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MONITORING AND FORECASTING THE BIOLOGICALLY ACTIVE ULTRAVIOLET RADIATION OF THE SUN

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Abstract. This article presents information about the importance of biologically active ultraviolet radiation from the Sun (UV-B), which is the subject of long-term (2011-2019) monitoring at the National Institute of Geophysics, Geodesy and Geography - Bulgarian Academy of Sciences. Information on the technique, the units of measurement and the summarized characteristics of the diurnal and seasonal course of UV-B are presented. On the basis of simple physical concepts of absorption of UV- radiation in the Earth's atmosphere is proposed an empirical model for forecasting its integral value, depending on the daily weather and season. According to the recommendations of the World Health Organization, a method for real-time notification of the permissible stay in the sun has been developed. In conclusion, the information on UV-index, which is provided on the website of the National Institute of Geophysics, Geodesy and Geography - Bulgarian Academy of Sciences is described in detail.

Key words: Solar ultraviolet radiation, UV-index, monitoring, empirical modelling

Introduction

Solar radiation includes ultraviolet (UV) radiation, visible radiation (light), and infrared (IR) radiation. The radiation is often characterised by its wavelength, usually expressed in nanometers ($1nm=10^{-9}m$). When describing biological effects ultraviolet radiation is often subdivided into three spectral bands: UV-C radiation (100-280nm), UV-B radiation (280- 315nm) and UV-A radiation (315-400nm). UV radiation can be measured as an irradiance – the power falling upon a surface unit area – in units of W/m^2, or as a radiant exposure, or dose – the energy falling upon a surface unit area during a specified period of time – in units of J/m^2 .

UV radiation is absorbed and scattered in the atmosphere. UV-C radiation is completely absorbed in the upper atmosphere by oxygen and ozone molecules. Most of the UV-B radiation is absorbed in the stratosphere by ozone molecules and only a few percent reach the surface of the Earth. Therefore, at the surface of the Earth the solar UV radiation is composed of a large amount of UV-A radiation and only a very small amount of UV-B radiation. UV-B radiation is known to be biologically damaging, whereas UV-A radiation is much less damaging but is known for its ability to tan the human skin. As ozone is the main absorber of UV-B radiation the UV-B intensity at the Earth's surface depends strongly on the total column of ozone in the atmosphere, thus on the thickness of the ozone layer (Kaleyna et. al, 2013a; Kaleyna et. al, 2013b). A factor, which describes the relation between the sensitivity of the UV-B intensity to changes in total ozone, is the so-called Radiation Amplification Factor (RAF). For small changes in the ozone layer thickness the RAF represents the percent change in UV-B intensity for a 1-percent change in the total column ozone (Kaleyna et. al, 2014).

Solar elevation is the angle between the horizon and the direction to the sun. The solar zenith angle (SZA) is often used in place of the solar elevation: it is the angle between the zenith and the direction to the sun. For high solar elevations the UV radiation is more intense because the rays from the sun have a shorter path through the atmosphere and therefore pass through a smaller amount of absorbers. As the UV irradiance depends strongly on the solar elevation it changes with latitude, season and time, being highest in the tropics, in summer and at noon.

The UV irradiance increases with altitude because the amount of absorbers in the overlaying atmosphere decreases with altitude. Measurements show that the UV irradiance increases by 6-8% per 1000 m increase in altitude.

At the surface of the Earth solar radiation is composed of a direct and a scattered (diffuse) components. Solar radiation is scattered on air molecules and on particles such as aerosols and water droplets. The direct component consists of the rays from the sun that has passed directly through the atmosphere without being scattered or absorbed. The diffuse component consists of rays that have been scattered at least once before reaching the ground. Scattering depends strongly on wavelength. The sky looks blue because blue radiation is scattered more than the other components. UV radiation is scattered even more and at the surface of the Earth the UV-B is roughly composed of a 1:1 mixture of direct and diffuse radiation.

The UV irradiance is higher when the sky is cloudless. Clouds generally reduce the UV irradiance but the attenuation by clouds depends on both the thickness and the type of clouds (optical depth of clouds). Thin or scattered clouds have only a little effect on UV at the ground. At certain conditions and for short times a small amount of clouds may even enhance the UV irradiance comparing the fully clear skies. In hazy conditions UV radiation is absorbed and scattered on water vapour and aerosols and this leads to decreasing of the UV irradiance.

