Proceedings of the Estonian Academy of Sciences,
2016, **65**, 1, 50–57
doi: 10.3176/proc.2016.1.05
Available online at www.eap.ee/proceedings

CLIMATOLOGY

Reconstruction of UVB and UVA radiation at Tõravere, Estonia, for the years 1955–2003

Margit Aun[a,b*], Kalju Eerme[a], Martin Aun, and Ilmar Ansko[a]

[a] Tartu Observatory, Observatooriumi 1, Tõravere, 61602 Tartumaa, Estonia
[b] University of Tartu, Ülikooli 18, 50090 Tartu, Estonia

Received 27 March 2015, revised 19 June 2015, accepted 18 September 2015, available online 28 January 2016

Abstract. Information on UV radiation levels and their changes in the past improves opportunities to investigate negative and beneficial effects of radiation. A reconstruction of the daily doses of ground-level solar irradiance in ultraviolet wavelength bands UVB (280–315 nm) and UVA (315–400 nm) in the years 1955–2003 was made for the site of Tartu Observatory at Tõravere, Estonia (58°16′N, 26°28′E, 70 m a.s.l.). Freely available software ARESLab (based on Multivariate Adaptive Regression Splines, MARS) was used for radiation modelling. Measured daily column ozone values, daily dose of global solar radiation, noon solar zenith angle, and cloudless UV daily doses calculated with the libRadtran software packet were used as the input data. The construction of the models was based on the UV spectral irradiance data measured at Tõravere from 2004 to 2006 with a minispectrometer AvaSpec-256. The models were tested on a 200-day data set from the year 2007. The coefficients of linear correlation between the calculated and measured daily doses were 0.98 in both wavelength ranges. Testing was also carried out on the data from Bentham DMc150F-U to investigate the possibility of providing information for missing measurement days with model calculations in order to obtain longer time series and better opportunities for investigating short-term changes and short-period dependence between UV doses and various weather and atmospheric factors and ground ecosystems.

Key words: UV radiation, reconstruction.

1. INTRODUCTION

UV radiation is an important factor influencing the biosphere. To estimate different environmental effects of UV radiation, weighted doses of UVB, UVA, and different action spectra and their fluctuation in time are needed. Measurements of UV radiation have been carried out during a relatively short time period. In general, continuous UV measurement data are available only for the last few decades. Initially measurements were performed with broadband filter instruments. Spectral data are available only since the early 1990s (WMO, 1995).

This raises the necessity for the modelling and reconstruction of UV radiation. Another reason is that different technical aspects, for example faulty instruments, may cause some short gaps in data. Because of the lack of measured UV radiation levels and their time evolution in the past years, various reconstruction methods have been developed and used (Haberreiter et al., 2005; Eerme et al., 2006; Outer et al., 2010; Bilbao et al., 2011). These methods are mostly based on observations and measurements of other climate- and UV radiation-related quantities, and empirical relationships are derived between variables (Lindfors and Vuilleumier, 2005). Also, the modelling of clear-sky irradiance values as an extra input has been used (Diffey, 1977; Mayer et al., 1997; Kaurola et al., 2000; Lindfors et al., 2007). More complex models have been built using neural networks (Feister et al., 2008; Medhaug et al., 2009; Junk et al., 2012) and Multivariate Adaptive Regression Splines (MARS) approaches (Krzyścin et al., 2004). MARS was introduced and fully described by Friedman (1991). Most of the studies use daily data as the necessary

[*] Corresponding author, margit.aun@ut.ee

auxiliary data are often unavailable in shorter time frames. Some of the methods require either data not available for most sites or software not accessible for many researchers.

So far most of the reconstructions have been focused on shorter wavelengths, mainly erythemal radiation. UVA and its changes have been mostly overlooked because its doses required for producing biological effects are much higher than for UVB. However, UVA penetrates the ozone layer and human skin better than shorter wavelengths (McMillan et al., 2008).

The aim of the present study is to adjust and apply a simple and accessible method for reconstructing UV doses for Tõravere, Estonia, in two wavelength ranges: UVB (280–315 nm) and UVA (315–400 nm). This model could also cover data gaps of UV measurements with model calculations, which will provide a longer time series and improve opportunities to investigate short-term changes and dependence between UV doses and various weather and atmospheric factors and ground ecosystems.

The reconstruction of erythemal UV doses for the Tõravere site was performed earlier for the years 1955–2004 by Eerme and co-workers (Eerme et al., 2002, 2006) based on statistical relationships between the measured erythemal UV doses and proxy data. In the present work a different method is used and no action spectrum is applied. Up to now the modelled clear-sky radiation has not been extensively used in comparisons of measured data or calculations of UV radiation in Estonia. Also, it is the first time that the MARS technique is applied based on data measured at Tõravere.

The models described in the paper were constructed using freely available ARESLab and libRadtran software with locally measured UV radiation data as well as local and satellite auxiliary data. The following sections of the paper deal with the applied methods and data as well as the building and testing of the models.

