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Atmospheric Chemistry and Physics Discussions

Spectral UV measurements in Austria from 1994 to 2006: investigations of short- and long-term changes

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Abstract

Influences of atmospheric variability on short- and long-term changes of spectral UV irradiance measured at the Sonnblick observatory (47.03 N, 12.57 E, 3106 m) during the period from 1994 to 2006 is studied. Measurements are performed with a Brewer ozone single spectrophotometer and with a Bentham DM150 spectroradiometer (double monochromator).

The influence of ozone, albedo and clouds on UV variability is evaluated separately using 10-year climatology. It is found that the effect of total ozone on short-term variability of UV irradiance at 305 nm can be more than 200% and on average more than 50%. Clouds can cause variability of 150% or more and on average 35%. Variability caused by albedo is maximum 32%. Long-term trends are investigated for the time period from 1994 to 2006 using the non-parametric Mann-Kendall trend test. Significant downwards trends (99% confidence level) were found for solar zenith angle 55° at wavelengths from 305 nm to 324 nm and CIE.

1 Introduction

The intensity of UV radiation reaching the earth's surface is influenced by the concentration of stratospheric ozone as well as by further atmospheric parameters, such as clouds, aerosols and surface albedo. Knowledge of spectral UV irradiance and its dependence on these parameters, which may change in the future, are prerequisites to quantitatively understand and estimate future UV radiation.

Increase of UV radiation during the last decades is reported where a decrease of stratospheric ozone has been observed (Kerr and McElroy, 1993; Zerefos et al., 1997, 2001; Bartlett and Web, 2000). The magnitude of this change and their causes are, however uncertain calling for more detailed investigations of the influence of clouds, albedo, and other atmospheric parameters on UV radiation (Kerr et al., 2003; Bais et al., 2007).

Several publications focus on the detection of long-term changes in UV doses (Herman et al., 1996; Seckmeyer et al., 1997; Weatherhead et al., 1997; Lindfors et al., 2003). The first spectrally resolved routine measurements started in the 1990s, and studies on long-term changes in spectral UV irradiance are hampered by the limited number of years of available data (Zerefos et al., 1997; Lakkala et al., 2003; Glandorf et al., 2005).

Clouds can cause strong variability of UV radiation and limit the detectability of ozone-induced trends in UV radiation (Glandorf et al., 2005; den Outer et al., 2005). Change of cloud cover caused by change of global climate is especially important for estimation of future UV radiation. Reuder et al. (2001) show that reduced cloud cover during summer can increase UV radiation up to 15%.

Albedo is of great importance, especially in snow-covered mountainous regions. UV-irradiance is strongly enhanced with snow covered ground due to multiple reflections between ground and atmosphere, even more under overcast-sky conditions because of increased atmospheric backscattering through clouds. McKenzie et al. (1998) showed that, due to snow, UV-B increased by about 30% under clear sky and about 70% under cloudy sky conditions at Lauder, New Zealand. Kylling and Mayer (2001a) investigated the influence of the snowline on UV-irradiance at 340 nm, studying snow-free conditions and then moving the snowline from 1000 to 0 m. With decreasing snowline, enhancement in UV of 23–27% for cloudless sky was obtained, while for overcast conditions the enhancement was around 40–60%.

Different methods are available in the literature that separate the different influencing factors causing short– and long-term changes in UV radiation (Fioletov et al., 2001; Kylling et al., 2001b; Arola et al., 2003). Earlier investigations show the effect of ozone on UV radiation, whereas analyzing the influence of clouds and albedo is more difficult. Clouds show strong variability, and measurements of albedo which may be used as model input data are hardly available.

In this study, the influence of clouds, ozone, and surface albedo on spectral UV radiation at the Sonnblick observatory (3106 m) is investigated using continuous spectral

UV-irradiance measurements and model calculations. The influence of the different factors on short-term UV variability is shown using the available UV data sets. The method to separate the effects of clouds, ozone, and surface albedo is adapted from Arola et al. (2003) who used this method to analyse measurements at two stations, at Sodankylä, Finland (67° N) and at Thessaloniki, Greece (40° N). Spectral UV irradiance time series are analyzed for possible trends. Measurements at Sonnblick observatory starting 1994 represent the longest time series of spectral UV irradiance data in Austria.

2 Method

Monitoring of spectral UV radiation and total ozone at Sonnblick observatory in Austria is performed since 1993. The Sonnblick observatory (47.05° N, 12.95° E) is in southwest Austria at the border between Salzburg and Carinthia on a mountain top at 3106 m altitude. It is surrounded by rock faces on the northern side and by a glacier on the southeastern side. The area shows a very pronounced topography. The valley adjacent to Sonnblick is 1300 m lower than the summit. Nearby summits in this region are at approximately the same altitude. 16% of the surrounding area is covered with glaciers and in winter 88% of the surface is covered with snow under the assumption that no snow covers the rock faces.

