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Instrumentation and Measurement of Ground-Level Ultraviolet Irradiance and Spectral Composition in Estonia

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Additional information is available at the end of the chapter

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1. Introduction

Solar radiation sustains and affects all forms of life on Earth and is relevant to a variety of technological applications. The effects of solar radiation depend strongly on its spectral composition in which the influence of ultraviolet radiation (UVR) is the largest. Natural factors like geographical latitude, Earth-Sun distance, and solar zenith angle (SZA) strongly influence the UVB (wavelengths 280-315 nm) irradiance and to a somewhat lesser extent the UVA (315-400 nm) radiation. The exposure of organisms to UVR is characterized by annual and diurnal cycles of solar irradiance's availability and by the variance (anomalies) of biologically-weighted irradiances within seasons.

Variations and trends in the availability and spectral composition of UVR are having various effects on atmospheric chemistry, plant health, litter decomposition and the carbon cycle, as well as on human health [1-10]. The effects of UV are mostly cumulative and depend on the spectral composition of received radiation energy. UVR is a globally important abiotic factor influencing ecosystem structure and functions in multiple ways [11]. The most influential UVB part of incident solar radiation is capable of breaking connections between atoms in organic molecules and exerts destructive effects on different materials. The net effect of UV radiation at the cellular level is a balance of damage and repair cellular key structures like DNA [5]. UVB radiation causes many biological and chemical processes, which are generally damaging to living organisms.

The impact of UVB radiation on vegetation changes with species and crops [6]. The effects of UVB radiation must be considered together with other climatic factors such as an increase in temperature and CO₂ levels, which can modify the response to UVB radiation. Irradiation at

wavelengths below 300 nm is extremely harmful to DNA. The ratio of irradiances in the UVB and UVA spectral ranges is one of the key factors for estimating its possible harmful influence.

Many important consequences can arise from the indirect effects of high UVB radiation through changes in the chemical composition and shape of the plants, or through changes in the abiotic environment. These indirect effects can include changes in the sensitivity of plants to being attacked by insects and pathogenic elements. The effects of UV radiation and those of other environmental factors at the ecosystem level are poorly known, as well as are those at molecular and organism levels.

Plants possess a number of defence systems against environmental stress factors in nature. Among such protection mechanisms is the altered synthesis of antioxidant substances as well as other secondary metabolites. Without repairs, the harmful photoproducts ultimately lead to cell death. To avoid this catastrophic effect, all organisms possess DNA repair systems that are able to recognize and remove UV photoproducts. The ultraviolet (UV) index is a standard vehicle for informing the public about the level of UV radiation reaching the Earth's surface and its potential harmful effects on human health. Although the received energy in the UVB band is only a small fraction of the extra-terrestrial solar radiation, it accounts for 80% of the harmful effects of sun exposure.

In most applications of the UVR data quantification of the received spectral doses a understanding of the mechanisms of influence on the cell, organism and ecosystem levels are needed. The variations of total incoming solar radiation as well as spectral composition, especially in the UVB range, beside geographical factors depend strongly on atmospheric factors, such as clouds, total ozone, aerosols and precipitable water vapour. Spectral energy is necessary to estimate over days, parts of days and over longer time intervals.

Despite there being different broadband and narrowband UV sensors in use, spectral UV measurements are still considered the irreplaceable, ultimate reference in a variety of applications. Spectral measurements allow the data to be applied to any biological process or chemical photoreaction with a known action spectrum. Weather conditions prescribing the availability and spectral composition of ground-reaching UV irradiance in key phenological phases of ecosystem development manifest significant year-to-year and longer-term periodic changes. These changes are reflected in ecosystem health and productivity. For sustainable agriculture and environmental management both the changes in quality of received irradiance and in ecosystem responses need to be investigated on a quantitative level. The present study financed by a programme of research and development of environmental technology is one of those attempts.

In the present chapter, the major features of systematic changes and the variability in ground-level UVR at subpolar latitude are considered. The work is based on ground-level UVR spectra recorded at a research institute, Tartu Observatory, (58°.16'N, 26°.28'E, 70 m a.s.l.) since 2004 together with the auxiliary information on broadband solar radiation and weather conditions recorded by the Tartu-Tõravere meteorological station of the Estonian Environmental Agency at the same site. The homogeneous datasets of the broadband solar radiation and weather conditions for the site extend back to the beginning of 1955 [12-17]. The total number of

broadband solar radiation and weather characterizing factors increased in the 1990s and 2000s. During the period of recording UV spectra the spectral dataset was well supplied with the necessary auxiliary information.

2. Data and methods

2.1. Solar radiation research in Estonia

Attempts at quantitative measurements of solar radiation have been made in Tartu since 1904 and increased in the 1930s after acquiring a modern Ångström pyrhelimeter to quite a high level [18]. The instrument was lost during World War II, and new efforts initiated by Juhan Ross began in the early 1950s. The results of regular studies have been published in several publications and in monographs. General climatic features of the broadband solar radiation in Estonia are presented in the *Handbook of Estonian Solar Radiation Climate* [19].

Major results on interannual and intraseasonal variations of broadband solar radiation in Estonia are presented as a chapter in the previous edition of the InTech book *Solar Radiation* [15]. The longest and most complete dataset on solar radiation in Estonia [20, 21] has been collected at a typical Estonian rural site at the Tartu-Tõravere Meteorological Station (58°.16'N, 26°.28'E, 70 m a.s.l.). The site, as well as that used before 1965, being located closer to Tartu town can be considered typical for Northern Europe. The landscape pattern around the location consists of arable fields, grassland areas and patches of mostly coniferous forest.

Between 1950 and 1965 the station was a part of the present research institute of Tartu Observatory and since 1965 it was operated by the Estonian Meteorological and Hydrological Institute, recently reorganized to part of the Estonian Environmental Agency as a State Meteorological Service. In 1996 the station was included to the system of Baseline Surface Radiation Network (BSRN) stations. Until 1996 the Yanishevski AT-50 actinometers and Savinov-Yanishevski M-115 pyranometers were used and then replaced by the Eppley Labor. Inc. pyrhelimeters and Kipp & Zonen pyranometers. The absolute accuracy of the ventilated Kipp & Zonen pyranometers is about $\pm 2\%$ and that of the pyrhelimeters $\pm 1\%$.

In the past, inter-calibration of sensors was regularly performed in Voeikov Main Geophysical Observatory (St. Petersburg, Russia), whereas it is now done in the World Radiation Center (Davos, Switzerland). Regular meteorological observations were performed at the site, including the hourly visual cloud detection, at all three basic levels. The long-term record of traditional broadband solar radiation and weather conditions helps the understanding of the regular changes and variations of UVR, which is the main objective of the present chapter.

2.2. UV broadband, narrowband and spectral measurements

Studies of atmospheric column ozone and UV radiation in Estonia were initiated by the Tartu Observatory in 1993 to consider the possibilities of studying relationships between the UVR and broadband irradiance characteristics. Regular direct sun column ozone measurements have been carried out between 1994-1999 using an especially suited laboratory spectrometer

SDL-1 supplied with a mirror system and applying the Dobson retrieval algorithm [22, 23]. Since 2003, direct sun column ozone measurements were performed using a MICROTOS-II instrument. Mostly, the satellite data were used for atmospheric column ozone [23]. Since summer 2002, a sun photometer of the NASA AERONET network measuring column aerosol optical depth (AOD) and precipitable water vapour operates there, and the aerosol studies group of the University of Tartu performs ground-level atmospheric aerosol-size distribution measurements. For the years before 2002 only pyrheliometer-measured broadband AOD data are available.