Part of the UV radiation that reaches the ground is absorbed by the Earth's surface and part of it is reflected back to space. The amount of reflected radiation depends on the properties of the surface. Most natural surfaces such as grass, soil and water reflect less than about 10% of the falling UV radiation. Fresh snow, on the other hand, may reflect up to about 80% of the falling UV radiation. During winter and spring and a cloud-free sky, the reflection of snow can increase UV radiation on inclined surfaces to values typical of summer. This is important at higher altitudes and at higher latitudes. Sand may reflect about 25% of the UV radiation and can increase the UV exposure at the beach. About 95% of the UV radiation penetrate into the water and 50% penetrate to a depth of about 3 m. An action spectrum describes the relative effectiveness of UV radiation at a particular wavelength in producing a particular biological response. The biological response may refer to various detrimental effects on biological subjects including humans, animals or plants. An action spectrum for a given biological effect is used as a wavelength-depending weighting factor to the spectral UV irradiance (280 to 400nm) and then integrating over wavelength to find the actual biologically effective irradiance (in W/m^2). The effective UV dose (in J/m^2) for a particular exposure period is found by summing (integrating) the effective irradiance over the exposure period. The most important for common use are the erythemal, DNA absorption and non-melanoma skin cancer action spectra.

Human exposure to solar radiation may result in acute and chronic health effects. The main affected are the skin, the eye and the immune system. Acute effects of UV exposure include erythema (sunburn) of the skin and photo keratitis of the eye. Benign abnormalities of melanocytes may occur from overexposure to UV during childhood or adolescence. Chronic skin changes due to UV are skin cancer, and photo aging. Chronic effects on the eye include cataract, pterygium, droplet keratopathies and squamous cell cancer of the conjunctiva.

Major risks and public health concerns related to exposure to UV are skin cancer and cataract. The majority of UV epidemiological studies have addressed skin cancer. Various studies have been carried out on UV related cancers, influences on the immune system and diseases of the eye. A comprehensive summary and review of current knowledge can be found in the WHO/UNEP/ICNIRP Environmental Health Criteria 160 "Ultraviolet Radiation", published by WHO, Geneva, in 1994 (World Health Organization,1994).

As sunburn is a frequent detrimental effect on human skin the CIE Erythemal action spectrum is recommended for use in assessing the skin-damaging effect of UV radiation.

The "Minimal Erythemal Dose" (MED) is used to describe the erythemal potential of UV radiation and 1 MED is defined as the effective UV dose that causes a perceptible reddening of previously unexposed human skin. However, because human individuals are not equally sensitive to UV radiation due to different self-protection abilities of their skin (pigmentation), 1 MED varies among the European population within the range of between 200 and 500 J/m^2 (McKinlay and Repacholi, 2000).

The best known acute effect of excessive UV radiation exposure is erythema, the familiar skin reddening termed sunburn. In addition, most people will tan from the UV radiation stimulation of melanin production, which occurs within a few days of exposure. A further, less obvious adaptive effect is the thickening of the outermost layers of the skin that attenuates UV radiation penetration to the deeper layers of the skin. Both changes are a sign of damage to the skin. Depending on their skin type, individuals vary greatly in their skin's initial threshold for erythema and their ability to adapt to UV exposure. Prolonged exposure to UV radiation also causes a number of degenerative changes in the cells, fibrous tissue and blood vessels of the skin. These include freckles, nevi and lentigines, which are pigmented areas on the skin, and diffuse brown pigmentation. UV radiation accelerates skin ageing, and the gradual loss of the skin's elasticity results in wrinkles and dry, coarse skin. Several studies have demonstrated that exposure to environmental levels of UV radiation alters the activity and distribution of some of the cells responsible for triggering immune responses in humans. Therefore, sun exposure may enhance the risk of infection with viral, bacterial, parasitic or fungal infections, which has been demonstrated in a variety of animal models. Furthermore, especially in countries of the developing world, high UV radiation levels may reduce the effectiveness of vaccines. Since many vaccine-preventable diseases are extremely infectious, any factor that results in even a small decrease in vaccine efficacy can have a major impact on public health.

