Modeling the natural UV irradiation and comparative UV measurements at Moussala BEO (BG)

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Abstract. Studies of and modeling the impact of natural UV irradiation on the human population are of significant importance for human activity and economics. The sharp increase of environmental problems – extraordinary temperature changes, solar irradiation abnormalities, icy rains – raises the question of developing novel means of assessing and predicting potential UV effects. In this paper, we discuss new UV irradiation modeling based on recent real-time measurements at Moussala Basic Environmental Observatory (BEO) on Moussala Peak (2925 m ASL) in Rila Mountain, Bulgaria, and highlight the development and initial validation of portable embedded devices for UV-A, UV-B monitoring using open-source software architecture, narrow bandpass UV sensors, and the popular Arduino controllers. Despite the high temporal resolution of the VIS and UV irradiation measurements, the results obtained reveal the need of new assumptions in order to minimize the discrepancy with available databases.

1. Introduction
Overexposure to solar radiation, especially in the ultraviolet (UV) range (wavelengths 280–400 nm) of the solar spectrum, is the predominant risk factor for the development of erythema (sunburn) and all forms of skin cancer in humans. The UV radiation is also of great importance in the degradation of construction and household materials. The depletion of the ozone layer and the resulting changes in the UV radiation exposure reflect negatively on the conditions of the atmosphere and the oceans, and on all human activities. Therefore, studies on the variability of UV irradiation and its impact acquire increased urgency.

The UV irradiation’s biological impact (positive or negative) varies enormously with its wavelength, so that it is subdivided into three zones: UV-A (400–320 nm), UV-B (320–280 nm) and UV-C (280–200 nm). McKinlay and Diffey [1], found that erythema is caused by irradiation within 295–320 nm, the effect peaking near 305 nm. Both the quality (spectrum) and quantity (intensity) of terrestrial UV irradiation vary with several factors, including the solar zenith angle (SZA), the altitude, and the absorption and scattering by gas molecules (e.g., ozone, nitrogen oxides), water vapor or cloud.

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formations in the atmosphere. In fact, the solar atmosphere is not in thermodynamic equilibrium, so that the solar UV spectrum cannot be described correctly by Plank’s blackbody spectrum (~5800 K). The calculated solar irradiance outside the atmosphere, but at the Earth’s mean distance from the sun, is termed as “solar constant” and is approximately 1367 W/m². However, similar values of the global horizontal solar irradiance (GHI) have been measured at ground level. The maximal solar UV irradiance and solar GHI (of 1500 W/m²) have been estimated at high elevations near Cuzco (over 6000 m), Peru, under the assumption of full snow cover and 20% enhancement due to scattered clouds, as reported by Lilley and McKenzie [2]. Figure 1 presents a model of the terrestrial solar spectra at sea level, including the combined effect of 33 simulations of the atmospheric gas absorption bands and the harmful solar UV bands.

The solar irradiation variability is predetermined by the space configuration, namely, the planets’ elliptical orbits and the Earth’s rotational axis inclination with respect to its orbital plane. In addition, the solar energy is not constant but varies with the 27-day apparent solar rotation and an 11-year cycle of sunspot activity. The variability depends also on the scattering and optical absorption of mostly those wavelengths (λ < 290 nm) that are sensitive to molecular vibrations of atmospheric gases [3]. Solar radiation is not just scattered, some radiation is absorbed by molecules and particles and re-emitted back as thermal infrared (IR) radiation.

The UV irradiation influence on human health is being investigated intensively [4, 5]. There are positive and negative effects. The DNA damage induced by UV radiation is wavelength-dependent because of the strong absorption by DNA chains at wavelengths below 320 nm. The health benefits of UV-A radiation are principally derived from the synthesis of vitamin D in the skin, which supports bone health. UV-B rays are extremely energetic and harmful to the skin; they cause skin damage such as erythema and are responsible for 65% of skin tumors.

The UV index (UVI) is a measure of the intensity of solar UV radiation at the Earth’s surface, weighted erythemally. According to the World Health Organization recommendations (2002) [6], the UV Index values can be grouped into five exposure categories (UVI: 0-12 units).

Figure 1. Adopted standard solar terrestrial spectra (ASTM G173) including harmful solar UV bands.

At present, the majority of countries have adopted four skin types:

(white -> yellow/white -> yellow/black -> black),
as a function of the tanning capacity and the UV dose [J/m²] limits [7].

The low irradiation in wintertime results in diseases associated with vitamin D deficiency. The threshold for insufficient vitamin D production is about 0.7 kJ/m² per day, the erythemally-weighted
UV dose is approximately 0.55 kJ/m² per day, with a corresponding peak UVI = 1.3 at noon. In contrast, in bright summertime, if one considers a person without sun-protection having the most sensitive skin type I (UV dose required to induce erythema of 250 J/m²) and UVI = 12, then the skin damage time of exposure is 13.9 min. Such short exposure times are usually underestimated in climatic UV measurements and solar irradiation forecasting.