Solar UV radiation measurements with filter instruments were performed at the Tartu-Tõravere Meteorological Station under scientific supervision by research scientists of Tartu Observatory [19]. The erythemally-weighted sensors UV-SET had been in operation since January 1998 [12-14]. A Kipp & Zonen narrowband filter instrument CUVB1 with an effective wavelength 306 ± 0.2 nm and bandwidth 2 ± 0.5 nm operates at Tartu-Tõravere meteorological station since 2002 [16]. Similar UVB instruments were installed at two other meteorological stations Tallinn-Harku ($59^{\circ}26'$ N, $24^{\circ}45'$ E) and Pärnu ($58^{\circ}23'$ N, $24^{\circ} 38'$ E). A Kipp & Zonen broadband UVA sensor as well as a YES broadband UVB sensor was installed at the site in 2005.

Spectral measurements of solar UVR were performed at the same site by Tartu Observatory. Since 2004, UVR spectra in the range 280-400 nm were collected using Avantes Inc. simple array spectrometer AvaSpec-256 with a 15-minute interval [24]. In 2009 these measurements were stopped due to the significant drop of array sensitivity. In 2008, the purchase of a spectrometric system based on the Bentham Instruments Ltd. DMc150F-U double monochromator was realized by funding from the EC REGPOT project EstSpace. The system was installed in Spring 2009. Spectra in the wavelength range 280-400 nm are recorded by this instrument, also every 15 minutes.

In both systems the radiation-collecting diffuser is placed on the roof and connected with a quartz fibre to the spectrometer installed in the special weather box in the building. Calibration of optical instruments has been performed at Tartu Observatory for several decades. It was based on the 1000 W quartz halogen standard lamp FEL calibrated by Oriel traceable to the USA National Institute for Standards and Technology (NIST) [25-27]. Spectrometer AvaSpec-256 needed recalibration after at least two months. The second disadvantage was a relatively high stray light level within this compact instrument and the necessity of the removal of its contribution in the recorded spectra.

A programme for the compensatory calculation of the stray light influence of the array spectrometer AvaSpec-256 was applied. The slit-scattering function of the spectrometer was measured directly using a 450 W xenon arc source and monochromator at the Metrology Research Institute, Aalto University, Finland. The stray light level of the AvaSpec-256 spectrometer was rather high (0.1-1%), but the slit-scattering function is symmetrical and without noticeable artefacts. The uncertainty estimation of the stray light correction is based on the empirical comparison of the simplified algorithm and deconvolution over the set of measured spectra. For the Bentham double monochromator, a calibrator CL 6 belonging to the set of

spectrometer auxiliary instruments was regularly used for checking the instruments' sensitivity, and the calibrator itself was regularly compared with a certificated FEL lamp.

2.3. Spectra collection

The spectral data collection system including software for the AvaSpec-256 spectrometer was designed at the Tartu Observatory. UVR spectra were recorded as separate files but were also grouped automatically on the calendar day level. This allows relatively easy selection of all spectra recorded during each day for further treatment and analysis. One of the main procedures in data treatment is calculating the received energy within different wavelength ranges and time intervals. The ratios of UVA/UVB irradiances were calculated automatically for each spectrum, allowing the ease of obtaining the same ratios in daily or part-day doses. In the case of the Bentham DMc150F-U spectrometer, the producers' software BenWin+ was used for instrument control and data recording.

The measured spectra were recorded in the memory of the control computer as separate files. The name of the file contains information on the time of recording (year, month, date, hour and minute of the beginning of spectrum record). Later the files were transformed to the Excel environment and organized as workbooks for each month and sheets for each day. Around the summer solstice, the amount of informative spectra per day was about 75 and around winter solstice it was about 25.

The database of spectra was supported by two other databases useful for grouping spectra on the bases of different seasonal and weather conditions. One of them contains all supporting daily data, such as the daily doses of direct, diffuse and global broadband radiation, daily sunshine duration, daily erythemally-weighted and UVB narrowband doses, atmospheric column ozone, AOD, cloud and snow cover data. Direct and global irradiance relative to assumed normal clear conditions for each day are included. Normal clear conditions mean those for a typical column ozone and AOD for that calendar day.

Smoothed annual cycles of daily normal clear daily sums of global and direct irradiance have been composed empirically using the respective data since 1955 and have been used as the reference in the reconstruction of erythemally-weighted daily doses back to 1955 [16]. The other auxiliary database contains hourly sums of broadband direct, diffuse and global irradiance useful for studying relationships between broadband and UV radiation in a day. The hours are accounted from local noon in real solar time to both sides.

The dataset of UV spectral irradiance allows performing of integration of spectral energy by wavelength ranges and time. For example, it allows easy calculation of UVB and UVA spectral energy for different time intervals. Often, there arose a necessity to integrate different action spectra-weighted energies over days, parts of days and over longer intervals like weeks or months. Those products are useful in making comparison of received spectral energy in various conditions. One possible application is a study of relationships between UV doses in different wavelength ranges and the hourly sums of the pyranometer-measured broadband irradiance.

3. Main features of annual and daily regular changes in UV irradiance in cloudless conditions

Environmental effects of UV irradiance at any site depend strongly on the availability of direct sunshine and on solar elevation during the sunshine episodes. Solar elevation modulates the UV irradiance and its spectral composition in the absence of sunshine. Solar elevation changes regularly from sunrise to sunset, reaching the highest value at noon in real solar time. Noon solar elevation manifests a regular annual cycle, being the smallest at winter solstice and the largest at summer solstice. Usually SZA is used instead of solar elevation for characterization of solar position on the celestial sphere. At the Tartu Observatory site the extreme values of noon SZA are 81.7° (solar elevation 8.3°) and 34.8° (solar elevation 55.2°), respectively. The most influential part of the UVR ground-level spectrum is the UVB range.

In the days around summer solstice, the threshold of the Bentham double monochromator's sensitivity is 294 nm at noon in sunshine conditions. In early mornings and late evenings, the threshold of sensitivity drops to approximately 310 nm. In cloudy weather, the irradiance levels may be somewhat lower and the threshold of sensitivity can be several nanometres larger than in clear conditions. At an SZA above 80° , the accuracy of spectral irradiance measurements is significantly lower than at higher sun conditions and the influence of column ozone and AOD on its spectral composition is less clear. In Figure 1 the diurnal cycles of threshold UVB wavelength and SZA during a nearly clear midsummer day are illustrated.

