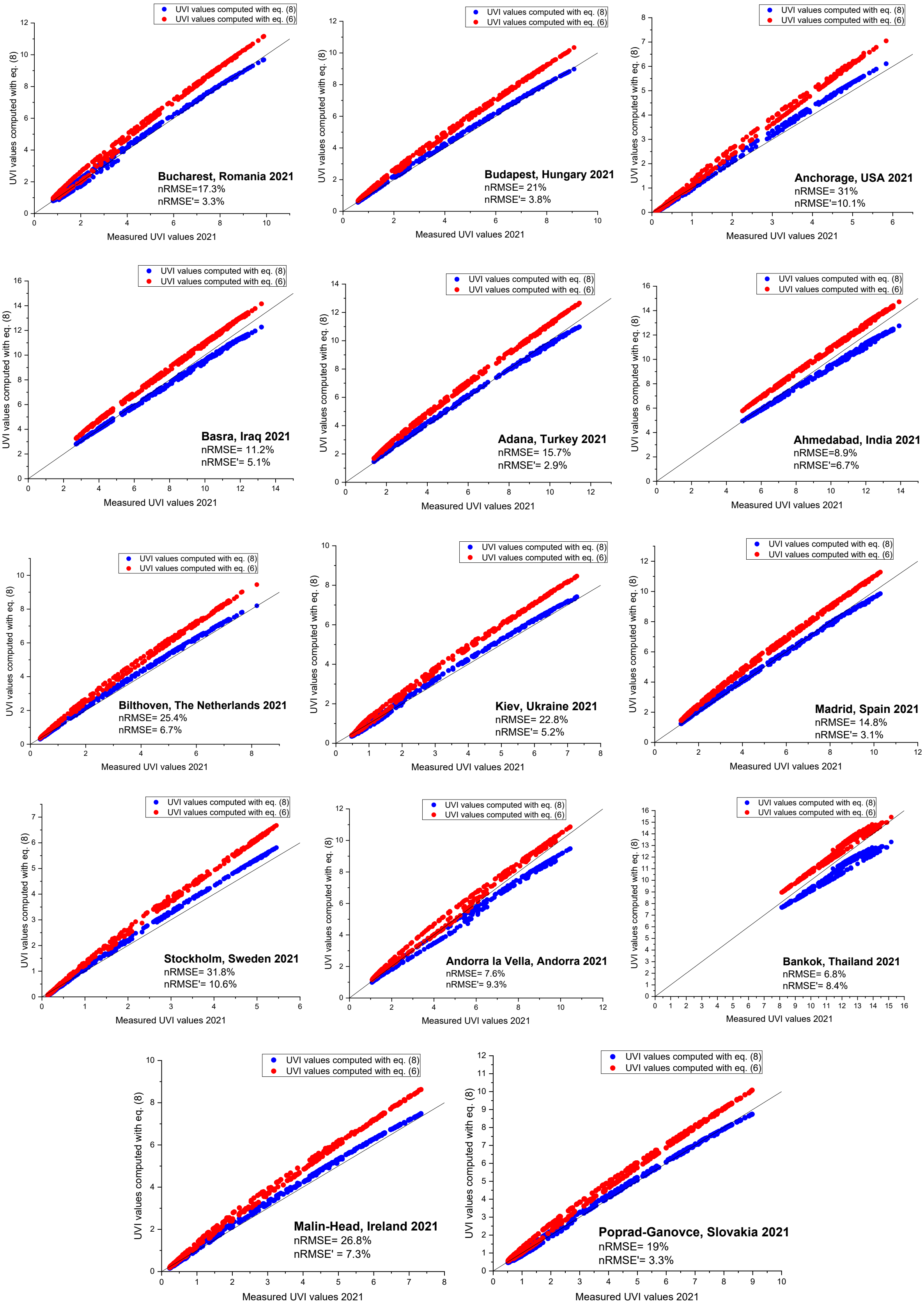


Figure 7. Comparison of UVI values computed with Eq. (6) and Eq. (8) versus the measured UVI in the investigated locations, for year 2021 (nRMSE' is for the results computed with Eq. (8))

Table 1. The accuracy of Madronich's model from 2007 (eq. 6) and of the updated one (eq. 8) in the investigated locations (A- Tropical Savanna Climate; B-hot semi-arid; C- Mild Temperate; D - subarctic climate)