2. Measurements and modeling

2.1. Instruments and measurements

In the work presented, we developed specific UV sensors and portable data-loggers following the open-source software and open-source hardware approach. The purpose of our UV sensor design based on open-source architecture [8] was to explore the UV irradiation with a higher temporal resolution (< 2 min).

The Arduino platform provided additional flexibility, a higher temporal resolution and automation to the on-field measurement techniques and procedures, thus demonstrating a successful new low-cost approach to the open-source fabrication of scientific tools. The novel lightweight sensors for UV solar irradiation are based on the properties of wide-bandgap semiconductor materials (in particular diamond, GaN, SiC and Al-Ga-nitrides), and are characterized by visible solar blindness, radiation hardness and ageing robustness.

In this study, we made use of the latest generation of digital sensors (VEML6070) to measure the UV irradiance and to calculate the UV Index. A narrow-band Fabry-Perot interference filter (patented FILTRON thin-film technology and CMOS fabrication process) was attached directly to the photodetector. A VEML 6070 sensor breakout (manufacturer specified accuracy of 10%) was employed to measure the global UV-A and UV-B irradiance between the wavelengths of 305 nm and 375 nm. It provides in-factory sensor calibration and 16-bit analog to digital circuitry on the same chip. The spectral response of the sensor is shown in figure 2. The UVI calibration procedure was performed under laboratory conditions. The corrected voltages were converted into UV indexes following the calibration equation below:

$$UVI = 0.044\int S(\lambda)Ery(\lambda),$$

where $SS(\lambda)$ is the solar irradiance spectrum and $Ery(\lambda)$ is the McKinlay-Diffey erythemal action spectrum defined in [1]. Under the assumption that the total UV radiation ($UVTotal$) is the UV irradiation measured by the sensor at the fixed ratio (defined by the sensor manufacturer) $UVA = 94.1\%$ of $UVTotal$, and $UVB = 5.9\%$ of $UVTotal$, then

$$UVI = 0.04UVTotal(0.941k1 + 0.059k2),$$

where $k1 = 0.00070$, $k2 = 0.05221$ are the averaged erythemal factors for UV-A and UV-B, respectively.

Our field campaign was conducted between 20 June and 10 July 2017, at the Moussala BEO (2925 m ASL) in Rila Mountain. The measurements were performed under cloudy- and near clear-sky conditions. The instrumental setup consisted of several commonly-used and specially-designed sensing instruments: a broadband Kipp-Zonen pyranometer for solar GHI irradiation, UV-A, UV-B selective sensors for UV irradiation measurements, pressure and humidity sensors and a MICROTOPS II Ozone Monitor-Sun-Photometer.

**Figure 2. UVA + UVB sensor sensitivity.**
The UV sensors readings were acquired and recorded as 2-min averages by an open-source hardware platform (Arduino-based Adafruit Feather M0 data logger). Open-source integrated development environment (IDE) programing tools and a computer code based on C++ were used to develop in-home flexible control software. The Observatory roof and the location of the UV sensors are shown in figure 3.

The light-weight, low-cost UV sensors were chosen due to the open-hardware architecture, easy replacement and protection against the high risks of lightning and atmospheric electrostatic discharges at the high mountain area during UV-active seasons.

![Figure 3. UV sensor equipment and bio-container at Moussala BEO.](image)

Comparisons of the UV instruments performed by other authors [9] characterize the accuracy of the professional and low-cost UV instruments to about 0.5 UVI and 1 UVI, respectively. The variability under these thresholds is not significant. The UV measuring equipment based on photon UV sensors is a good low-cost instrumentation able to evaluate UV health risks and provide recommendations to the general public.

2.2. Modeling

Besides measurement activities, modeling the radiative transfer of UV radiation is deemed an important factor in assessing the UV irradiation effects. We considered the UV reduction due to clouds on the basis of daily doses.

In the model used, the daily values of the clear-sky global solar radiation \( (GHI_{\text{clearsky}}) \) were calculated using an empirical relation [10]. A fitted expression as a function of the cosine of the zenith angle \( \mu \) was derived from clear-sky radiometer readings in The Netherlands, Germany, and Greece, and measurements at EU sites which are validated to cover the intra-regions, such as the Bulgarian site of interest.

This, the daily UV-reduction factor \( (GDF) \) vs. solar \( GHI \) (day-to-day basis) was assumed to be

\[
GHI_{\text{clearsky}} = 1120(0.15 + \mu) \exp(-0.213R_{\text{eff}}) \quad \text{den Outer, [1998]},
\]

where \( R_{\text{eff}} \) is solar radiation’s relative path length through a curved atmosphere; \( R_{\text{eff}} \) varies from 1 for overhead sun (\( \mu = 1 \)) to ~ 15 at sunset (\( \mu = 0 \)).