The Sonnblick observatory is a station of the Austrian Weather Office that monitors synoptic and climatological meteorological data. They also record the cloud and ground surface conditions. The cloud fraction above and below the observatory as well as the cloud type are visually observed six times a day. The snowfall and the depth of the snow cover are measured once a day and the snowline is observed, and these data are used in this study.

2.1 Instrumentation and measurements

Spectral UV measurements at Sonnblick observatory have been performed with a Brewer spectrophotometer (single monochromator) since 1993 and a Bentham DM150 spectroradiometer (double monochromator) since 1997. The Brewer is used to measure global UV irradiance in the spectral range from 290–325 nm using a step width of 0.5 nm and total column ozone. Two independent calibrations are performed on a regular basis (1–2 months) with a portable 50 W lamp obtained from SCI-TEC company and with a self-built portable 1000 W lamp-assembly which is calibrated with another NIST (National Institute of Standards and Technology) calibrated 1000 W lamp in our laboratory. The Bentham spectroradiometer is used to measure global UV irradiance in the spectral range 280–500 nm with a step width of 0.5 nm. It is calibrated regularly with the self-built 1000 W lamp-assembly, a NIST calibrated 1000 W lamp and a PTB (Physikalisch-Technische Bundesanstalt, Germany) calibrated 1000 W lamp.

2.2 Short-term changes in UV-B irradiances

The analysis is based on UV irradiance measurements, and the radiative transfer model is a tool to estimate the effects of the contributing factors on the observed variability of UV irradiance. Simulations were carried out with the radiative transfer model SDISORT developed by Stamnes et al. (1988) to divide the influence of ozone, surface albedo, aerosols and clouds on UV variability. In a first step, model calculations of the actual input data solar zenith angle, total column ozone, surface albedo, clouds and aerosols are performed to reconstruct the actually measured data of the Brewer. Calculations are performed for constant solar zenith angle 63±2° for the entire period from 1994 to 2003. Then model calculations using climatological input data of the same period are performed. The daily climatology of each input variable is estimated on the basis of the 10-year data.

The influence of a specific parameter X on the variability of UV radiation is then estimated as the quotient of the modelled radiation using the actual value of parameter

X and climatological data of the remaining variables and the modelled radiation using climatic data of all variables, including parameter X. The amplitude of each parameter is calculated using Eq. (1)

$$\text{Ampl.} = \frac{\text{monthly max. of all years} - \text{monthly min. of all years}}{\text{monthly mean over all years}} \quad (1)$$

With this definition, the amplitude can be regarded as the maximum possible variability caused by the parameter X. This determining quantity is computed for each influencing parameter. The standard deviation is calculated and regarded the representative quantity for the mean variability.

2.2.1 Model input data

Ozone

Daily mean of total column ozone from Brewer measurements are input data to reconstruct the measured UV data. The daily climatology of ozone is calculated as the average of the ozone measurements from 1994 to 2003. To further reduce the high variability in the daily mean values, a moving-average filter with 13 day period (day±6) is applied.

Albedo

An algorithm is introduced that uses routine observations of snow condition (snow height, time since last snowfall) and snow line from the Austrian Weather Service to estimate the effective surface albedo in the UV range on a daily basis.

Figure 1 shows the average enhancements of irradiance at 305 nm with decreasing snowline for clear-sky and overcast conditions. The ordinate shows the quotient of the irradiance at different snowlines and the mean irradiance at a snowline of 3000 m. For

clear sky conditions and at snowline of 800 m this quotient is 1.24 (±0.04) and at snowline 1500 m it is 1.14 (±0.03). Cloudiness enhances the influence of the albedo due to multiple reflections between surface and lower bond of the clouds. 600 measurements with 8/8 cloud cover are included in Fig. 1 to represent overcast conditions. Under 8/8 cloud cover, UV irradiance at 305 nm is enhanced by a factor of 1.7 when the snowline is 800 m instead of 3000 m.