2. DATA AND METHODS

2.1. UV measurements

Continuous spectral measurements of UV radiation at Tõravere started in July 2004 with a minispectrometer AvaSpec-256 (Ansko et al., 2008), which was replaced by Bentham DMc150F-U in 2009. The site of Tartu Observatory and Tartu-Tõravere Meteorological Station (58°16′N, 26°28′E, 70 m a.s.l.), operated by the Estonian Environment Agency since 1 July 2013, is a rural site in southern Estonia, characterized by a low level of air pollution due to its quite long distance from larger cities and industries. The optical design of the AvaSpec-256 spectrometer is based on the symmetrical Czerny–Turner design with a 256 pixel detector array. Calibration of the instrument is performed via tungsten-halogen standard lamps FEL. Because of the decreasing sensitivity of the array in time, the spectrometer was calibrated several times a year. The instrument and its uncertainties have been thoroughly described in earlier papers (Ansko et al., 2008; Aun et al., 2011). To keep homogeneity of the data, Bentham DMc150F-U measurements were not included in the stage of building the models.

2.2. Auxiliary data

Total solar radiation has been measured at Tartu-Tõravere meteorological station consistently since 1955, mainly with the Yanishevski AT-50 actinometers and Savinov–Yanishevski M-115 pyranometers. In 1996 the Eppley Laboratory Inc. pyrheliometers and Kipp & Zonen pyranometers were installed.

The total ozone content in the atmosphere was obtained mainly from the data sets of Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI) and partly from local direct sun measurements with a MICROTOPS-II instrument. Data series for total ozone are available since 1979. In the cases of single missing daily data, monthly averages of the respective year were used. Prior to 1979 the monthly averages of the years 1979–1989 were selected as the best estimation. Due to technical problems with TOMS data, there are major data gaps in ozone values from 1993–1996. For filling the data gaps in the case of less than 15 available daily values for a month, monthly averages from 1990–1999 were used.

Spectral aerosol data for the Tõravere site are available from the Aerosol Robotic Network (AERONET, http://aeronet.gsfc.nasa.gov/) since June 2002 when Cimel sun photometer started measurements at Tõravere. Before that only broadband aerosol optical depth (AOD) data are available for this site.

2.3. Model characteristics

Freely available ARESLab and libRadtran software were selected for constructing the models. ARESLab (Jekabsons, 2011) is a Matlab/Octave toolbox for building piecewise-linear and piecewise-cubic regression models using the MARS technique. libRadtran is a software package for making radiative transfer calculations in Earth’s atmosphere, described by Mayer and Kylling (2005).

The input data used for building the models and then using the latter for reconstructing past UV doses include UV spectral irradiance, global solar radiation, total ozone, noon solar zenith angle (SZA, calculated with libRadtran), and clear-sky UVB and UVA daily doses (calculated with libRadtran).

2.4. libRadtran calculations

libRadtran version 1.6-beta and its uvspec model were used for the calculations of clear-sky daily UVB and UVA radiation doses. For the model calculations the disort2 radiation transfer solver was used and standard atmospheres 'mid-latitude winter' and 'mid-latitude summer' were selected from the included options. The summer season lasted from 21 March to 22 September. Correction of extraterrestrial irradiance for the Sun–Earth distance was made by an included time function. Total ozone values were selected as described in Section 2.2.

Snow albedo can reach up to 0.9 in the case of fresh clean snow, but the average value at a measurement site is much lower due to the fragmentation of the snow cover (caused by trees, buildings, roads, etc.). The age and purity of snow also vary. Schwander et al. (1999) found the average albedo in the presence of snow cover to be 0.38. The albedo values for the measurement site were chosen to be 0.4 for snow and 0.03 for snow-free conditions as shown in Schwander et al. (1999) and Rieder et al. (2008).

Aerosol was partly described by standard built-in options of libRadtran as before June 2002 only broadband AOD data are available for the Tõravere site. Rural type of aerosol was selected and two seasons were used: spring–summer (March–August) and autumn–winter (September–February). Ångstrom parameter was retrieved for each calendar month average from the years 2002–2010 from AERONET. Due to the heavy cloudiness in the period from November to February, the amount of data for that period is smaller than for the rest of the year. December is not covered with data and January is poorly covered. For both months the data averaged for January were used, assuming similarity of conditions in these two months. The irradiance calculations with libRadtran were made after every 15 min for both wavelength ranges for all days in 1955–2003 with daily doses integrated.

3. CONSTRUCTION OF MODELS

Two models were created with ARESLab for constructing the time series of past UV yearly doses: one for the UVB and the other for the UVA radiation. ARESLab uses training data cases with x_i as input data and known outcome y, which is the measured daily UV dose. UV daily doses calculated from the measured irradiances of the years 2004–2006 at Tõravere were used in the process of building the models. Altogether 440 days were included. The remaining days were excluded due to gaps in AvaSpec-256 measurements (more than 2 consecutive measurements missing; missing measurements at the beginning or at the end of the day) or for too large noon SZA (more than 80 degrees). The measured daily UV doses were standardized for building the model.