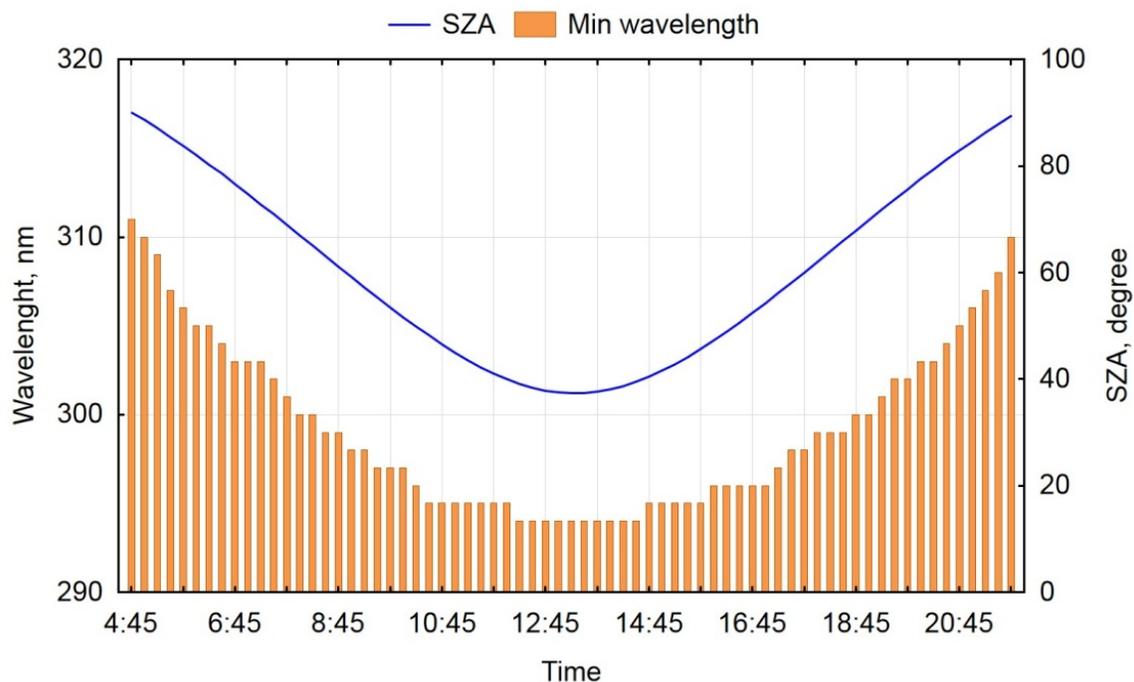


Figure 1. Diurnal cycles of SZA and shortwave threshold for UVB irradiance in midsummer cloudless conditions

The recorded UVB range in recorded spectrum is much shorter than the UVA range. The width of the first varies during the day from 5 to 20 nm. In the UVA range, it is constant and much larger, 85 nm. Due to the small and varying contribution of the UVB range, the ratio of the received irradiance energy or power also varies across a wide range. To avoid very small numbers, it is better to use the version UVA/UVB for presenting this ratio instead of UVB/UVA.

It is commonly known that the spectral composition of the UVB irradiance depends on stratospheric column ozone. At a large SZA the optical path of incoming solar rays is long, and diffuse radiation dominates. In those conditions much of the UVB radiation is absorbed by tropospheric ozone and attenuation reaches longer wavelengths than at high sun conditions. As a result the UVB day is seemingly shorter than the UVA day. In the UVA spectral range the level of irradiance is higher, and radiation is not absorbed by ozone. Beside the atmospheric column ozone another modulating factor of UVR is AOD. Its influence also tends to be larger in the UVB range.

In Figure 2 the diurnal cycles of irradiance at some UVB and UVA wavelengths are presented. The selected day, 12 July 2010, was almost clear. Only a very small amount of *cumulus* (*Cu*) clouds between 13 and 17 in local time were met. Total ozone was 299 DU and the AOD at the UV wavelength 340 nm was relatively large, at 0.428. In cases of good atmospheric transparency it is around 0.1 and its median and trimean values in 2002-2012 have been close to 0.2. The conventional mean is not a relevant characteristic of the AOD due to a strong asymmetry of distribution.

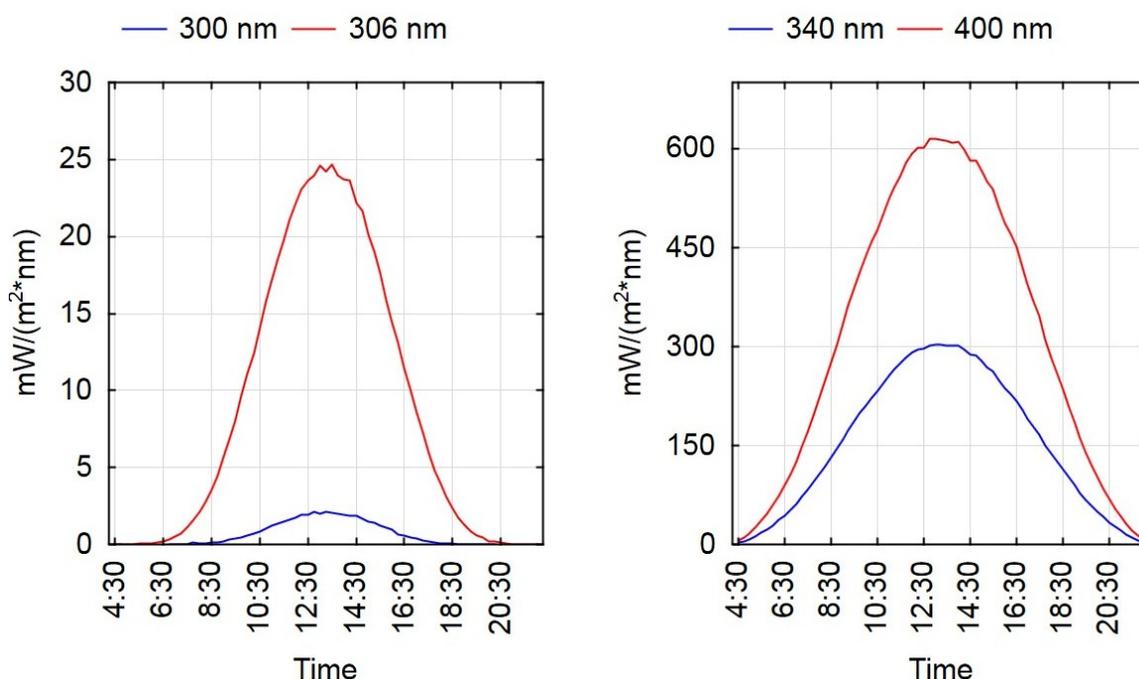


Figure 2. Diurnal cycles of spectral irradiance at selected UVB (left) and UVA (right) wavelengths on an almost clear summer day 12 July 2010

Finding of relevant data is restricted by the deficit of cloudless days. The ratio UVA/UVB in the received daily spectral energy accumulates from the recorded spectra. The contribution from the spectra recorded at smaller SZA is larger in it. Immediately after sunrise and before sunset the UVB irradiance is strongly suppressed and the value of the UVA/UVB ratio often reaches 500 to 600 at SZA around 87° . At an SZA above that value the UVA/UVB ratio manifests strong instability due to the low reliability of recording UVB irradiance and is not presented in the figures. With the decreasing SZA the relative contribution of UVB irradiance increases.

In Figure 3 the average dependence of UVA/UVB ratio on SZA is presented in almost cloudless weather conditions for the abovementioned full day. In Figure 4 the same is presented for another almost clear day on 13 April when noon SZA reaches only 62° and column ozone, 376 DU, is close to its normal spring level. The value of AOD at 340 nm is once again quite large, at 0.493.