The "effective" albedo that affects the surface UV irradiance is an averaged albedo of the surrounding area. Regression analysis delivered parameterisation of the "effective" albedo, A according to Eq. (2)

$$A = 0.659 - 2.04 \cdot 10^{-4} \cdot G + 4.97 \cdot 10^{-3} \cdot N - 3.23 \cdot 10^{-3} \cdot T \quad (2)$$

In Eq. (2), G is the snow line (in m), N is the depth of the fresh fallen snow (in cm) and T is the time since the last snowfall (in days). Fresh fallen snow increases the effective albedo whereas the albedo decreases with increasing snowline and days after the snowfall. 500 cases are included developing regression Eq. (2). The explained variance of this parameterisation is 70%, and the effective albedo varies from 0.02 to 0.89. Figure 2 shows calculated values of the effective albedo at Sonnblick observatory. Climatological mean values of the albedo determined for the 10 year period are 0.3–0.6 during winter and spring and 0.09–0.25 during summer. Effective albedo of 0.63–0.78 determined for snowline 800 m is comparable to the model calculations presented by Weihs et al. (2000). Rengarajan et al. (2000) measured the albedo at the Sonnblick observatory in winter. Their experimentally determined values in the range from 0.73 to 0.78 are well comparable to the albedo values determined in this study at low snow line 800 m.

Aerosols

Observations of the direct solar radiation with Brewer spectrophotometer at five channels 306.3 nm, 310.1 nm, 313.5 nm, 316.8 nm and 320.1 nm were used for the aerosol optical depth (AOD) calculation. Figure 3 shows monthly means of the aerosol

optical depth at 306.3 nm in the period from 1997 to 2002. Optical depths of aerosols at the Sonnblick are 0.03–0.08. Using this range, the calculated variation of UV irradiation is about 3% at 305 nm (Weihs et al., 1999). These results underline the fact that aerosols have a small influence on UV irradiance in high mountainous regions.

Clouds

Model calculations in presence of clouds use the actually observed cloud cover. Cloud transmission data measured with Bentham DM150 spectrometer and cloud observations are used in the analysis. Ratios of measured UV intensities and modelled clear sky values (i.e. the cloud modification factor) for the actual zenith angle and ozone amount are used to analyze the dependence of some defined UV-B and UV-A wavelength intervals on cloud amount. The study delivers dependencies of the cloud modification factor on total cloud amount, cloud type, wavelength, solar zenith angle and ground albedo, which are used in the present investigation (Simic et al., 2006).

2.2.2 Comparison of measured and calculated absolute UV levels

Calculations of the UV irradiation are performed to test whether they can reproduce the actual irradiance measurements under clear sky condition. In Fig. 4 the ratios of measured and modelled UV irradiation at 305 nm and solar zenith angle 63° are shown for the time period 1994–2003. In 95% of the investigated cases in the time period from 1994 to 2003, the calculated UV irradiations are maximum 12% higher and 8% lower than actually measured irradiations.

2.3 Long-term changes

Long-term changes are calculated for different wavelengths (305 nm, 310 nm, 315 nm, 324 nm and CIE) and solar zenith angles (45°, 55° and 65°). Monthly mean values are calculated for each combination of wavelength and solar zenith angle for the pe-

riod from January 1994 to December 2006 except for months with too few data or too high cloud cover. The monthly climatological mean values where obtained by averaging every month over the period of investigation. The relative departures from the long-term mean values where computed by comparing monthly mean values to the climatological mean values of the respective month. The time series were checked for the existence of trends using the non-parametric Mann-Kendall (MK) trend-test (Mann, 1945; Kendall, 1975). The results of the MK test were tested against the hypothesis of no detectable trend, i.e. the data being normally distributed. This was done at several significance levels from α=0.1 down to α=0.001, where α is the probability of rejecting the alternative hypothesis erroneously. The magnitudes of the underlying trends were estimated using two methods of linear regression: the least-square method and the non-parametric Theil-Sen slope estimate (Hollander and Wolfe, 1999), the latter being less sensitive to outliers and missing values, which may occur in periods of instrument maintenance and calibration and harsh environmental conditions. The results are shown in percent per decade.

To complement the spectra and to enable data filtering for various atmospheric parameters and conditions, detailed 3-hourly cloud and snow observations from the Austrian Weather Service at Sonnblick observatory were included and appended to the appropriate UV-measurements. All spectra were checked and corrected with the SHICrivm algorithm by Slaper (2002). Additionally, the spectrums were CIE-weighted and integrated.

It was decided to check for trends in clear-sky spectra only, which means that situations with total cloud cover greater than three eighths were omitted. Further reducing the maximum allowed cloud cover would have considerably lessened the number of available data-sets. Due to the decreased variability in clear-sky irradiances as opposed to all-sky conditions, significant trends are supposed to be more easily detected in relatively short time series, as proposed by Glandorf et al. (2005).

3 Results and discussion

3.1 Short-term changes

The influences of total column ozone and albedo on 305 nm irradiance during the period 1994–2003 is shown in Fig. 5 for April (left column) and August (right column). The ordinate shows the ratio of actual data and daily climatological data. All calculations are performed for a constant solar zenith angle of 63±2° for the whole period from 1994 to 2003. Amplitude and standard deviation, as described above, are included. Maximum effect of total ozone on short-term variability of UV radiation at 305 nm is 186% in April and 102% in August. Albedo induced maximum variability is 32% in April and 14% in August. Figure 6 shows the evaluation for May, additionally considering the effects of changing cloud cover. On a short time scale, clouds can affect the irradiance at 305 nm by maximum 147%.