Calculated clear-sky UV doses, total ozone, measured global solar radiation, and noon SZA were used as input data. Also snow cover and cloudiness were tested as the input data, but these had no or an insignificant impact on the model's performance. A potential reason for the exclusion is their influence on the measured global solar radiation values. The model input was normalized in the range 0 to 1.

The regression model was built using the MARS technique. Two phases are used in the process. The first, forward phase starts with just an intercept term (which is the mean of the response values), after that all database fields are tested by adding basis functions to get the largest reduction in the training error. At the end of the first phase, a large model that overfits the data is built, which means the model works well with data used for building the model, but does not generalize well with new data. In the second, backward deletion phase, the model is simplified by deleting least important basis functions based on generalized cross validation value, which is calculated using the mean squared error and model parameters (Krzyścin, 2003; Jekabsons, 2011).

The testing of the models to evaluate their performance was carried out with the data collected in 2007 (200 days). Both models showed good results manifesting linear correlation coefficients of measured and calculated daily doses above 0.98 in both wavelength ranges (Fig. 1). The daily doses of measured and modelled UVB and UVA radiation are shown in Fig. 2. No general systematic difference to either side was detected. The sum of the modelled daily doses of the days used for testing for UVA was about 2% smaller than the sum of the measured doses. The modelled daily doses had a lower peak values in the summer period. For UVB the difference in peak values was smaller. In general, the modelled values were less precise in winter months, partly due to the presence of snow, which makes the radiation field more complex. The inaccuracy of the model increases also with SZA. However, doses from that period play a minor role in the yearly total.

The models were also tested on data received from Bentham DMc150F-U measurements. The period from 1 April to 30 September 2012 was chosen to evaluate the suitability of the models to fill data gaps from different instruments. For the chosen time frame of 183 days, 101 had measurements. The correlation was only slightly weaker than for AvaSpec-256 measurements: 0.94 for UVB (Fig. 3) and 0.96 for UVA (Fig. 4). No systematic deflection was detected. The majority of ratios of measured daily doses to calculated daily doses stayed within the range 1 ± 0.2. The days with a larger divergence were days with very low daily doses (overcast sky), when the ratio values are more sensitive

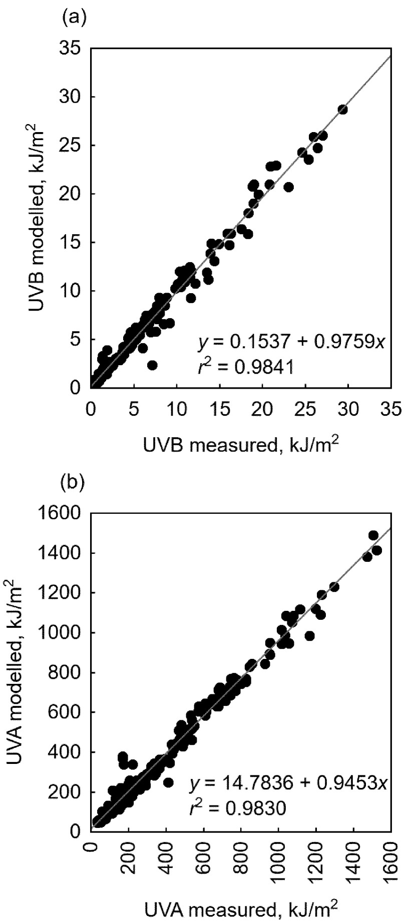

Fig. 1. Correlation between the measured and modelled UV daily doses in 2007 for UVB (a) and UVA (b).

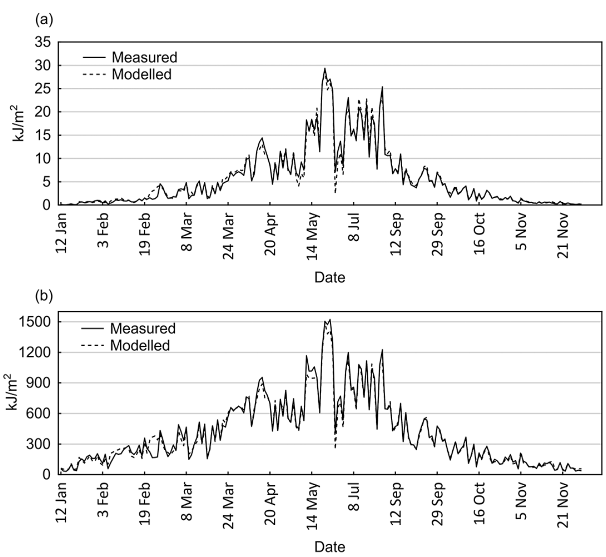

Fig. 2. Comparison of 200 measured and modelled UVB (a) and UVA (b) daily doses in 2007.

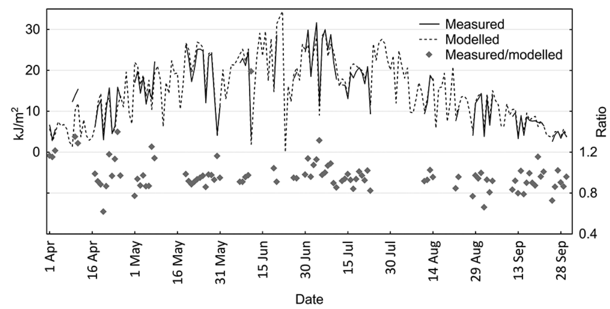

Fig. 3. Comparison of measurements and modelled UVB daily doses in March–September 2012.