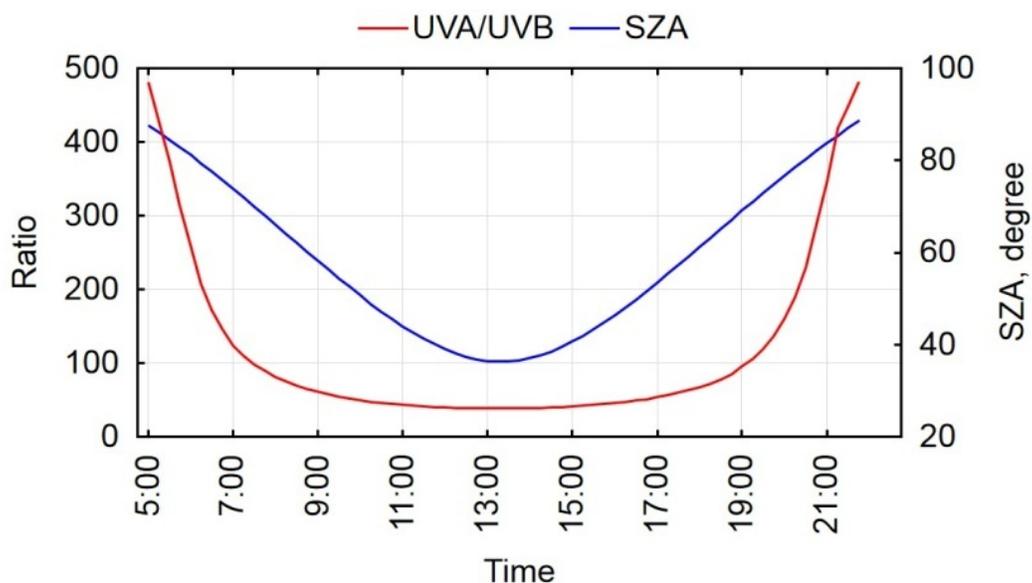


Figure 3. Diurnal cycles of UVA/UVB irradiance ratio in almost clear summer day 12 July 2010

The smallest of UVA/UVB values are met around the daily smallest SZA. Around summer solstice the range of diurnal changes in the UVA/UVB ratio reaches 15 times, but in some cases is only eight to ten times. With the decrease of SZA to 70° the ratio UVA/UVB drops to about 100 and after reaching SZA 50° to about 50. In the Northern European summer conditions most of the UV radiation is received during six hours around noon.

An example of relative contribution from these six hours in the full day dose is presented in Figure 5 at wavelengths 300 to 400 nm for clear day in July.

One can see that at wavelengths around 300 nm the contribution from these six hours is 85 to 90% of the daily total, and decreases with increasing wavelength due to decrease of ozone absorption. Around wavelength 330 nm the noon six hours contribution reaches a 60% level and remains at an almost constant level.

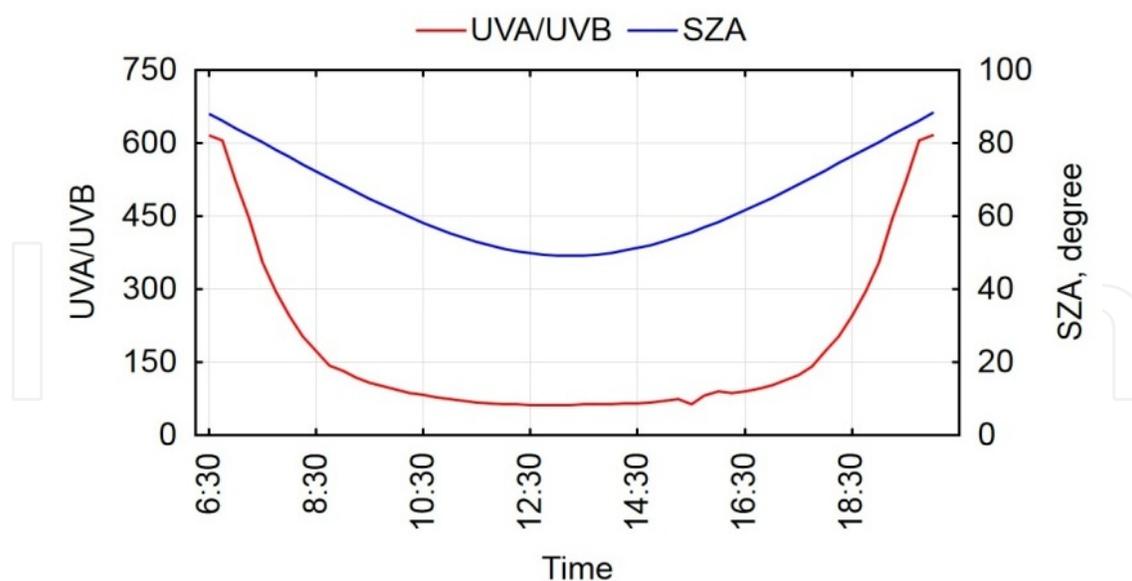


Figure 4. Diurnal cycles of UVA/UVB irradiance ratio in almost clear spring day 13 April 2010

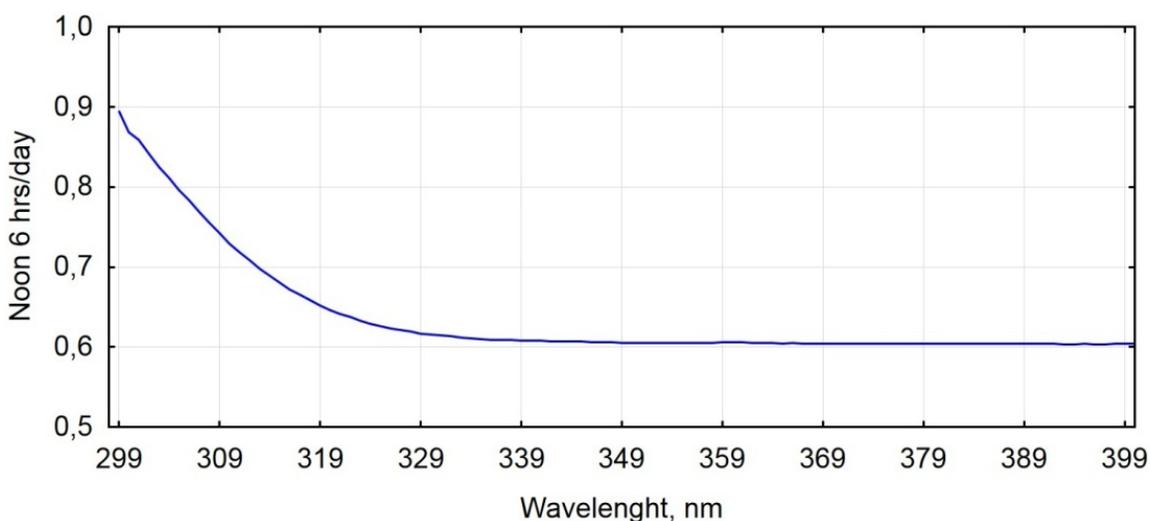


Figure 5. Dependence of the ratio of UV irradiances from six noon hours and full day on wavelength

On cloudy days the ratio manifests variations due to attenuation and enhancement of irradiance by clouds. The contribution from six hours around noon is a useful indicator only from May to August when the outdoor activities of the population take place frequently in sunshine.

During sunshine episodes the ground-level UVR and its spectral composition are modulated by atmospheric column ozone and aerosols. Atmospheric column ozone manifests an annual cycle with the maximum around 390 Dobson Units (DU) in March-April and a minimum of around 270-280 DU in October-November [23]. From the first half of May until the middle of September the column ozone decreases quite linearly and the variations around this linear decrease are mostly moderate, within ± 20 DU. Larger variations were recorded in spring, from February until the middle of May, and also in October-November. Within that period,

prolonged episodes reaching a week or even more in length were recorded when column ozone was even more than 50 DU lower of its normal seasonal level.