The purpose of this study is to present detailed information on the importance, methods of measurement and application of biologically active ultraviolet radiation from the Sun (UV). This paper illustrates the method of monitoring and the possibilities for forecasting the biologically active ultraviolet radiation of the Sun at the National Institute of Geophysics, Geodesy and Geography (NIGGG) - Bulgarian Academy of Sciences. The practical application of the UV index is presented in detail on the NIGGG website.

Monitoring equipment and organization

UV-B measurements are performed with equipment manufactured by Solar Light Company, Philadelphia. Two independent semi-kits are supported, consisting of a sensor located on the roof of the NIGGG building, a device for recording data in digital form (data logger) and a personal computer program developed by the company, performing the setup of the equipment and control over it. The sensor contains a detector, a GaAs semiconductor located in the horizontal plane, an optical system ensuring the transmission of a certain range of wavelengths and a device for maintaining a constant temperature of the detector. The operation of the detector is based on the ability of semiconductors to generate an electrical voltage proportional to the flow of light energy that irradiates it. Recording device transforms the voltage indications in digital form, averaging in the set time interval and recording the values in RAM from which the program transfers them to the disk memory of the working computer.

The basic unit for the UVB level is referred to as the UV index. It is a dimensionless quantity related to the energy flow of solar radiation:

$$I_{UV} = k_{er} \int_{250nm}^{400nm} E_{\lambda} S_{er}\left(\lambda\right) d\lambda \qquad (1)$$

where E_1 is the spectral density of solar radiation [W/(m^{2}nm)], S_{er} is the so-called erythemal function, which equalizes the impact on human skin of the components of the solar spectrum and the coefficient k_{er}=40 m^2/ W turns the energy flow into a dimensionless index, which is convenient for information to a wide range of people.

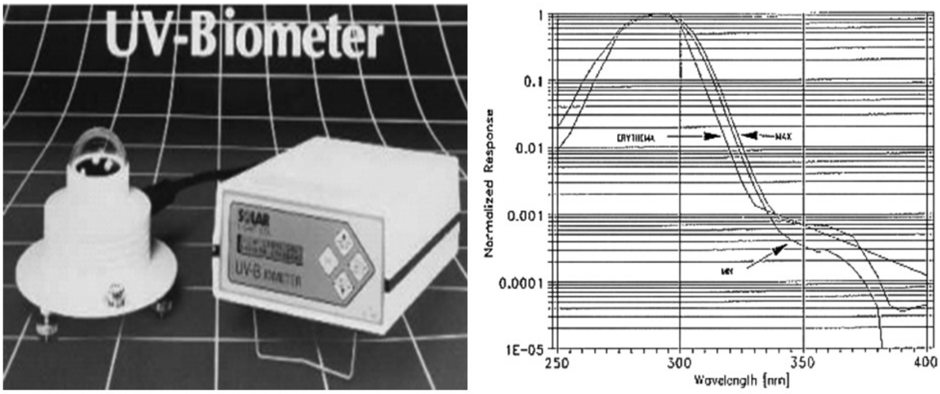

Fig. 1. Left panel- sensor and data recording device, right panel - erythemal function of the device.

The control program records in text form the average hourly values of the relative radiation dose (dose rate), which represents the ratio of the ultraviolet radiation flux to this value 0.05833W/m^2, which causes sunburn in people with sensitive skin, exposed for 1 hour. From these values the UV index can be determined as:

$$I_{UV} = \text{Dose Rate ´ } 0.05833 \text{ ´ } 40. \tag{2}$$

Assuming an inversely proportional dependence of the time for obtaining sunburn on the flow of ultraviolet radiation, the reciprocal value of the dose gives the allowable stay in hours.

According to the definition of the UV index, the permissible dose for 1 hour corresponds to I_{UV}=2.3332. Therefore, the time required to obtain a sunburn can be defined as:

$$\textit{Time till sunburn}\ [\text{hours}] = 2.3332/\mathrm{I}_{\mathrm{UV}}. \tag{3}$$

Using the UV index to determine the degree of risk of sunburn.