Model calculations are performed for each month. Table 1 summarizes the results obtained at 305 nm for the amplitude representing maximum variability and for standard deviation representing mean variability: Ozone can affect UV-irradiance on a short time scale by up to about 200% (mean variability up to about 50%). Clouds can cause variability of UV irradiance by up to about 150% (typical mean variability of about 30%). Aledo has the greatest influence on the variability of UV irradiance in April. During summer, clouds contribute to the major part of variability whilst ozone dominates during spring. This is explained by strong variability of total column ozone during winter and spring and enhanced cumulus convection during summer.

Figure 7 shows the maximum variability in monthly mean values of 305 nm irradiance caused by total column ozone, clouds and albedo. The effect of ozone on short-term variability of monthly mean irradiance can be more than 50% in spring whereas the effect of clouds is largest during summer and early autumn. Variability caused by albedo ranges from 3% to 13%. Investigations of Arola et al, 2003 show for the station Sodankylä (67° N) in Finland that the effect of total ozone on short-term variability of monthly mean UV irradiance at 305 nm can be almost 100%. The greater effect of

ozon found in arctic station Sodankylä may be expected due to the strong interannual ozon variability. Variability caused by albedo in May in Sodankylä is 21% (average at monthly level 7%) and 32% (average at monthly level 6%) is found at the Sonnblick observatory. Thus variability caused by albedo at both stations is in the same range.

3.2 Long-term changes

Figure 8 show relative departures of UV radiance from climatological monthly mean values. Wavelengths of 305 nm, 310 nm, 324 nm and CIE and solar zenith angles of 45°, 55° and 65° are shown for the time period from 1994 to 2006. Data are approximated with linear regression lines, and the results are shown in percent per decade. Trends given in the upper right corner are calculated with the Theil-Sen method. Symbols in parenthesis indicate the significance of the trend [(−): insignificant (α>0.1), (+): significant ($\alpha \leq 0.1$), (*): highly significant ($\alpha \leq 0.01$)]. In Table 2, the results of the evaluations are summarized. Calculations are also performed with the least-square method, and the obtained results coincide well in cases with highly significant trends.

For wavelength 305 nm, downward trend of −9%/dec at solar zenith angle 45° (90% confidence level) and −24%/dec at 55° (99% confidence level) are determined for the period from 1994–2006. The trend is highly significant for solar zenith angle 55°, where the largest data set is available. Analysis of 310 nm, 315 nm and 324 nm basically delivers a comparable behaviour, however the trends are somewhat smaller, i.e. the regression-line slopes becoming less negative as the wavelength increases. Trends found in CIE integrated monthly mean values consequently show to be less negative than those found at 305 nm but steeper than those at 315 nm and 324 nm.

Decrease of UV irradiance at low wavelength would suggest an increase of stratospheric ozone during the investigated time period from 1994 to 2006. Total ozone measurements with the Brewer spectrophotometer at the Sonnblick observatory however do not show this trend. In Sodnakylä, Finland spectral irradiance at 305 nm in April decreases when the time period from 1993 to 2001 is investigated whereas it increases considering the period from 1990 to 1997 (Lakkala et al., 2003). Investi-

gations of long-term variability of monthly mean solar spectral irradiance at 305 nm and 324 nm in Thessaloniki, Greece show positive trends at both wavelengths for the period 1990–2006 (Bais et al., 2007). The investigated time period has a strong influence on the calculated long-term change of spectral UV irradiance at Sonnblick observatory. When spectra measured during the time period from 1994 to 2001 are analysed, mainly positive trends are found for different wavelengths and solar zenith angles (Simic, 2005). Glandorf et al. (2005) evaluated several wavelengths and solar zenith angles of the longest spectral UV irradiance measurements in Europe, in Thessaloniki and Sodnakylä. They conclude that even the longest series are too short to show distinct trends due to the large variability of UV irradiance.

4 Summary

The influence of ozone, clouds, and surface albedo on spectral UV radiation at the Sonnblick observatory (3106 m) is investigated using continuous spectral UV-irradiance measurements and model calculations. Measurements at Sonnblick observatory starting 1994 represent the longest time series of spectral UV irradiance data in Austria and are used in the present investigation.