Aerosol-size distribution is characterized by the fine mode fraction, e.g., how much the submicronic particles contribute to the AOD at 500 nm. Smoke often contributes more than 90% of small particles' influence in AOD, reducing radiation more strongly at shorter wavelengths [28-31]. Smoke was a major reason for a large AOD in years when there were prolonged dry periods in summer. The major season of forest fires in the region is in July-August and that of landscape burnings in late April to early May.

In most of the years, the dryness and frequency of fire outbreak are moderate. In 2002-2012 the AERONET system recorded AOD values above the threefold and twofold median were met at Tartu-Tõravere meteorological station in about 6% and 17%, respectively, out of all 1500 days of the AERONET measurement data. The influence of the landscape fire episode in April-May 2006 on the UV spectrum is described in [32]. In conditions of seasonal normal ozone between 379 and 391 DU three almost clear days with AOD values at 340 nm between 0.979 and 1.299 were found.

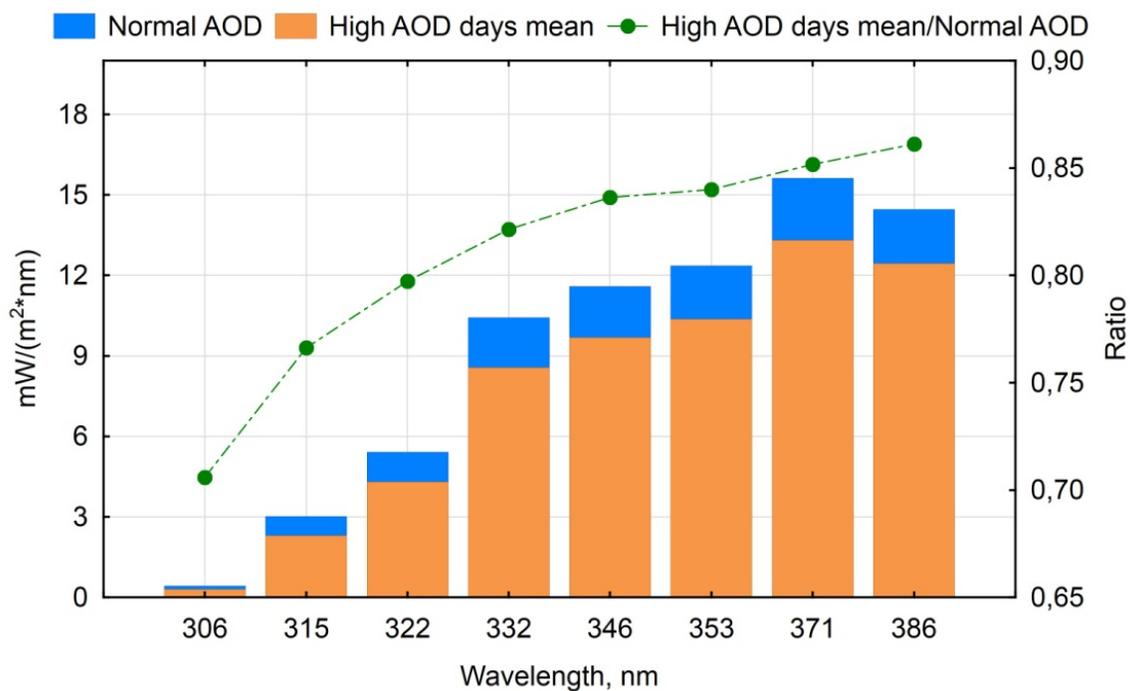


Figure 6. Comparison of mean daily spectral doses for the group of days manifesting smoke induced large AOD and a clear day with almost equal noon SZA, similar column ozone 384 DU and moderate AOD (0.16 at 340 nm)

The cloud influence is often described by the cloud modification factor (CMF). CMF is defined as a ratio of measured cloudy irradiance to that of normal conditions of clear sky. Here we use a similar aerosol modification factor (AMF) to compare total influence on the UVR. The AMF in daily irradiance totals was found to be 0.84 in UVA and 0.75 in UVB ranges. It is comparable to the CMF of middle-level clouds. The major difference is that the AMF decreases with

wavelength decrease in the whole UV range while CMF manifests in the UVA range decrease with the increase of wavelength. Comparison of mean spectral daily doses for the mentioned days manifesting smoke-induced large AOD and a clear day with almost equal noon SZA, similar column ozone 384 DU and moderate AOD (0.16 at 340 nm) is presented in Figure 6.

4. Variations of UV irradiance and spectral composition in cloudy conditions

Clear skies are not common at the study site or in the neighbouring Northern European area. The clear conditions are met most frequently in March. In April to September the number of cloudless days in a month is only one to two on average [33]. Most of the solar radiation energy is received in May to August. In broadband solar radiation the relative contribution of direct sunshine energy is highest on average in May, reaching 45% to its assumed clear value. By August it steadily decreases to 40.5% [15].

Similarly a change of the global radiation energy takes place, from 70% of the assumed clear in May to 66% in August, on average. The lowest direct irradiance energy relative to the assumed clear, 13%, is received in November when the average global irradiance relative to clear is the lowest, at 20%. In low sun conditions during October to February, the overcast conditions prevail and the received UVR energies are small. The aerosol and total ozone contributions in their variability are much less than those from cloudiness. Overcast skies in the summer half-year are also met less frequently than the partly cloudy days, which are typical for the climatic region of study. Clouds may significantly reduce the ground-level irradiance but also enhance it by reflections from bright clouds. A key question is in what conditions the UVR level is reduced or enhanced [34-37].

The Cloud Modification Factor (CMF) is defined as a ratio of measured cloudy irradiance to that of normal conditions of clear sky. When the Sun is shaded by clouds the irradiance is reduced and CMF is below 1. When the Sun is not shaded the reflection from clouds near the Sun may enhance the irradiance, and CMF may exceed 1. In Figure 7 an example of both effects is presented in the case of SZA 36° when fortunately both situations occurred during the same day in conditions of variable Cu, Cb and Ac cloudiness.

The data for the cloudless background were taken from spectral dataset of another day. One can see that both enhancement and attenuation increase the relative contribution of UVA radiation in the UVR spectrum. Daily total cloud effect depends much on the cloudiness characteristics during noon hours when the received energy is the largest. In dry summers there are fewer clouds in that time period and less influence on the UVR spectra. In wetter summers, both the attenuation and enhancement are stronger due to the convection of moist air. Total effect depends on the cloud amount and on their vertical extent. Most of the daily variations in UV irradiance in May to August occur during three hours before and after the midday. Statistical relationships between broadband solar irradiance and dose, and those of UVA are stronger than between broadband solar irradiance and UVB radiation.