World Health Organization recommends I_{UV} values up to 2 to completely safe. Values between 3 and 7 as requiring precautions especially for people with sensitive skin. At values above 7, exposure of uncovered skin to sunlight is not recommended. In this way, the publication of real - time UV data available to the user allows everyone to assess the risk of sunburn and take the necessary measures to avoid it (World Health Organization, 2002).

More precise researches about the protecting against the harmful effects of sunburn divides human skin into four main types:

Type 1 *very sensitive, people with very light skin;*
Type 2 *sensitive, people with light skin;*
Type 3 *normal, people with light brown skin;*
Type 4 *weakly sensitive, people with brown skin.*

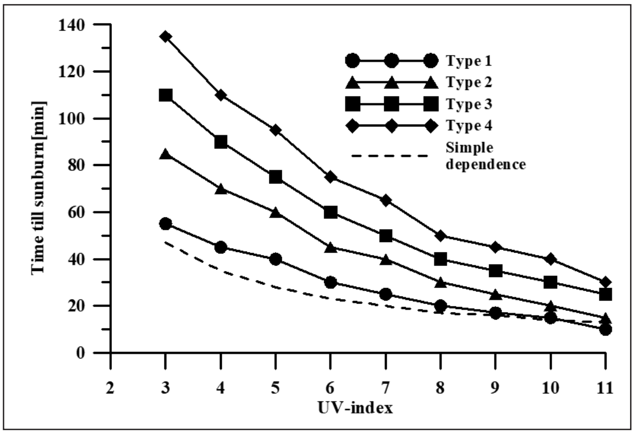

Fig. 2. Dependence of the allowable stay under solar radiation of UV- index and type of human skin. A dotted line shows the simplified dependence of formula (3).

Based on these dependencies, the allowable time for staying under the Sun's radiation of people with different sensitivity to sunburn can be determined with sufficient accuracy.

Main dependences of UV-index on the diurnal time and atmospheric conditions.

The flux of biologically active UV radiation can be considered constant, it is slightly affected by the activity of the Sun. The UV index is defined as the flux of radiation through a horizontal area of a single size (m^2), therefore, other things being equal, the value of the index will depend on the zenith angle of the Sun.

Fig. 3 shows a simplified model of the passage of UV radiation through the Earth's atmosphere. Different components of air have the ability to absorb the energy of radiation. In the stratosphere, UVB is absorbed mainly by the ozone layer and water vapor. In the figure the area of absorption of the UVB is simply presented as homogeneous. At the zenith angle of the Sun (denoted by c) is different by 0, the path of radiation through the absorption layer increases and it decreases in proportion to the cosine of the zenith angle. The impact of the radiation flux on the horizontal Earth's surface also reduces it in proportion to the cosine of the zenith angle. In the absence of additional absorption by the cloud layer in the troposphere, the dependence of the UV index on the zenith angle of the Sun can be assumed with sufficient as:

$$I_{UV} = I_{UV0} \cos^2 \chi \tag{4}$$

where I_{UV0} denotes the UV - index that can be measured at the position of the Sun at the zenith. This value is conditional, because at the latitude of Bulgaria the Sun is never at its zenith. The zenith angle of the Sun depends on the time of day and the day of the year as follows:

$$\begin{gathered}\cos\chi = \sin\varphi\sin\varphi_0 + \cos\varphi\cos\varphi_0\cos\left(\frac{\pi}{180}\left(15\left(UT-12\right)-\theta\right)\right) \\ \varphi_0 = \frac{\pi}{180}23.45\sin\left(\frac{360}{365}\left(DOY-21\right)\right)\end{gathered}. \tag{5}$$

With *j* is marked latitude, *q* is longitude, *UT*- universal time (along the Greenwich meridian) and *DOY* is the day of the year.

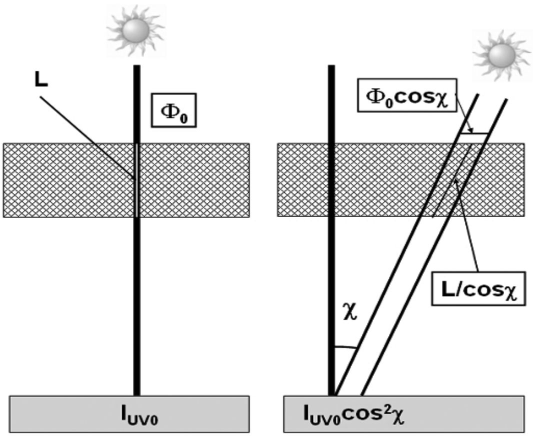

Fig. 3. Simplified representation of the passage of ultraviolet radiation through the Earth's atmosphere.