1. UV irradiance at wavelength 305 nm under clear sky condition is calculated and compared with the actual measurements. In 95% of the investigated cases in the time period from 1994 to 2003, the calculated UV irradiations are maximum 12% higher and 8% lower than actually measured irradiations. Essential for a good correlation of measurement and model is the determination of an effective albeo at the observatory. Determination of an effective albedo uses the snow line, the depth of the fresh fallen snow and the time since the last snowfall.

2. Measurements at Sonnblick observatory at 305 nm show a pronounced influence of snowline on the UV irradiance. Decreasing the snowline from 3000 m to 800 m

enhances the UV irradiance by factor 1.24 for clear sky conditions and by factor 1.7 for 8/8 cloud cover.

3. The effect of total ozone on short-term variability of UV irradiance at 305 nm can be more than 200% (average more than 50%). Clouds can cause variability of 150% or more (average 35%). Maximum variability caused by albedo is 32% in April (average 6%) and 12–15% in the summer moths (average 3%). In summer and autumn, total ozone and clouds strongly influence the variability of UV radiation, whereas in winter and spring ozone has the more pronounced effect.

4. Spectral UV irradiance at 305 nm, 310 nm, 324 nm and CIE and solar zenith angles of 45°, 55° and 65° from 1994–2006 is analyzed for possible trends. Significant downwards trends (99% confidence level) were found for solar zenith angle 55° at all wavelengths. At solar zenith angles of 45° and 65°, downwards trends of UV irradiance were found for several wavelengths (90% confidence level).

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Table 1. The amplitude of the influencing factors total ozone, clouds and albedo on UV irradiance at 305 nm calculated as (maximum–minimum)/mean are shown in the respective first lines. Every single measurement during the time period from 1994 to 2003 is included. Standard deviations are denoted below in italic.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ozone	2.11	2.56	1.79	1.86	1.41	1.17	1.10	1.02	1.10	1.27	1.49	1.53
	0.38	*0.56*	*0.37*	*0.33*	*0.22*	*0.20*	*0.17*	*0.17*	*0.20*	*0.20*	*0.28*	*0.27*
clouds	1.23	1.22	1.19	1.51	1.47	1.24	1.58	1.15	1.46	1.21	1.16	–
	0.30	*0.31*	*0.32*	*0.32*	*0.31*	*0.32*	*0.33*	*0.29*	*0.35*	*0.30*	*0.33*	
albedo	0.27	0.26	0.31	0.32	0.21	0.15	0.12	0.14	0.13	0.18	0.24	0.23
	0.04	*0.05*	*0.04*	*0.06*	*0.04*	*0.03*	*0.03*	*0.02*	*0.02*	*0.04*	*0.04*	*0.04*

Table 2. Linear trends in relative departures of UV radiance from climatological monthly mean values, wavelengths from 305 to 324 nm and CIE, solar zenith angles of 45°, 55° and 65° are evaluated for the time period 1994–2006. Trends are calculated with the Theil-Sen method and are given in percent per decade, symbols to the right indicate the significance of the trend [$^{-}$: insignificant (α>0.1), $^{+}$: significant ($\alpha \leq 0.1$), *: highly significant ($\alpha \leq 0.01$)].

SZA	305 nm	310 nm	315 nm	324 nm	CIE
45°	-9.5^{+}	-11.1^{+}	-10.5^{+}	-9.8^{+}	-10.3^{+}
55°	−23.9*	−19.9*	−15.6*	−14.4*	−19.5*
65°	-3.8^{-}	-5.7^{+}	-4.6^{+}	-6.0^{+}	-4.4^{-}

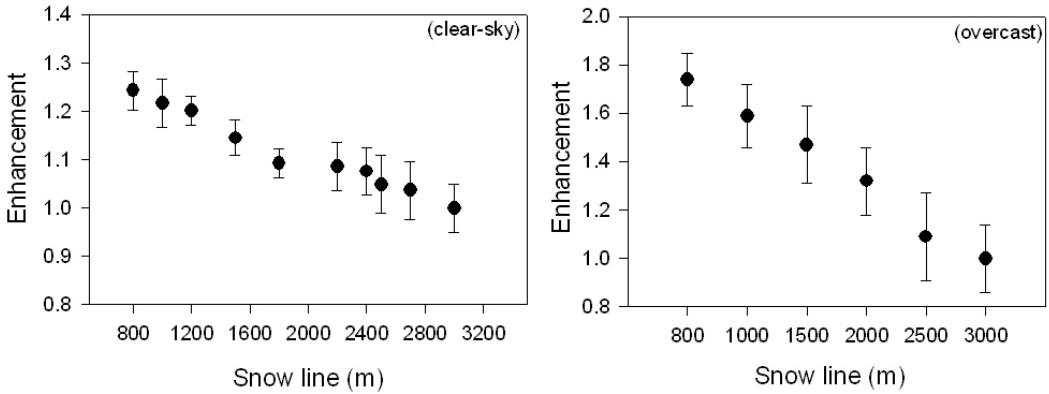

Fig. 1. Measured snow line enhancements at 305 nm for clear sky condition (left figure) and overcast condition (right figure).