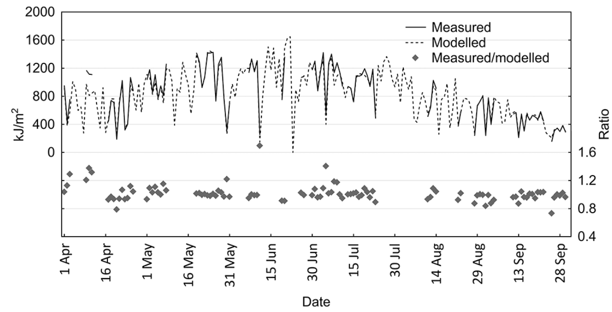

Fig. 4. Comparison of measurements and modelled UVA daily doses in March–September 2012.

to absolute difference. Before using the model on Bentham data, more data have to be included for testing to see if alterations are necessary.

4. RESULTS AND DISCUSSION

The constructed models were used for calculating the UV yearly doses in UVB and UVA spectral ranges for the period 1955 to 2003 (Fig. 5).

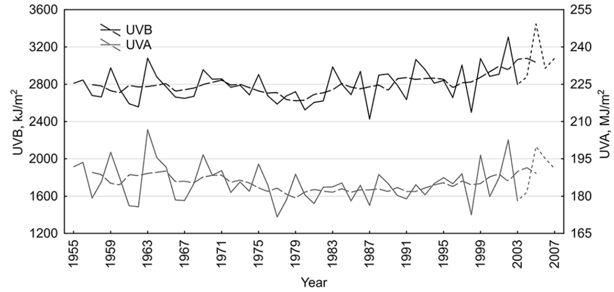

Fig. 5. Yearly doses of UVB and UVA radiation with a 5-year moving average from 1955 to 2007 at Tõravere. Reconstructed values until 2003 (solid line) and 2004–2007 measurements in combination with calculated values (dashed line).

The 5-year moving average values show higher levels of UVA and UVB radiation until the beginning of the 1970s. After 1971 a decline in the radiation level occurred, reaching the lowest values in 1979 for both spectral ranges. While UVA stayed fairly constant on a lower level until the middle of the 1990s, UVB started to increase since the 1980s, exceeding its values in the 1960s by the beginning of the 2000s. For comparison with other authors, a linear trend from 1979–2003 was calculated: 4.1% statistically significant increase per decade in UVB and about 1% increase per decade in UVA, which are statistically insignificant. Similar trends since the 1980s have been described by many other authors. Bilbao et al. (2011) found an upward trend of 3.5% per decade for the erythemal UV radiation in Spain in summer. Outer et al. (2010) described an increase in the erythemal UV radiation level during the past three or four decades, which has accelerated since the 1980s in various sites in Europe. The present radiation level was found to be 4–8% higher than before the 1980s. An increase of the UVB radiation was also detected by Krzyścin (2003) as a linear trend of 2.5% per decade for the snowless part of the year in 1988–2000 at Belsk, Poland; Lindfors and Vuilleumier (2005) noted a linear upward trend of erythemal UV yearly doses in 1979–1999 at Davos, Switzerland.

The trends considered here and their linear approximations are comparable and relevant within relatively short time intervals. Without considering longer timescales those trends may lead to an inadequate understanding of climate variations and long-term change. It is impossible to describe long-term changes on the basis of measured solar irradiance (since 1955 at Tõravere). A longer precipitation timeline, starting in 1866, is available for Estonia. It shows a 25–30 year periodicity (Järvet and Jaagus, 1996; Nõges et al., 2012). The latest wet period in 1978–1990 matches the lower levels of UV radiation in the constructed time series. A high-level period of precipitation prior to that was from the end of the 1940s until the middle of the 1950s. Hence, linear trends calculated for the chosen time just show the situation during that period. Another high level of precipitation in the next cycle around the middle of the 2010s might again reduce UV radiation.

The results of the present reconstruction were also compared with the results of reconstructed erythemal UV doses at Tõravere (Eerme et al., 2002, 2006) and with the results of broadband radiation studies for the same site (Eerme et al., 2010; Eerme and Aun, 2012). Changes in yearly doses acted similarly for the two reconstructions. For the reconstructed erythemal radiation for Tõravere the upward trend since 1979 was 3.6% per decade. The linear correlation of the two reconstructions was 0.8 between UVB and erythemal radiation. When the two reconstructed yearly dose values are normalized from 0 to 1, the difference between the two reconstructions is between –0.15 and 0.2 with three exceptions: a distinctive mismatch occurs in the years 1983, 1992, and 1993 (Fig. 6), where the later reconstruction shows larger values. The reason for the divergence of the two reconstructions seems to come from the different impact of ozone on UVB and erythemal radiation and its consideration in models.