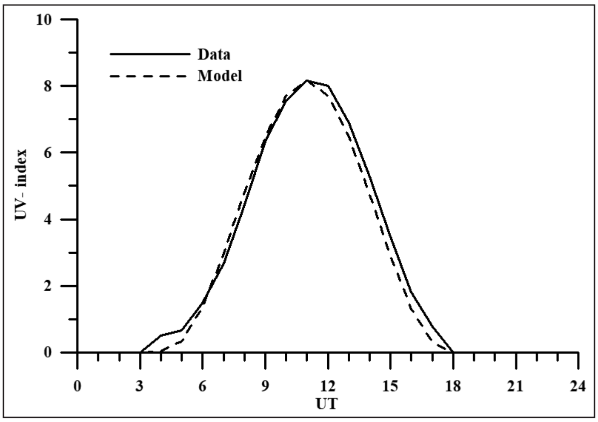

Fig. 4. Comparison of average data for August and model according to formula 4 and 5.

Fig. 4 shows a comparison between the average hourly data for August during the period 2011-2019 and the model values calculated by formulas 4 and 5. The dependence of the diurnal time, represented by the square of the cosine of the zenith angle of the Sun, satisfactorily describes the diurnal course of the UV- index. Equations (4) and (5) make it possible to predict the values of the UV- index in clear weather depending on the time of day and the date.

Results of the monitoring of the UV-index for the period 2011-2019.

The values of the UV index strongly depend on the cloud cover, that is why the statistical processing of data during the study period is difficult, especially during the winter and equinox months, when days with very clear sky are rare.

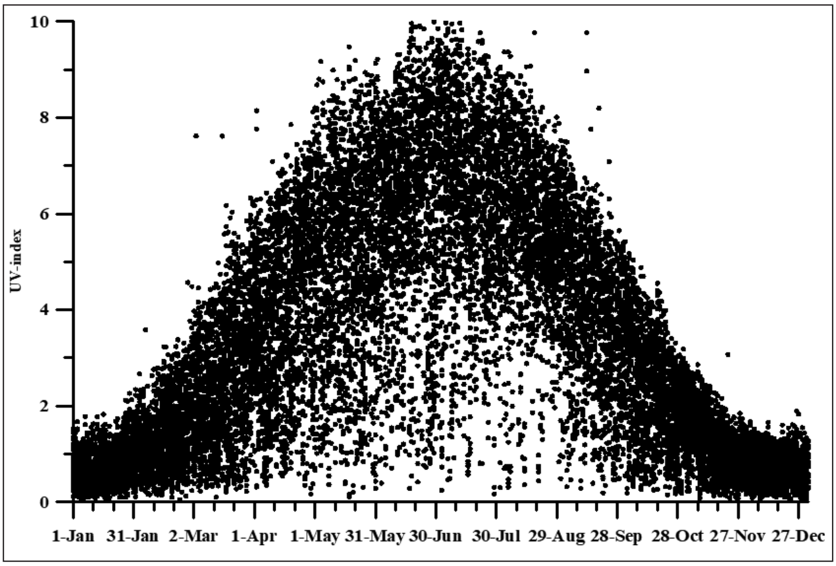

Fig. 5. Composed year from the measured values for the period 2011-2019 at local time 11, 12 and 23 hour.

As an illustration, Fig. 5 shows the measured values for the entire period 2011-2019 at 11, 12 and 13 hour local time (around noon). There is a significant scattering of data due to the different degree of cloudiness in the respective dates of the years, as well as the presence of obviously invalid values due to equipment errors. In order to obtain a relatively reliable value of the noon UV- index for the date, the respective medians, lower and upper deciles were calculated from the data for each day. The median is a value that halves the values below and above it, the upper decile is a value above which 10% of the data is found. The lower decile is a value below which 10% of the total data remains. The upper decile is a suitable value for estimating the UV- index in clear weather.