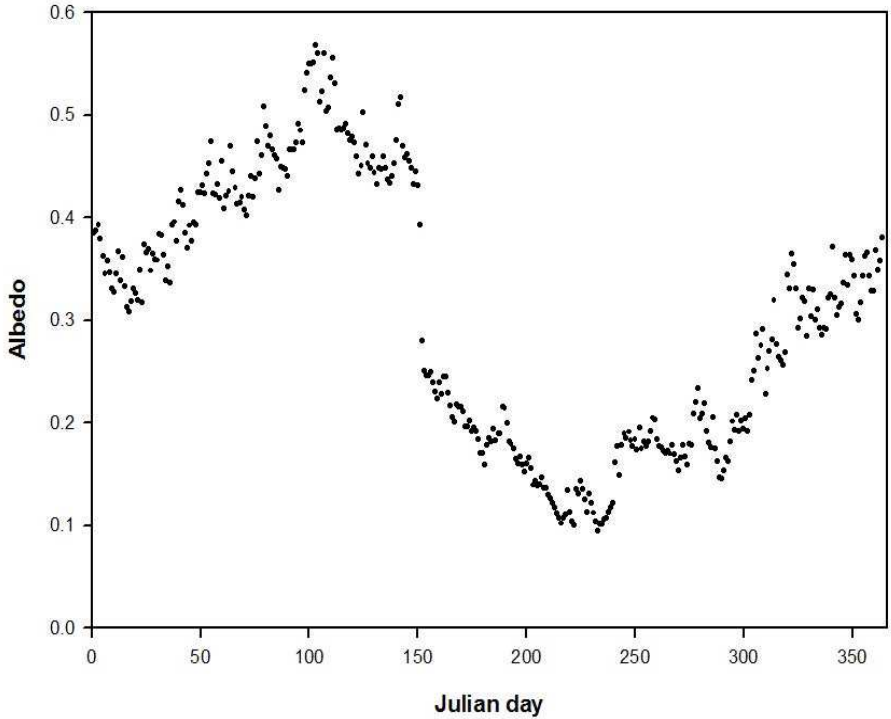

Fig. 2. Calculated daily climatological mean of effective albedo at Sonnblick observatory, computed with Eq. (1), 10-year period.

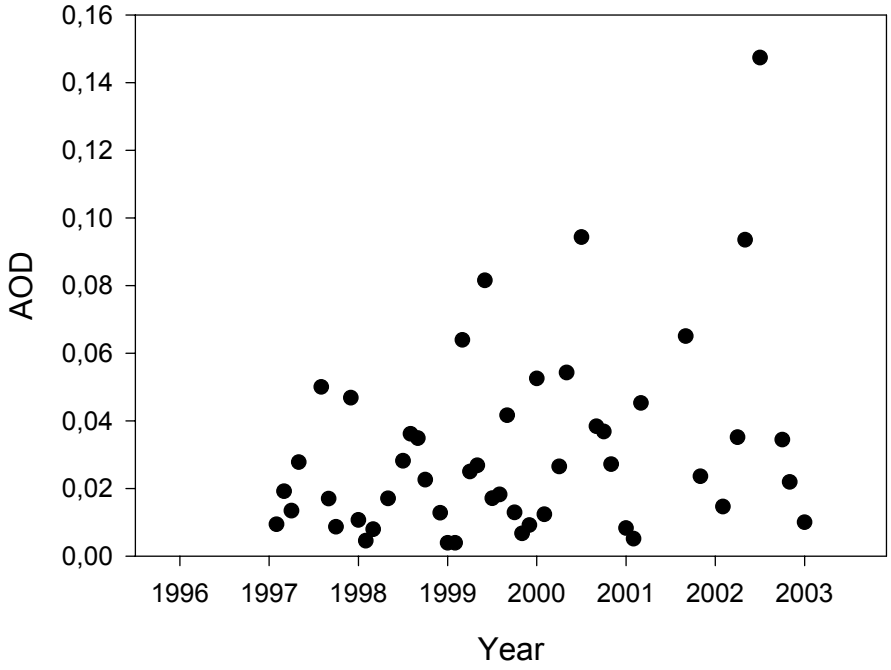

Fig. 3. Monthly means of measurements of aerosol optical depth at 306.3 nm at the Sonnblick observatory.