Yearly doses of UVB have a much stronger correlation with ozone (–0.57) than yearly doses of erythemal radiation. The period from the beginning of the 1980s until the middle of the 1990s manifests a decline in average ozone values with local minimums in 1983, 1992, and 1993, mentioned above as the years of a mismatch between the two reconstructions. Those minimums follow two large volcanic eruptions: those of El Chichón (1982) and Mount Pinatubo (1991). Aerosols transported into the atmosphere from a volcanic event change the chemistry of the atmosphere and have a destructive effect on ozone (Glasow et al., 2009). Also the reconstruction of erythemal doses uses turbidity as a separate factor to account for changes in aerosol. The reconstruction for erythemal radiation is more strongly correlated with global solar radiation (0.89, for UVB 0.67).

The results of the present work are also supported by the detected trends in global solar radiation and total ozone (Fig. 7) as well as in aerosol loadings. The calculation of linear correlations between different variables gives an expectedly strong correlation between global solar radiation and UVA radiation (0.98) and more moderate correlation with UVB (0.67), whereas yearly mean O_3 has a statistically significant negative correlation with UVB doses (–0.57).

Global solar radiation has mainly varied due to changes in cloudiness, which is the most important factor influencing also the UV radiation reaching the ground. Cloudiness data for Tõravere have been analysed by Eerme and Aun (2012). Higher UV levels until the beginning of the 1970s than average are partly due to less cloudy conditions. That period is also characterized by higher average free space from low and medium clouds from March to September

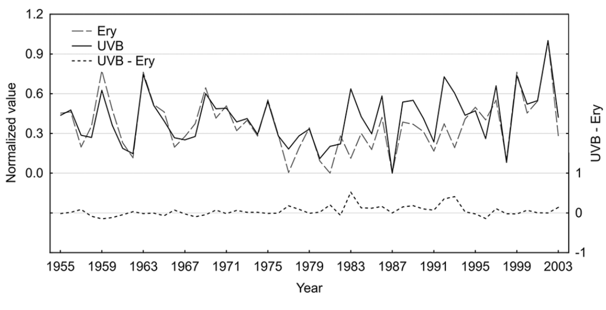

Fig. 6. Normalized reconstructed yearly doses of UVB and erythemal (Ery) UV from 1955 to 2003 at Tõravere (Eerme et al., 2006).

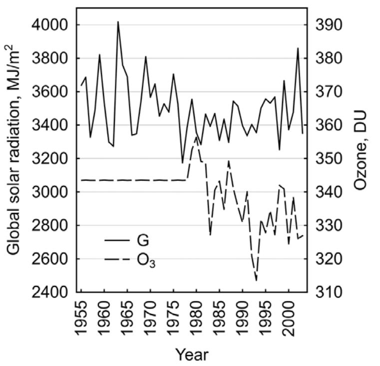

Fig. 7. Annual global solar radiation doses and mean annual total ozone from 1955 to 2003 at Tõravere.

(Eerme and Aun, 2012). These months give also the highest contribution to the annual radiation income. At the same time annual mean cloudiness increased in 1964–1986 by about 11% in case of low-level clouds (Russak, 1996). Changes in global solar radiation at Tõravere from 1955 to 2010 in spring and summer are described in more detail in (Eerme, 2012).

When the amount of clouds is small, the ozone and aerosol contribution to modulating the UV radiation level increases. To assess the role of ozone in modulating UV radiation, a similar technique was used as the one applied by Lindfors and Vuilleumier (2005) and Outer et al. (2010). The yearly sums of UVB from the period 1981–1990 were looked at. The average UVB from the reconstructed yearly doses was calculated and the difference of each calculated value from the average in percentage was found (Fig. 8). The reconstruction was made again for the selected period, using climatological monthly ozone values instead of measured single day

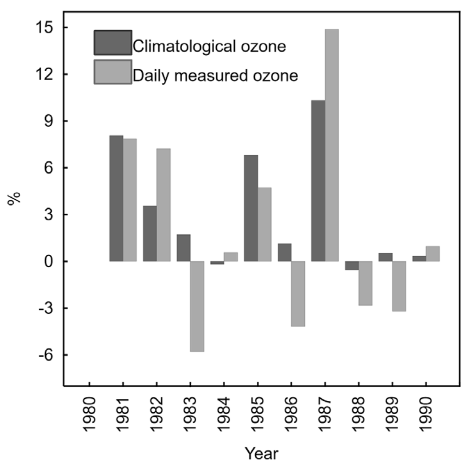

Fig. 8. Percentage difference between the average modelled UVB yearly dose and yearly doses of 1981–1990 calculated using two different ozone values: daily measured values and long-term monthly averages.

values. Differences in percentages from the original reconstruction average were found (Fig. 8). Original reconstruction differences from the average are caused by changes in total solar radiation (due to changes in cloudiness and aerosols) and ozone. Reconstruction using climatological ozone values shows the difference caused only by global solar radiation, the rest is caused by ozone.