Fig. 6 shows the climatology of the UV index for the period 2011-2019. For each calendar month and for every hour are calculated the medians, upper and lower deciles. For each calendar month and for each hour, the medians, upper and lower deciles of the set of measured values are calculated. The diurnal and seasonal course of the UV-index satisfactorily follows the diurnal and seasonal course of the zenith angle of the Sun according to formula 5. The values of the upper deciles can be taken as values in clear weather, the lower deciles as values in significant cloudiness, and the medians as values in average seasonal cloudiness. The maximum value of the UV index for Bulgaria turns out to be 9.

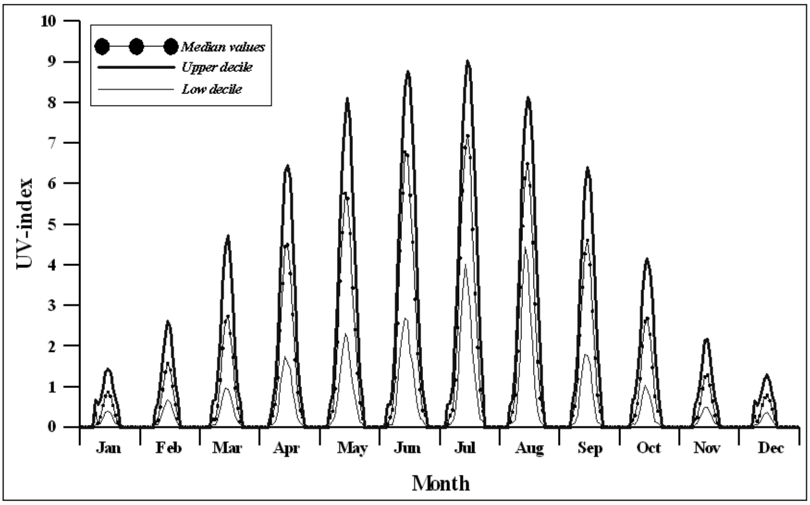

Fig. 6. Climatology of the UV-index for the period 2011-2019.

UV- index forecasting.

The empirical model for forecasting the UV-index developed in NIGGG is based on the measurements conducted for the period 2011-2019 and on the basic regularities of the diurnal and seasonal variability according to Equations 4 and 5 (Bojilova et. al, 2020).

Fig. 7 demonstrates climatological values of the quantity I_{UV0} obtained for each day of the year from the upper deciles of the measurements in the hours around the local noon according to Equation 4. If the UV-index depended only on the zenith angle of the Sun, this value should not change during the year, but its dependence on the season is observed. Practically constant values are obtained only in the months of July, August and September. During the winter season, the increase of aerosol concentrations in urban conditions is likely to have an impact, which may cause additional absorption of UV radiation even on cloudless days. During the spring months, the spring maximum is also affected by the concentration of stratospheric ozone, which can also cause additional absorption. The obtained empirical daily values of I_{UV0} allow to predict the value of the UV- index or each hour of the respective date in clear weather according to formulas 4 and 5, taking into account the additional seasonal dependences of the absorption of UV radiation from the atmosphere.

If there is a forecast for cloud cover (in percent) for the respective day, the forecast values can be adjusted using the recommendation of the World Health Organizations, according to the research of which in case of cloudiness 100% UV-index drops to 20% of the value time. Assuming that the decrease of the UV index from the clouds has a linear character, the final formula for predicting the UV-index becomes:

$$I_{UV}\left(DOY,LT\right)=\left(1-80R_{cl}\right)I_{UV0}\left(DOY\right)\cos\chi\left(DOY,UT\right). \qquad (6)$$

R_{cl} is the relative cloudiness in percent, and I_{UV0} are the values shown in Fig. 7.