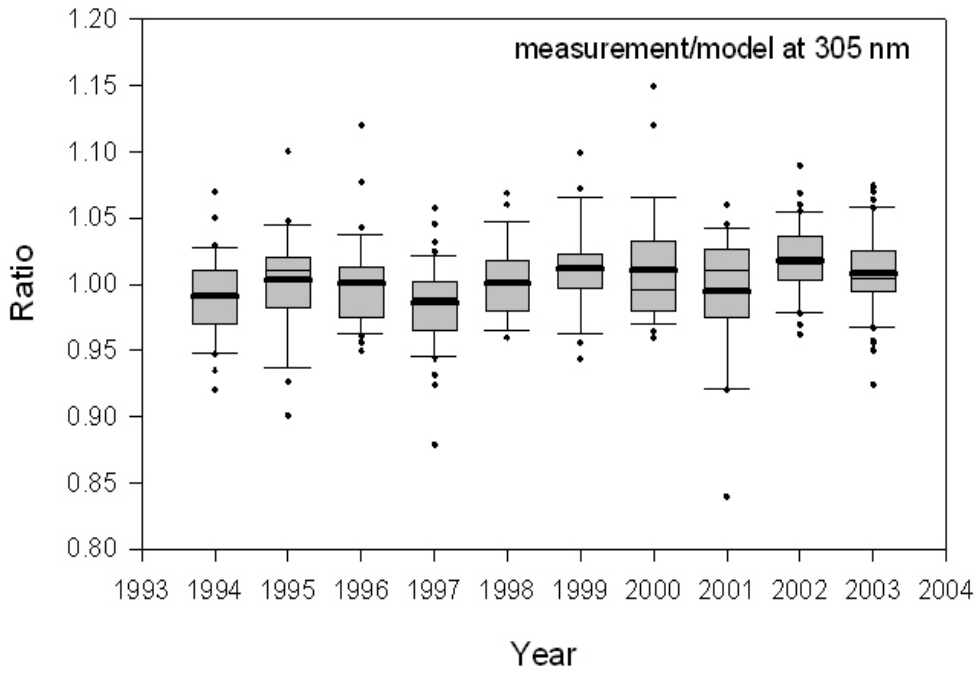

Fig. 4. Ratios of measured and modelled irradiances at 305 nm and solar zenith angle 63° in the period from 1994 to 2003 presented in a box plot diagram. The boundaries of the boxes indicate 25th and 75th percentile, and Whiskers above and below the box indicate the 90th and 10th percentiles.

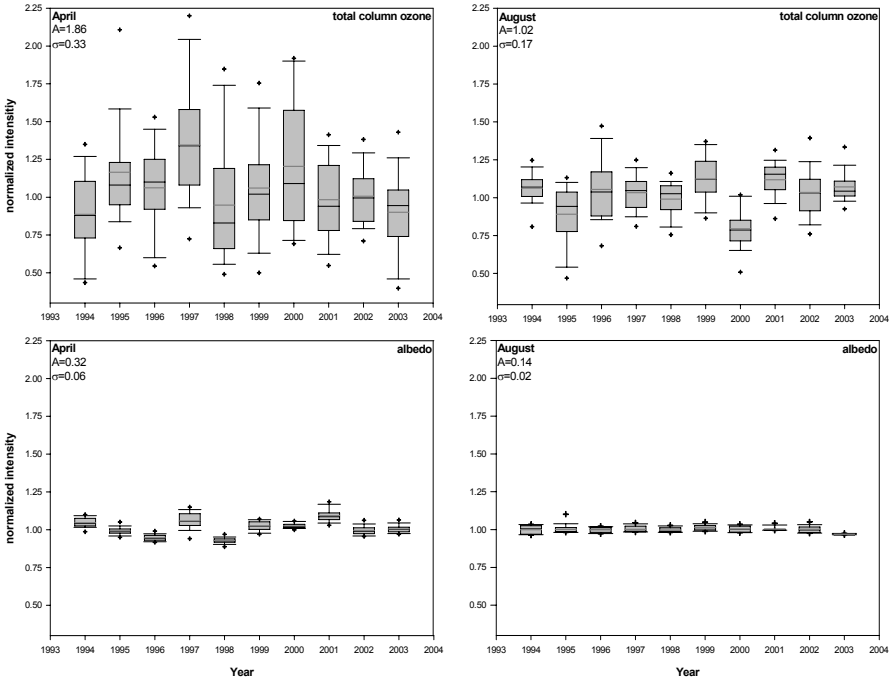

Fig. 5. Box-plot presentation of the influence of total column ozone (top row) and albedo (bottom row) on variability of UV-irradiance at 305 nm in April and August, amplitude (A) and standard deviation (σ) are shown, the boxes are bounded by the 25% and 75% quartile.