For the years 1955–1978 monthly averages from the years 1979–1989 were used. As the average ozone values started to decrease in the 1980s, for the period 1955–1978 the used ozone values might be slightly lower than the actual values as in (WMO, 1991) a decrease of ozone column of 4.7% per decade for May to August 1978–1991 in St. Petersburg (60°N, similar to our study site) is reported. As the average of the period was selected, the used values can be estimated to be a few percentage points lower than the actual values. The total ozone values prior to 1978 were also calculated using interpolation of data from London et al. (1976) and from the WMO World Ozone and Ultraviolet Data Center (WOUDC), but even lower averages were found for most months compared to the values finally used. Lower ozone values can cause some overestimation of UVB radiation, but as the main factors influencing UV (SZA and cloudiness) have a much larger influence and variation, this difference is not decisive, especially considering that day-to-day variations of ozone can also be larger.

Although higher aerosol loadings commonly tend to appear in spring and in July–August, there are significant differences between years. In the period 2004–2009 only one year, 2006, had systematically larger than usual AOD values during a longer period, from 25 April to 6 May, caused by extensive landscape fires in Eastern Europe (Stohl et al., 2007). In other years the spread of fires was rather moderate, and relatively large AOD values appeared only as short episodes. The lowest AOD values tend to occur in autumn (September–November). Aerosol loadings at Tõravere are strongly influenced by wind direction, as there are no major stationary anthropogenic pollution sources nearby (Russak, 1996). A steady increase in AOD at 550 nm occurred in Estonia from 1951 to 1982 due to the growth in industry and transport and a rapid decrease in recent decades due to measures taken to protect the environment (Russak et al., 2007). Zerefos et al. (2009) describe global dimming and brightening (decrease and increase in shortwave solar (SW, 0.2–5 μm) radiation range and also in UVA separately) that are due to changes in atmospheric aerosol loadings. Global dimming and brightening are also described in many other papers (e.g. Stanhill, 2005; Wild et al., 2005; Cutforth and Judiesch, 2007; Kambezidis et al., 2012). These changes are included in the present work only through the measured global solar radiation.

5. CONCLUSIONS

The constructed models described in the present paper show a strong linear correlation of calculated values with measurement data, thus giving a solid basis for covering periods with no available measured data. A plausible view of changes in the past UV levels is displayed. The results are supported by main features in the time series of auxiliary data and in earlier reconstructions.

The testing of the models on data from another instrument not included in constructing the models showed almost as good correlation with measurements. Thus the calculated data could be used for covering data gaps in ongoing UV measurements. More data should be included to testing before deciding whether alterations are necessary.

Seasonal-scale low levels in the calculated UV time series, related to cloud amounts above average, coincide well with those in measured broadband incoming solar irradiance. The same is valid for higher than usual seasonal doses.

Relatively high yearly doses of UVB and UVA radiation were characteristic of the study site until the beginning of the 1970s. Since then a decline reaching a minimum in 1979 occurred. The recovery of the UVB level started from 1980, and by the beginning of the 2000s it exceeded the previous high level of the 1960s. The UVA yearly doses stayed at a constant low level until the 1990s and then started to grow. The differences between the temporal evolution of UVB and UVA yearly doses are partly caused by the anomalies of the atmospheric column ozone and partly related to two major volcanic eruptions, El Chichon and Mount Pinotuba.

ACKNOWLEDGEMENTS

We thank the AERONET team for the efforts in establishing and maintaining the Tõravere AERONET site and the Estonian Environment Agency for providing meteorological data. The work was supported by the European Regional Development Fund by financing the Estonian environmental project 3.2.0801.11-0041 'Estonian radiation climate'.

REFERENCES

Ansko, I., Eerme, K., Lätt, S., Noorma, M., and Veismann, U. 2008. Study of suitability of AvaSpec array spectrometer for solar UV field measurements. *Atmos. Chem. Phys.*, **8**, 3247–3253.

Aun, M., Eerme, K., Ansko, I., Veismann, U., and Lätt, S. 2011. Modification of spectral ultraviolet doses by different types of overcast cloudiness and atmospheric aerosol. *Photochem. Photobiol.*, **87**, 461–469.

Bilbao, J., Roman, R., Miguel, A. de, and Mateos, D. 2011. Long-term solar erythemal UV irradiance data reconstruction in Spain using a semiempirical method. *J. Geophys. Res.-Atmos.*, **116**, D22211.

Cutforth, H. W. and Judiesch, D. 2007. Long-term changes to incoming solar energy on the Canadian Prairie. *Agric. Forest Meteorol.*, **145**, 167–175.

Diffey, B. L. 1977. The calculation of the spectral distribution of natural ultraviolet radiation under clear day conditions (for UV dosimeter correction). *Phys. Med. Biol.*, **22**, 309.

Eerme, K. 2012. Interannual and intraseasonal variations of the available solar radiation. In *Solar Radiation* (Babatunde, E. B., ed.), pp. 33–52. InTech, Croatia.

Eerme, K. and Aun, M. 2012. A review of the variations of optical remote sensing conditions over Estonia in 1958–2011. *Int. J. Remote Sens. Appl.*, **2**(3), 12–19.