Based on 125 ground stations, Matthijsen et al. [2000] defined:

\[
GDF = a(GHI/GHI_{\text{clearsky}})^b = UV/UV_{\text{clearsky}} \quad \text{Bodeker and McKenzie, [1996]),}
\]

where \( a = 1.05 \) and \( b = 0.84 \).

The daily clear-sky UV doses \( (UV_{\text{clearsky}}) \) were calculated at sea level using their dependence on the ozone column TOZ and on the solar zenith angle SZA. The daily mean ozone column data were obtained from the satellite total ozone mapping database.

The comparison with the ground-based data obtained by the MICROTOPS II Ozone Monitor revealed differences of more than 30%; these may be attributed to the wide grid of the satellite
datasets, the non-relevant cloudiness index and the lack of a parameter describing the altitude (atmospheric pressure) effect.

3. Results and discussions
The largest variability and the maximum amplitude were observed in early summer during the June–July transition. As can be seen in figure 4, the highest UVI value of 9.32 was registered at 12:12 h on 27 June 2017 (the hottest day of the campaign). The large amplitude variability (more than 90% in a time span of 4 min) occurred under mixed (partly) cloudy conditions due to the strong reflection from high cloud edges and the increased vertical transmissivity inside the clouds enhancing the diffuse UV component.

Figure 4. Measurement of the daily solar UV irradiation, environmental temperature and humidity at a high mountain area (Moussala Peak) during the hottest summer week of 2017.

We consider the “deep gaps” (figure 5) observed in the UV index in comparison with the solar GHI during the late afternoon at high SZA to be of paramount significance. Typically, the UV irradiation is calculated as a percentage of the averaged solar GHI values – with similar peaks and flat or slow variations. In the case reported here, the UV short-term variations are of quite different behavior as to be attributed to water drops in low clouds. It is more reasonable to assume that under partly cloudy conditions (40–60%) with sharp peaks (as on 27 June 2017), more than 80% the UV absorption should be attributed to tropospheric clouds of aerosols or pollution gases. We did not measure critical values.

Figure 5. Daily distribution of the UV index, solar GHI and the corresponding risk zones (27 June 2017).
of UVI = 10-12. The average daily ozone column in the same day was 316.5 DU. One study [Erlick and Frederick, 1998] has demonstrated that the attenuation due to aerosols is generally stronger in the UV region than at longer wavelengths. Regardless of their origin, such huge fluctuations in the UV irradiation will cause harmful effects on materials, solar photovoltaic (PV) installations and human skin. Obviously, UV irradiation measurements with a higher temporal resolution can reveal new interactions in the atmospheric UV absorption. Further studies of the tropospheric vertical UV profile could be performed by UV sensors mounted on drones or balloons.

A comparison of our daily UV and solar GHI measurements and online available databases [11] can be extracted from the data presented in table 1. The erythemal UV values of the SoDa database are closer to the ground measurements of the UV daily dose, namely, the same trend and equal overestimation of 34–38% is seen. In what concerns the accuracy of the available solar GHI databases, Meteotest data are closer than other databases to our ground measurements when the cloud cover was less than 20% (29 June), the tolerance being less than 0.1%. On that standard summer day, the daily total solar GHI radiation was close to 8992 Wh/m² day, while the daily maximum approached 1032 W/m².

Table 1. Comparison between daily parameters from solar UV measurement, simulation and available databases.