Location	Longitude	Latitude	Climate (Köppen climate classification)	2003		2021		
				nRMSE (%) (eq. 6)	nRMSE (%) (eq. 8)	nRMSE (%) (eq. 6)	nRMSE (%) (eq. 8)	MBE (%)
Bucharest Romania	26.10°E	44.43°N	Cfa	17.7	10.9	17.3	3.3	1.6
Budapest Hungary	19.04°E	47.49°N	Cfa	21	3.9	21	3.8	3.1
Bilthoven The Netherlands	5.2°E	52.12°N	Cfb	25.1	6.5	25.4	6.7	5.3
Ahmedabad, India	72.67°E	23.05°N	Bsh	9.1	6.3	8.9	6.7	-5.8
Adana, Turkey	35.35°E	36.98°N	Csa	15.8	2.8	15.7	**2.9**	**0.04**
Basra, Iraq	47.65°E	30.41°N	Bwh	11.2	5	11.2	5.1	-3.7
Anchorage, USA	149.9° W	61.22°N	Dfc	29.1	8.9	31	10.1	5.3
Poprad-Ganovce, Slovakia	20.29°E	49°N	Dfc	18.8	3.3	19	3.3	0.9
MalinHead, Ireland	7.34°W	55.37°N	Cfb	26.6	7.6	26.8	7.3	5.4
Bangkok, Thailand	100.61° E	13.66°N	Aw	6.4	8.8	6.8	8.4	**-8**
Andorra la Vella, Andorra	1.52°E	42.51°N	Cfb	8.3	8.1	7.6	9.3	-7.3
Stockholm, Sweden	18.08°E	59.33°N	Dfb	31.3	10.9	31.8	**10.6**	7.4
Madrid, Spain	3.7°W	40.42°N	Csa	14.7	2.9	14.8	3.1	-0.7
Kiev, Ukraine	24.94°E	60.17°N	Dfb	22.8	5.8	22.8	5.2	3.4

To asses the bias of the updated equation, considering also the climate type according to the Koppen climate classification [41], MBE for all locations was computed for year 2021 and the values are presented in figure 8. For the investigated locations with climate types A and B (A- Tropical Savanna Climate; B-hot semi-arid) there seems to be a negative bias, while for locations in climate type D (subarctic climate) a positive bias occurs. For temperate climates (type C) there is no definite bias. More elaborate analyses, made on data from more locations, are needed to draw a conclusion on effect of climate type (which affects also the aerosol type) on the coefficients of the semi-empirical equation for UVI and to investigate the applicability of the model at high or low latitudes.

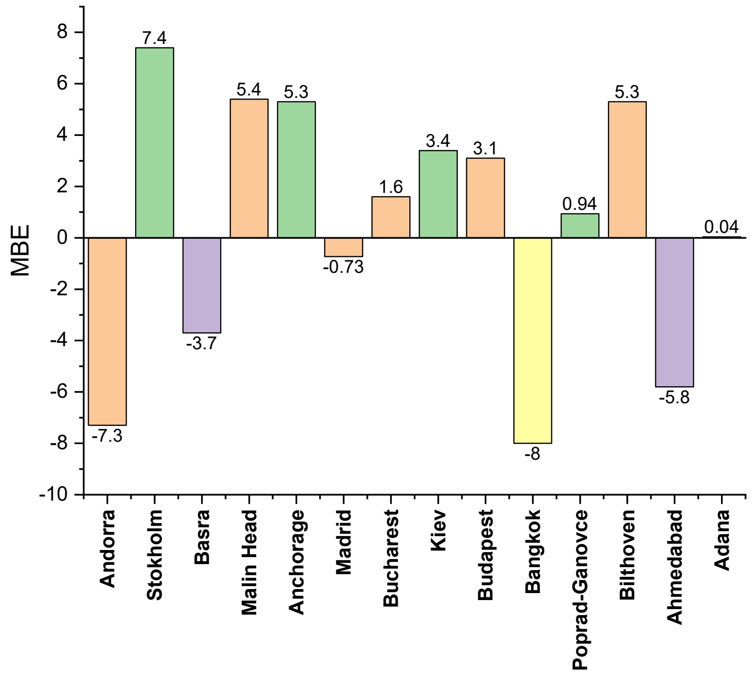


Figure 8. Mean Bias Error for all locations in 2021 (orange – climate type C; green – climate type D; yellow – climate type A; purple – climate type B)

4. Conclusion

There are many changes in UV radiation in the present, due to aerosols, clouds, surface reflectivity, positive and negative depending on latitude. At northern mid-latitudes, positive trends of UV radiation observed after the mid-1990s are attributed mainly to decreases in clouds and aerosols. Complex projections for the UV radiation for the end of the 21st century, relative to 2010–2020, based on the projections on ozone, clouds, and aerosols [4] state that these changes will continue, leading to the need for an updating of the empirical and even parametrical equations for computing the UVI.

This work reports on the updating of the semi-empirical equation proposed by Madronich in 2007 for UVI, by updating its coefficients, as they encapsulate the state of the atmosphere. Ozone and UVI data for Bucharest from 2019-2021 was used for fitting the equation. The accuracy of the estimation of the UVI for Bucharest improved from nRMSE = 17.3% to nRMSE=3.3%. The obtained updated equation was also used for various locations, showing a great improvement of the estimation accuracy in 12 of the 14 chosen locations, regardless of their latitude. The dependence of the accuracy on the climate of the locations was also discussed: the equation produces a negative bias for locations having climate types A and B (A- Tropical Savanna Climate; B-hot semi-arid), a positive bias for the investigated locations situated in climate type D (subarctic climate) and no definite bias for temperate climates (type C). More studies are needed for addapting the equation for different climate types.

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