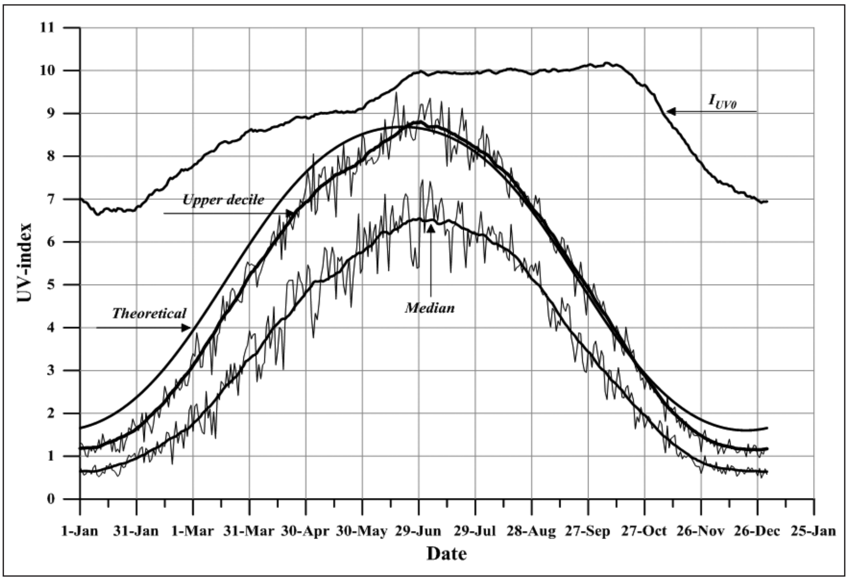

Fig. 7. Comparison between upper decile of the UV-index, median values of the UV-index, the theoretical values of the UV-index and I_{UV0}.

The recommendations of the World Health Organization allow an additional opportunity to correct the forecasts of the UV-index, taking into account the influence of altitude and the reflectivity of the environment.

Approximately every hundred meters above sea level UV-index increases by 1%. In the presence of an environment with expressive reflectivity, the time for safe stay is reduced as follows:

- snow cover - 1.9 times;
- sand - 1.15 times;

- sea foam - about 1.25 times;
- water - about 1.1 times.

Final remarks.

This study presents a detailed analysis of the importance of biologically active ultraviolet radiation from the Sun, as well as the monitoring and practical application of the UV index for the territory of Bulgaria. In order to provide information available to anyone interested in the condition of UV radiation at the Bulgarian Academy of Sciences, NIGGG has developed a special website presenting the current condition and relevant forecasts. The Web Page is publicly available: http://data.niggg.bas.bg/uv_index/uv_index_bg.php.

The graph of the UV-index for the current day is presented, which is updated automatically every hour. The values shown on the NIGGG page are colored with the colors recommended by the World Health Organization, indicating the degree of danger of getting sunburn, as well as the allowable time for stay according to equation 3.

A separate graph on the same web page shows the forecast for the next day - values that are obtained in clear weather, medium cloudiness and dense clouds (rain or snow). The values corresponding to the cloud forecast are shown in a separate color.

A separate application (http://data.niggg.bas.bg/uv_index/uvmaps_bg.htm) shows an animated map of Bulgaria with values of the UV index in clear weather, corrected for altitude.

The information services provided on the NIGGG website also include an interactive calculator (http://data.niggg.bas.bg/uv_index/time_sunb.htm), through which the user can calculate the time for safe stay on the Sun depending on the date and time, skin type, altitude and reflective properties of the surroundings. It includes also information to the user about the protective cream, which will ensure a safe stay for an unlimited time and a Practical Guide translated into Bulgarian and published by the World Health Organization.

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Мониторинг и прогнозиране на биологически активната ултравиолетова радиация на Слънцето

П. Мухтаров, Н. Милошев, Г. Гаджев, Р. Божилова

Резюме: В статията е представена информация за значението на биологически активната ултравиолетова радиация на Слънцето (UV- B), която е обект на дългогодишен (2011-2019) мониторинг в Националния институт по Геофизика, Геодезия и География към Българска академия на науките. Представени са сведения за техниката, измерителните единици и обобщените характеристики на денонощния и сезонен ход на UV- B. На базата на опростени физически представи за поглъщането на UV- радиацията в земната атмосфера е предложен емпиричен модел за прогнозиране на нейните стойности в зависимост от датата и сезона. Съгласно препоръките на Световната Здравна Организация е разработен метод за оповестяване в реално време за допустимия престой под слънчевите лъчи. Описани са детайлите на разработените он-лайн приложения, свободно достъпни на интернет страницата на НИГГГ.