| Parameter: Daily mean solar GHI | 27 June’17 | 28 June’17 | 29 June’17 |
|---------------------------------|------------|------------|------------|
| measured UV dose                | 0.879 [W.h/m².day] | 0.640 [W.h/m².day] | 0.916 [W.h/m².day] |
| calculated UV irradiation       | 0.639 [W.h/m².day] | 0.622 [W.h/m².day] | 0.681 [W.h/m².day] |
| SoDa database:                  | 17.69 [W/m²] | 15.53 [W/m²] | 20.05 [W/m²] |
| UV-A                            | 424.65 [Wh/m².day] | 372.86 [Wh/m².day] | 481.29 [Wh/m².day] |
| UV-B                            | 0.55 [W/m²] | 0.49 [W/m²] | 0.61 [W/m²] |
| Erythemal UV                    | 13.21 [W/m².day] | 11.77 [W/m².day] | 14.70 [W/m².day] |
| Erythematic UV                  | 0.055 [W/m²] | 0.049 [W/m²] | 0.062 [W/m²] |
| 1.336 [W/m².day]                | 1.190 [W/m².day] | 1.488 [W/h/m².day] |
| Meteotest database:             | 20.09 [W/m²] | 16.69 [W/m²] | 20.52 [W/m²] |
| UV-A                            | 482.16 [Wh/m².day] | 400.56 [Wh/m².day] | 492.48 [Wh/m².day] |
| UV-B                            | 0.84 [W/m²] | 0.70 [W/m²] | 0.85 [W/m²] |
| Erythemal UV                    | 20.16 [W/m².day] | 16.80 [W/m².day] | 20.40 [W/m².day] |
| Erythematic UV                  | 0.079 [W/m²] | 0.079 [W/m²] | 0.080 [W/m²] |
| 1.896 [W/m².day]                | 1.896 [W/m².day] | 1.920 [W/m².day] |
| Temis database: erythemal UVI   | 9.7         | 9.4         | 10.3        |
| Temis database: erythematic UV  | 5.5 [kJ/m²] | 5.4 [kJ/m²] | 5.9 [kJ/m²] |
| measured solar GHI              | 5650.9 [Wh/m².day] | 8004.9 [Wh/m².day] | 8992.2 [Wh/m².day] |
| calculated solar GHI            | 6187 [Wh/m².day] | 6187 [Wh/m².day] | 6242 [Wh/m².day] |
| SoDa database: solar GHI        | 231 [W/m²] | 359 [W/m²] | 266 [W/m²] |
| 5544 [Wh/m².day]                | 8616 [Wh/m².day] | 6384 [Wh/m².day] |
| Meteotest database: solar GHI   | 369 [W/m²] | 370 [W/m²] | 374 [W/m²] |
| 8856 [Wh/m².day]                | 8880 [Wh/m².day] | 8976 [Wh/m².day] |
| NASA database: solar GHI        | 255 [W/m²] | 269 [W/m²] | 315 [W/m²] |
| 6120 [Wh/m².day]                | 6470 [Wh/m².day] | 7570 [Wh/m².day] |

In contrast, under partly cloudy condition (27 June), the daily maximum of solar GHI = 1520 W/m² is an extremely high value for Moussala Peak (latitude 42°10'45"N, longitude 23°35'07"E, altitude 2925 m ASL), as is the peak ambient temperature exceeding 30 °C. Such a “record” value registered in early summer exceeds even the extra-terrestrial solar irradiation and must be taken into account in the planning of future solar PV systems, outdoor construction works and safety measures against forest fires and equipment malfunctions.
4. Conclusions
Our new open-source UV monitoring system is currently under evaluation. The preliminary results show a good agreement between our UV sensor design and high-end state-of-the-solar GHI instruments. We thus demonstrated the benefits of coupling heterogeneous sensors and detectors for measuring solar irradiation. The open-source software and hardware approach is a convincing argument that the cost of scientific equipment can be radically reduced by applying open-source designs in combination with Arduino electronics. The entire process of rapid design accelerates the development of scientific tools and innovations.

The insufficient quality of the numerical UV prediction models seem to be the main origin of the gap between the results of modeling and measuring the UV irradiation. The cloud cover is a complex object for parametrization which needs further efforts. Further analyses are ongoing.

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References
[1] McKinlay A and Difffey B 1987 A reference action spectrum for ultra-violet induced erythema in human skin eds Passchier W F and Bosnjakovic B F M (Elsevier, Amsterdam) 83-7
[2] Liley B and McKenzie R 2006 Reprint NIWA, New Zealand
[3] Diffey B L 2002 Elsevier Science, Methods 28 4–13
[4] Milon A, Sottas P E, Bulliard J L and Vernez D 2007 J. Expo Sci. Environ Epidemiol. 17 58–68
[5] Rivas M, Rojas E, Araya M C and Calaf G M 2015 Oncol. Lett. 10/4 2259-64
[6] World Health Organization 2002 Global Solar UV index: A Practical Guide
[7] Estupian J, Raman S, Crescenti H, Streicher J and Barnard W 1996 J. Geophysical Res. 101 /D1 16807-16
[8] Amini N, Matthews J E, Dabiri F, Vahdatpour A, Noshadi H and Sarrafzadeh M 2009 Proc. Int. Conf. Biomedical Electronics and Devices (14-17 Jan. 2009 Porto Portugal)
[9] Jegou F, Godin-Beekman S, Correa M P, Brogniez C, Auriol F, Peuch V H, Haeffelin M, Pazmino A, Saiag P, Goutail F and Mahe E 2011 Atmos. Chem. Phys. 11 13377–94
[10] Matthiissen J, Slaper H and Reinen H A J M 2000 J. Geophysical Res. 105/D4 5069–80
[11] Pagola I, Gaston M, Brnados A and Fernandez-Peruchena C 2014 Energy Procedia 57 1037 – 43