Eerme, K., Veismann, U., and Koppel, R. 2002. Variations of erythemal ultraviolet irradiance and dose at Tartu/Tõravere, Estonia. *Clim. Res.*, **22**, 245–253.

Eerme, K., Veismann, U., and Lätt, S. 2006. Proxy-based reconstruction of erythemal UV doses over Estonia for 1955–2004. *Ann. Geophys.*, **24**, 1767–1782.

Eerme, K., Kallis, A., Veismann, U., and Ansko, I. 2010. Long-term variations of available solar radiation on seasonal timescales in 1955–2006 at Tartu-Tõravere Meteorological Station, Estonia. *Theor. Appl. Climatol.*, **101**, 371–379.

Feister, U., Junk, J., Woldt, M., Bais, A., Helbig, A., Janouch, M., et al. 2008. Long-term solar UV radiation reconstructed by ANN modelling with emphasis on spatial characteristics of input data. *Atmos. Chem. Phys.*, **8**, 3107–3118.

Friedman, J. H. 1991. Multivariate adaptive regression splines. *Ann. Stat.*, **19**, 1–67.

Glasow, R. von, Bobrowski, N., and Kern, C. 2009. The effects of volcanic eruptions on atmospheric chemistry. *Chem. Geol.*, **263**, 131–142.

Haberreiter, M., Krivova, N. A., Schmutz, W., and Wenzler, T. 2005. Reconstruction of the solar UV irradiance back to 1974. *Adv. Space Res.*, **35**, 365–369.

Järvet, A. and Jaagus, J. 1996. The impact of climate change on hydrological regime and water resources in Estonia. In *Estonia in the System of Global Climate Change* (Punning, J.-M., ed.), pp. 84–103. Institute of Ecology, Tallinn.

Jekabsons, G. 2011. ARESLab, Adaptive Regression Splines toolbox for Matlab/Octave.http://www.cs.rtu.lv/jekabsons/regression.html (accessed 27.03.2015).

Junk, J., Feister, U., Helbig, A., Görgen, K., Rozanov, E., Krzyścin, J. W., and Hoffmann, L. 2012. The benefit of modeled ozone data for the reconstruction of a 99-year UV radiation time series. *J. Geophys. Res.-Atmos.*, **117**, D16102.

Kambezidis, H. D., Kaskaoutis, D. G., Kharol, S. K., Moorthy, K. K., Satheesh, S. K., Kalapureddy, M. C. R., et al. 2012. Multi-decadal variation of the net downward shortwave radiation over south Asia: the solar dimming effect. *Atmos. Environ.*, **50**, 360–372.

Kaurola, J., Taalas, P., Koskela, T., Borkowski, J., and Josefsson, W. 2000. Long-term variations of UV-B doses at three stations in northern Europe. *J. Geophys. Res.-Atmos.*, **105**, 20813–20820.