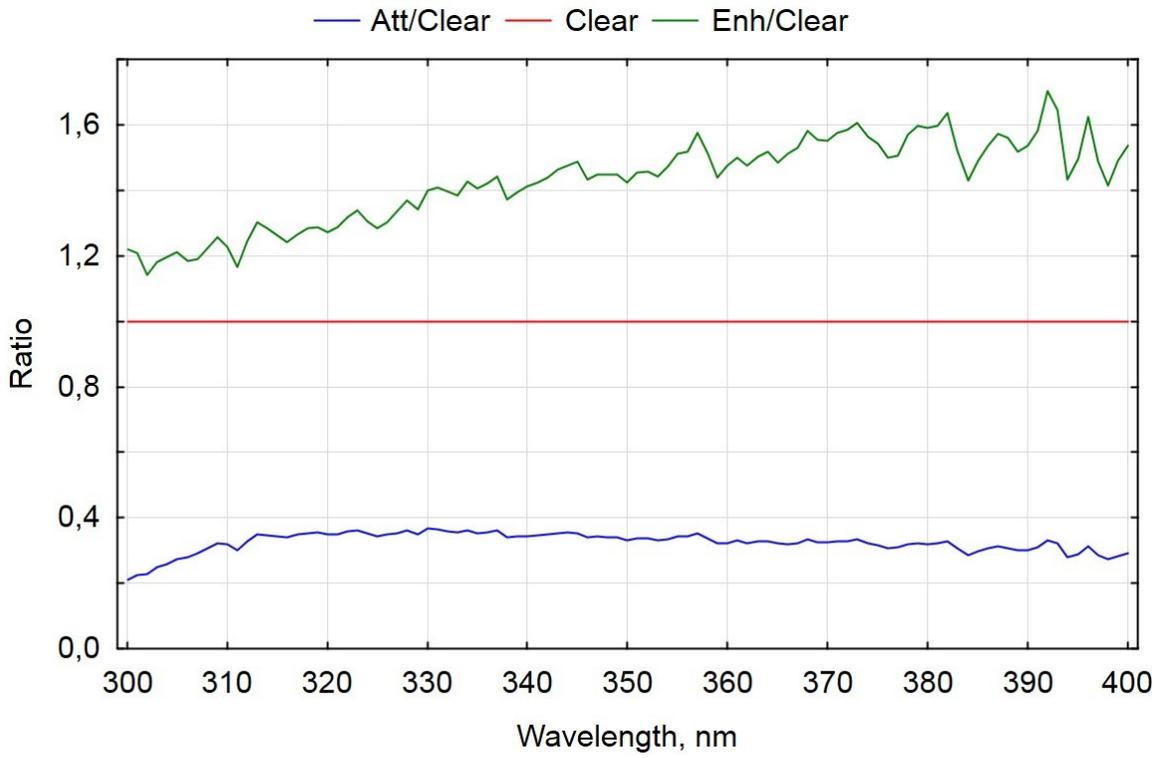


Figure 7. Example of enhancement and attenuation of UV spectral irradiance by clouds at SZA 36°

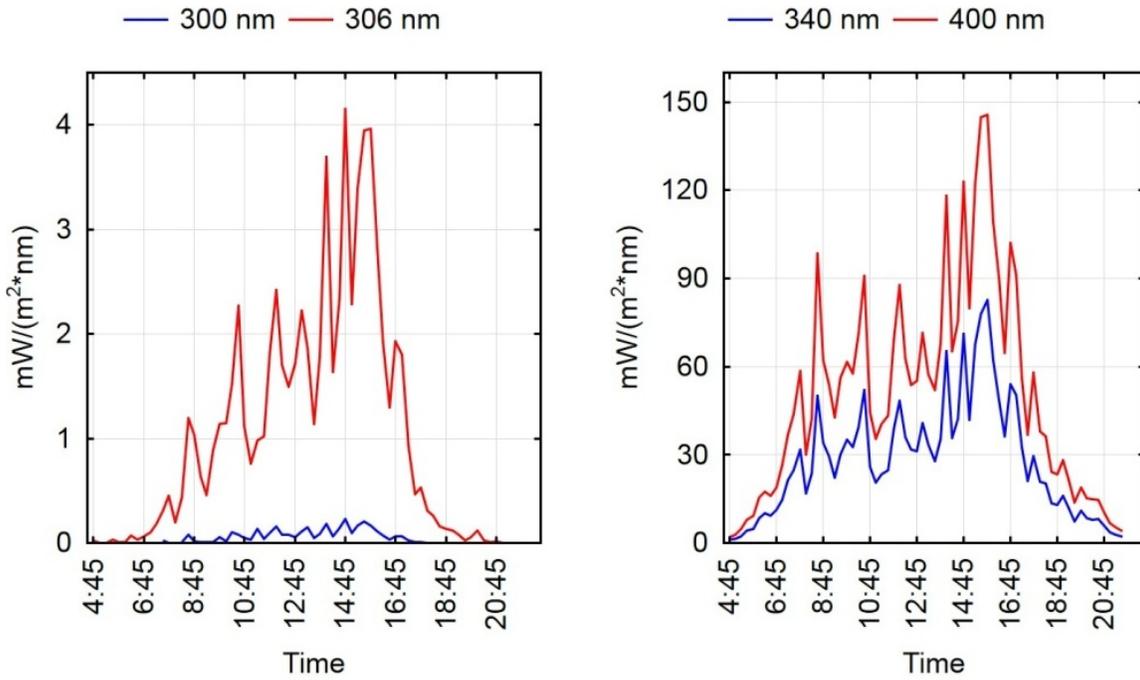


Figure 8. Diurnal cycles of spectral irradiance in overcast by thick *Frb* cloudiness at selected UVB (left) and UVA (right) wavelengths, 21 June 2010

Some examples of variable diurnal cycles of UV irradiance spectral density at selected wavelengths are presented in this section. In our work [38] it was noted that in seemingly uniform overcast conditions the recorded ground-level UV irradiance varies across a wide range.

In Figure 8 diurnal cycles of the UVB irradiance at wavelengths 300 and 306 nm and of the UVA irradiance at wavelengths 340 and 400 nm are presented in the case of thick *fractusnimb* (*Frnb*) cloudiness. One can see strong variations over the relatively low irradiance level.

In Figure 9 diurnal cycles at the same wavelengths are presented in conditions of almost no direct sunshine but close to three times more global irradiance. The cloud cover on that day (5 July 2012) consisted of bright and more transparent *altocumuli* (*Ac*), *stratocumuli* (*Sc*) and *cumulonimbus* (*Cb*) clouds.

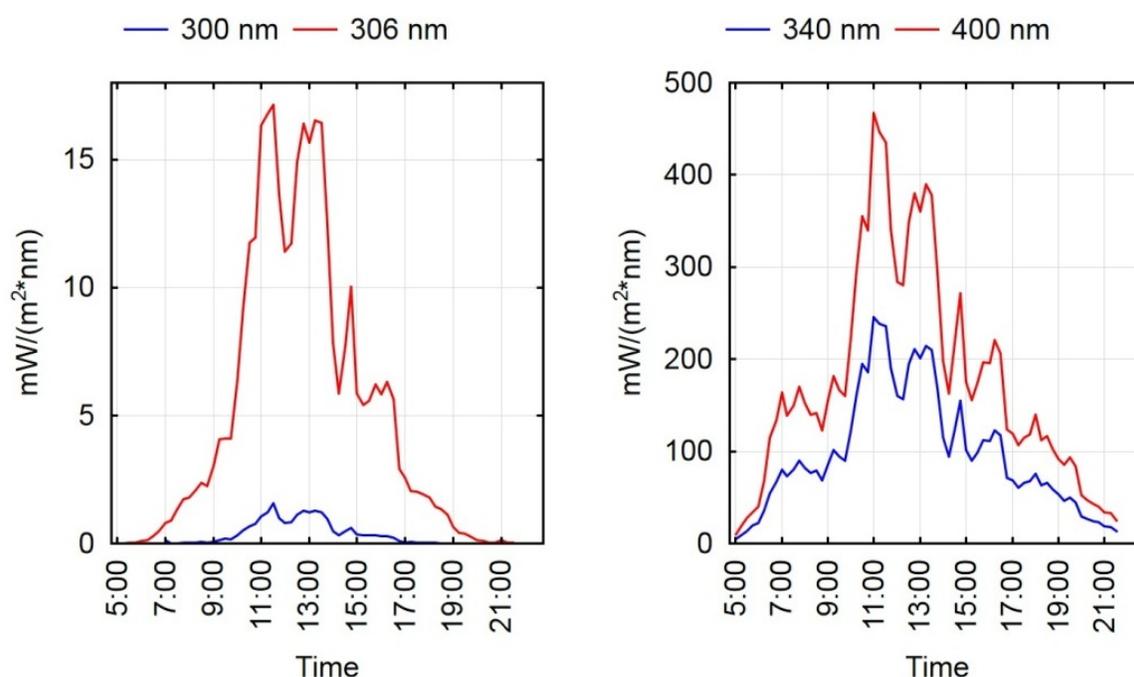


Figure 9. Diurnal cycles of spectral irradiance in overcast by thinner *Ac*, *Sc*, *Cb* cloudiness at selected UVB (left) and UVA (right) wavelengths, 5 July 2012