Krzyścin, J. W. 2003. Nonlinear (MARS) modeling of long-term variations of surface UV-B radiation as revealed from the analysis of Belsk, Poland data for the period 1976–2000. *Ann. Geophys.*, **21**, 1887–1896.
Krzyścin, J. W., Eerme, K., and Janouch, M. 2004. Long-term variations of the UV-B radiation over Central Europe as derived from the reconstructed UV time series. *Ann. Geophys.*, **22**, 1473–1485.
Lindfors, A. and Vuilleumier, L. 2005. Erythemal UV at Davos (Switzerland), 1926–2003, estimated using total ozone, sunshine duration, and snow depth. *J. Geophys. Res.-Atmos.*, **110**, 1–15.
Lindfors, A., Kaurola, J., Arola, A., Koskela, T., Lakkala, K., Josefsson, W., et al. 2007. A method for reconstruction of past UV radiation based on radiative transfer modeling: applied to four stations in northern Europe. *J. Geophys. Res.-Atmos.*, **112**, D23201.
London, J., Bojkov, R. D., Oltmans, S., and Kelley, J. I. 1976. *Atlas of the Global Distribution of Total Ozone July 1957 - June 1967*. National Center for Atmospheric Research, Boulder, Colorado.
Mayer, B. and Kylling, A. 2005. Technical note: The libRadtran software package for radiative transfer calculations – description and examples of use. *Atmos. Chem. Phys.*, **5**, 1855–1877.
Mayer, B., Seckmeyer, G., and Kylling, A. 1997. Systematic long-term comparison of spectral UV measurements and UVSPEC modeling results. *J. Geophys. Res.*, **102**, 8755–8767.
McMillan, T. J., Leatherman, E., Ridley, A., Shorrocks, J., Tobi, S. E., and Whiteside, J. R. 2008. Cellular effects of long wavelength UV light (UVA) in mammalian cells. *J. Pharm. Pharmacol.*, **60**, 969–976.
Medhaug, I., Olseth, J. A., and Reuder, J. 2009. UV radiation and skin cancer in Norway. *J. Photochem. Photobiol. B*, **96**, 232–241.
Nõges, P., Jaagus, J., Järvet, A., Nõges, T., and Laas, A. 2012. *Kliimamuutuse mõju veeökosüsteemidele ning põhjaveele Eestis ja sellest tulenevad veeseireprogrammi võimalikud arengusuunad*. Estonian University of Life Sciences, Tartu (in Estonian).
Outer, P. N. den, Slaper, H., Kaurola, J., Lindfors, A., Kazantzidis, A., Bais, A. F., et al. 2010. Reconstructing of erythemal ultraviolet radiation levels in Europe for the past 4 decades. *J. Geophys. Res.-Atmos.*, **115**, D10102.
Rieder, H. E., Holawe, F., Simic, S., Blumthaler, M., Krzyścin, J. W., Wagner, J. E., et al. 2008. Reconstruction of erythemal UV-doses for two stations in Austria: a comparison between alpine and urban regions. *Atmos. Chem. Phys.*, **8**, 6309–6323.
Russak, V. 1996. Atmospheric aerosol variability in Estonia calculated from solar radiation measurements. *Tellus A*, **48**, 786–791.
Russak, V., Kallis, A., Jõeveer, A., Ohvril, H., and Teral, H. 2007. Changes in the spectral aerosol optical thickness in Estonia (1951–2004). *Proc. Estonian Acad. Sci. Biol. Ecol.*, **56**, 69–76.
Schwander, H., Mayer, B., Ruggaber, A., Albold, A., Seckmeyer, G., and Koepke, P. 1999. Method to determine snow albedo values in the ultraviolet for radiative transfer modeling. *Appl. Optics*, **38**, 3869–3875.
Stanhill, G. 2005. Global dimming: a new aspect of climate change. *Weather*, **60**, 11–14.
Stohl, A., Berg, T., Burkhart, J. F., Fjæraa, A. M., Forster, C., Herber, A., et al. 2007. Arctic smoke – record high air pollution levels in the European Arctic due to agricultural fires in Eastern Europe in spring 2006. *Atmos. Chem. Phys.*, **7**, 511–534.
Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C. N., Dutton, E. G., et al. 2005. From dimming to brightening: decadal changes in solar radiation at Earth's surface. *Science*, **308**, 847–850.
WMO. 1991. *Scientific Assessment of Ozone Depletion: 1991. Global Ozone Research and Monitoring Project – Report No. 25*. Geneva, Switzerland.
WMO. 1995. *Scientific Assessment of Ozone Depletion: 1994. Global Ozone Research and Monitoring Project – Report No. 37*. Geneva, Switzerland.
Zerefos, C., Eleftheratos, K., Meleti, C., Kazadzis, S., Romanou, A., Ichoku, C., et al. 2009. Solar dimming and brightening over Thessaloniki, Greece, and Beijing, China. *Tellus B*, **61**, 657–665

1955.–2003. aasta UVB- ja UVA-kiirguse rekonstrueerimine Tõravere andmete põhjal

Margit Aun, Kalju Eerme, Martin Aun ja Ilmar Ansko

Ultraviolettkiirgusel (UV-kiirgus) on ökosüsteemidele eelkõige kahjulik, kuid ka kasulik mõju. Nende mõjude paremaks mõistmiseks on UV-kiirguse dooside ja spektraalse koostise muutuste kohta vaja võimalikult palju infot, vajalikud mõõtmised on toimunud aga suhteliselt lühikesel perioodil. Enamasti on eelnevad tööd keskendunud erüteemsele kiirgusele ja vähem on eraldi uuritud UVB- (280–315 nm) ning eriti UVA- (315–400 nm) kiirgust. Hindamaks ajas toimunud muutusi, rekonstrueeriti maapinnani jõudnud UV kiiritustiheduse päevadoosid UVB ja UVA lainepikkuste vahemikes perioodil 1955–2003 Tõravere (58°16′N, 26°28′E, 70 m üle merepinna), praeguse Tartu observatooriumi asukoha kohta.

Modelleerimiseks kasutati vabavarana saadaval olevat ARESLab-i (põhineb MARS-il). Sisendväärtustena kasutati mõõdetud päeva osooni hulka, summaarse päikese kiirguse päevadoose, arvutatud keskpäevaseid päikese seniitnurki ja libRadtraniga arvutatud pilvitu ilma UV-kiirguse päevadoose. Mudelite õpetamiseks kasutati Tõraveres ajavahemikul 2004–2006 minispektromeetriga AvaSpec-256 mõõdetud UVB ja UVA doose. Testimiseks kasutati 2007. aasta mõõtmistulemusi. Lineaarse korrelatsiooni koefitsient mõlemas lainepikkuste vahemikus mõõdetud ja arvutatud päevadooside vahel oli 0,98. Mudeleid testiti ka Tõraveres hiljem tööd alustanud Bentham DMc150F-U spektromeetri andmete põhjal. Seni esimesed suures mahus UV-kiirguse mudelarvutused annavad võimaluse täita mõõtmistega katmata lühemad perioodid. Pikemad katkematud aegread annavad võimaluse uurida lühiajalisi muutusi ja sõltuvusi UV-kiirguse dooside ning erinevate ilmastiku ja atmosfääri ning maapealsete ökosüsteemide komponentide vahel.