The UV irradiance levels were significantly larger than in the previous thick cloudiness case. In Figure 10 to Figure 12 the daily cycles of spectral irradiance at the same selected wavelengths were presented in partly cloudy conditions. In Figure 10 the daily broadband direct irradiance relative to clear was 0.29; in Figure 11 it was 0.49 and in Figure 12 the largest 0.82.

The relative global irradiances in these selected days were 0.67, 0.75 and 0.92, respectively. The selected days were 8 July, 9 July in 2012 and 17 July in 2009. Clouds were typical combinations of *cirrus* (*Ci*), *Cb*, *Cu*, and *Ac* in two first cases. Only two cloud types, *Ci* and *Cu*, were met in the third case.

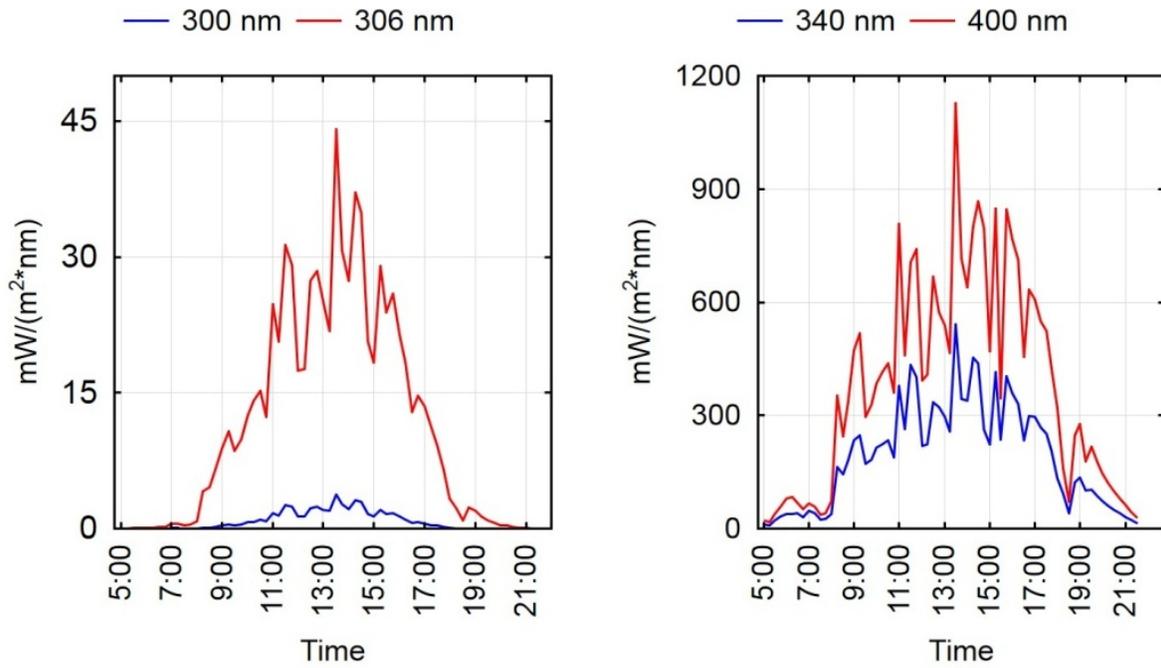


Figure 10. Diurnal cycles of spectral irradiance at selected UVB (left) and UVA (right) wavelengths at relatively large amounts of partial cloudiness, 8 July 2012

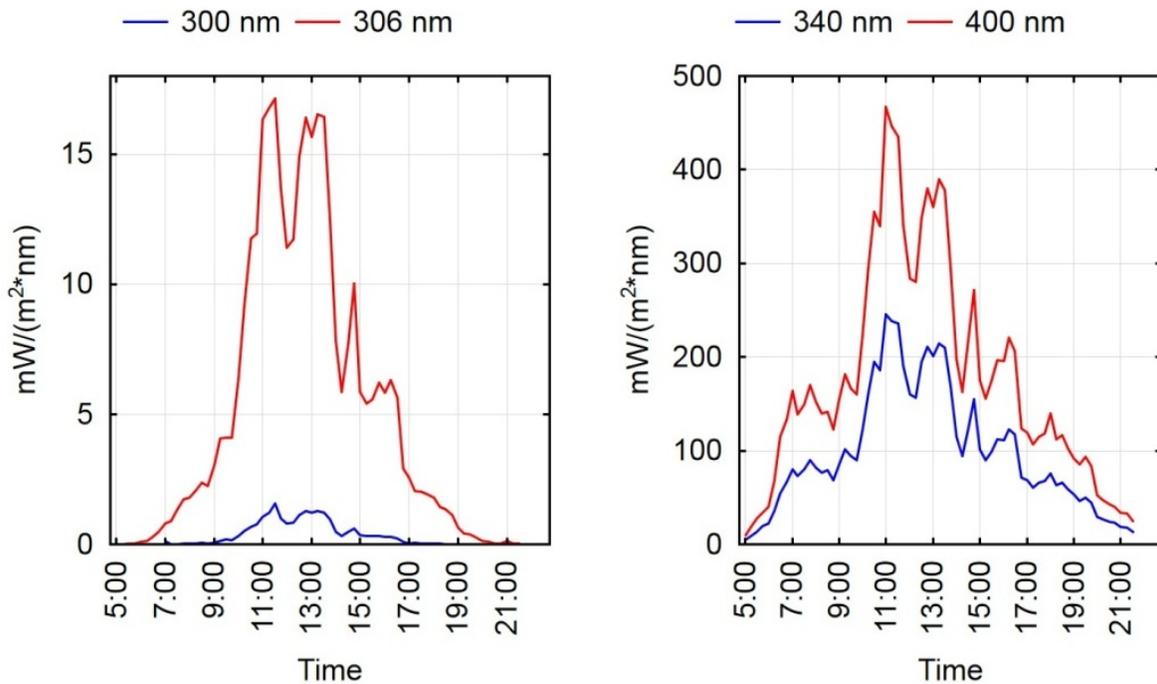


Figure 11. Diurnal cycles of spectral irradiance at selected UVB (left) and UVA (right) wavelengths at mean amounts of partial cloudiness, 9 July 2012

All of these cases might be considered as typical good weather cloud situations in summer months. A common feature is that in morning and evening the change of UVR with time is relatively smooth.

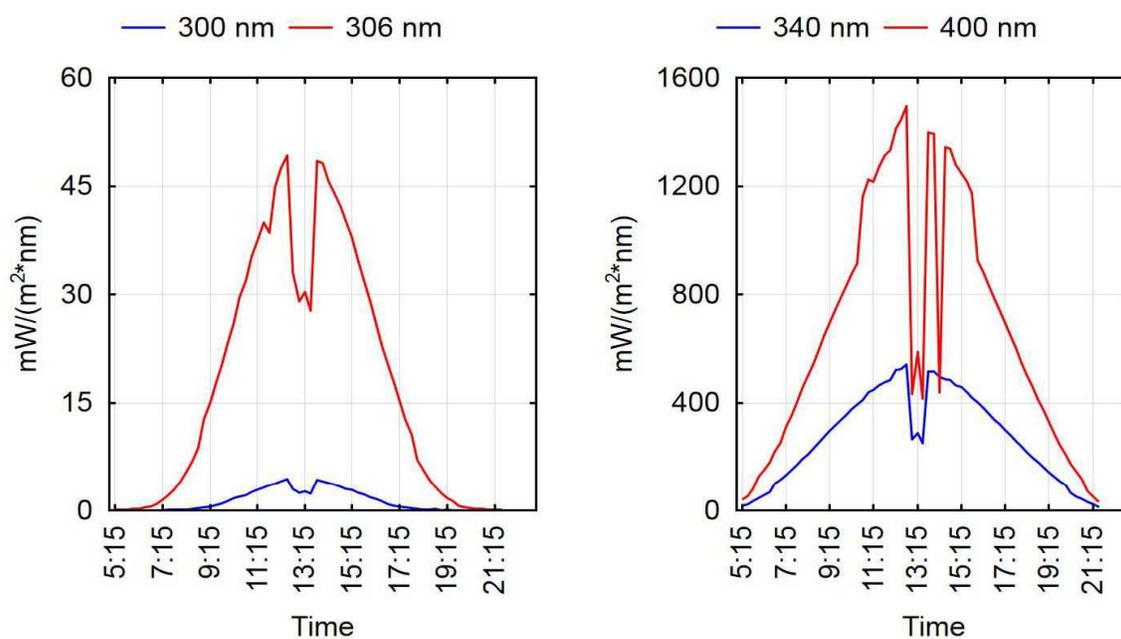


Figure 12. Diurnal cycles of spectral irradiance at selected UVB (left) and UVA (right) wavelengths at small amounts of partial cloudiness, 17 July 2009

Contrasting variations begin after heating the surface to the ability of initiating convection, producing *Cu* and *Cb* clouds. Locally produced convective clouds are the major factor causing variability in ground-level solar irradiance. There also exists background cloudiness, often consisting of *Ci*, *Ac*, *Sc* clouds and contributing to the variability of ground-level spectral irradiance. Frontal clouds are also frequent in some years, manifesting high cyclonic activity. Then full days or parts of days are overcast. Usually the attenuation of solar radiation in those conditions is larger [39]. Generally, the attenuation by clouds in the UV range is somewhat less than in the whole incoming solar radiation. In the UVA range the attenuation decreases with the decrease in wavelength and is the smallest reaching UVB spectral range where the increasing absorption by tropospheric ozone leads to an increase of attenuation.

5. Summary and conclusions

Environmental effects of UV irradiance at any site depend on the received radiation energy and its spectral composition. The availability of the most efficient UVB irradiance depends on the presence of direct sunshine and on solar elevation. Geographical site and time-dependent regular daily cycle of solar elevation reaches its highest value at noon in real solar time. Noon solar elevation manifests a regular annual cycle, being the smallest at winter solstice and the largest at summer solstice. The highest levels of solar irradiance including UVR in clear weather conditions are recorded at noon.

At summer solstice the shortwave threshold at the study site in the UVB range is 294 nm in normal column ozone and atmospheric transparency conditions. In early morning and late

evening the shortwave threshold drops to approximately 310 nm. The UVA spectral range of recorded irradiance is always equal to 316 to 400 nm. In the UVB range it is much shorter, and varies during the day from 5 nm to 20 nm. Due to absorption by tropospheric ozone and partly by aerosols the UVA/UVB ratio of irradiances in the UVA and UVB spectral ranges changes during a year and during a day in wide range.

Immediately after sunrise and before sunset it may reach about 500-600 nm, and decreases to less than 50 in summer noon hours. In cloudless conditions the major modulators of the ground-level UV irradiance are column ozone and spectral aerosol optical depth. Variations in both may result in comparable effects in irradiance levels and spectral composition. The influence of these factors is important to consider in the presence of sunshine. Cloudless UV irradiance may vary more than twice at the same SZA in the UVB spectral range. In most of the UVA range the influence of column ozone is negligible and variations in irradiance result from AOD variations. At solar elevations below 10° (SZA above 80°) the accuracy of spectral irradiance measurements is lower than at higher sun conditions and the spectral influence of column ozone and AOD is less clear.

The regular annual cycle of the atmospheric column ozone with the maximum (380-390 DU) in March-April and minimum (270-280 DU) in October-November is a reason for the differences in UVB irradiance levels in spring and autumn. These differences become obvious during sunshine episodes, which tend to be less frequent in autumn and in some years are extended in spring. On the contrary, in spring episodes when column ozone drops to close to usual levels, autumnal ones are met.

Snow conditions at the study site contributing significantly to the surface albedo have been variable in recent decades. In spring in some years snow persists until the middle of April (noon SZA around 48°) but in other years the presence of snow remains episodic during the whole winter. In autumn there have been separate years when snow cover appeared for some time in October (noon SZA around 69°). In other cases there had been almost no snow by January. Albedo of snow is high, sometimes close to 0.90, for fresh snow and much smaller for wet and dirty snow. Reflection from the fresh clean snow increases the recorded irradiance significantly. In autumnal period the irradiance level is low before reflecting from surface and its UVB part very small. Since the beginning of November, snow does not increase vitamin D synthesizing irradiance to necessary level. Without snow the surface albedo is only a few percent.

A major contributor to variations of both UVB and UVA irradiance in Northern Europe and Estonia is cloudiness. In cloudy weather the irradiance levels tend to be somewhat lower and the threshold of sensitivity several nanometres larger than in cloudless conditions. Cloud influence on the UVR spectra is related to attenuation and enhancement of irradiance.

Attenuation of solar irradiance happens when the Sun is shaded by cloud. When the Sun shines and bright clouds are close to the visible solar disk, reflection and scattering by these clouds often leads to larger irradiances than in cloudless conditions. A cloudy sky background is a significant irradiance modulating factor. Daily total cloud effect depends much on the cloudiness characteristics during noon hours when the received energy is the largest. In dry

summers there are less clouds in that time period and less influence on the UVR spectra. In wetter summers, both the attenuation and enhancement are stronger due to the convection of moist air.

The largest daily doses of UVR spectral density are recorded in the presence of medium cloud amounts. At small cloud amounts, clouds are less frequently located close to the Sun. At large cloud amounts shading of the Sun by clouds and attenuation of irradiance dominates. In moderate cloud amounts sunshine episodes are relatively frequent and related to the enhancement of irradiance. Both enhancement and attenuation increase the relative contribution of UVA radiation in the UVR spectrum. Daily total cloud effect depends much on the cloudiness characteristics during noon hours when the received energy is the largest. Total effect depends on the cloud amount and on their vertical extent. Deep convective clouds attenuate the UVB range of incoming irradiance significantly more than shallow stratiformed clouds. The CMF of stratiform clouds like *Sc* does not necessarily decrease with decreasing wavelength, as is commonly considered for cloudy atmospheres.

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