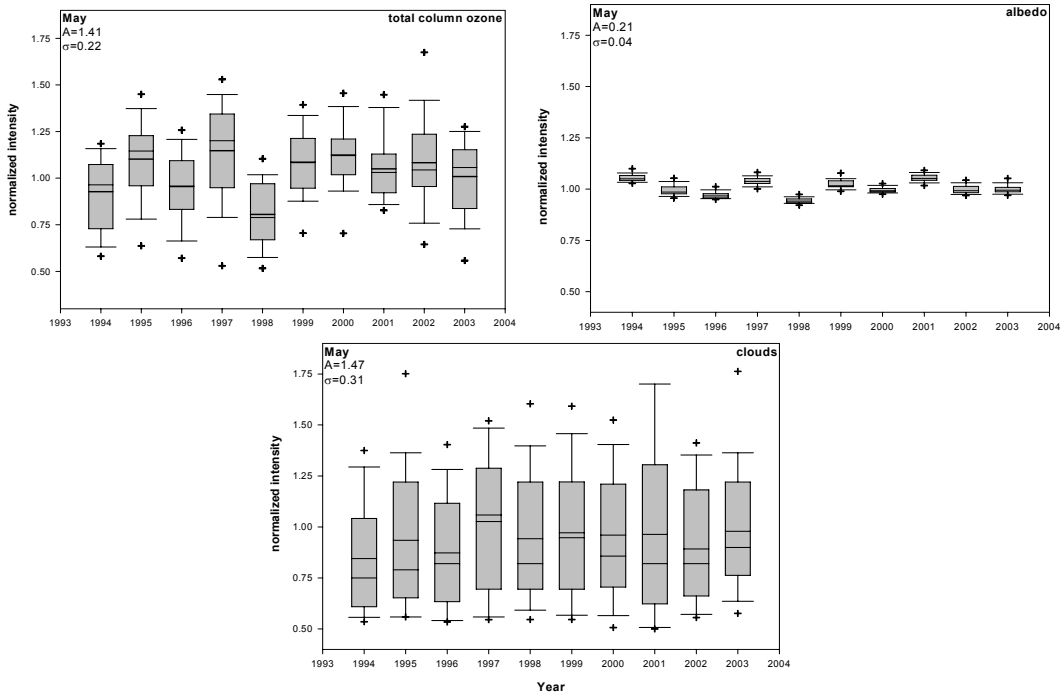

Fig. 6. Box-plot presentation of the influence of total column ozone, clouds and albedo on variability of UV-irradiance at 305 nm for May. Ozone and clouds are the governing influences whereas the contribution of albedo is small.

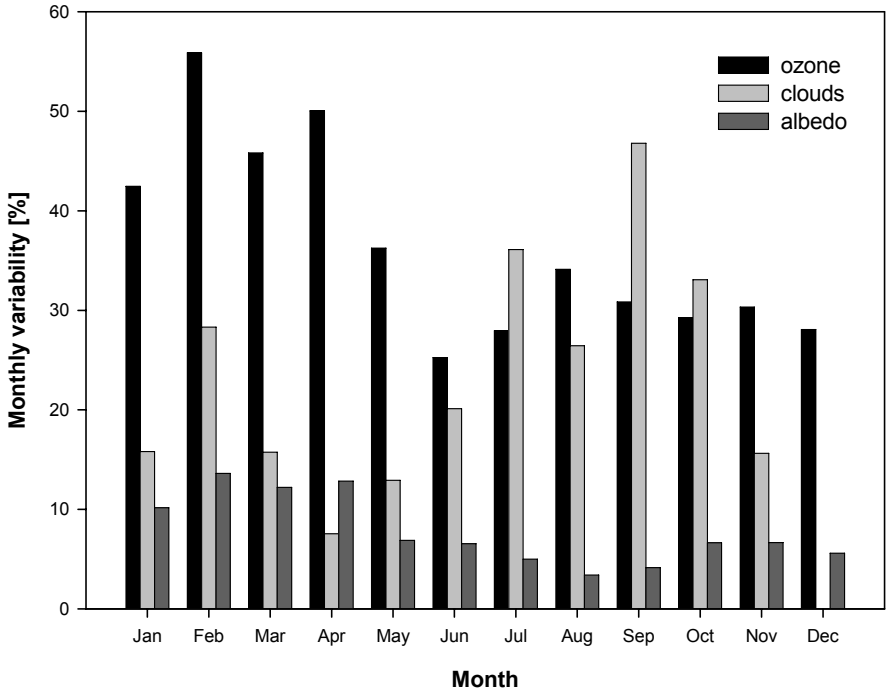

Fig. 7. Maximum variability in monthly mean values of 305 nm irradiance caused by total column ozone, clouds and albedo.

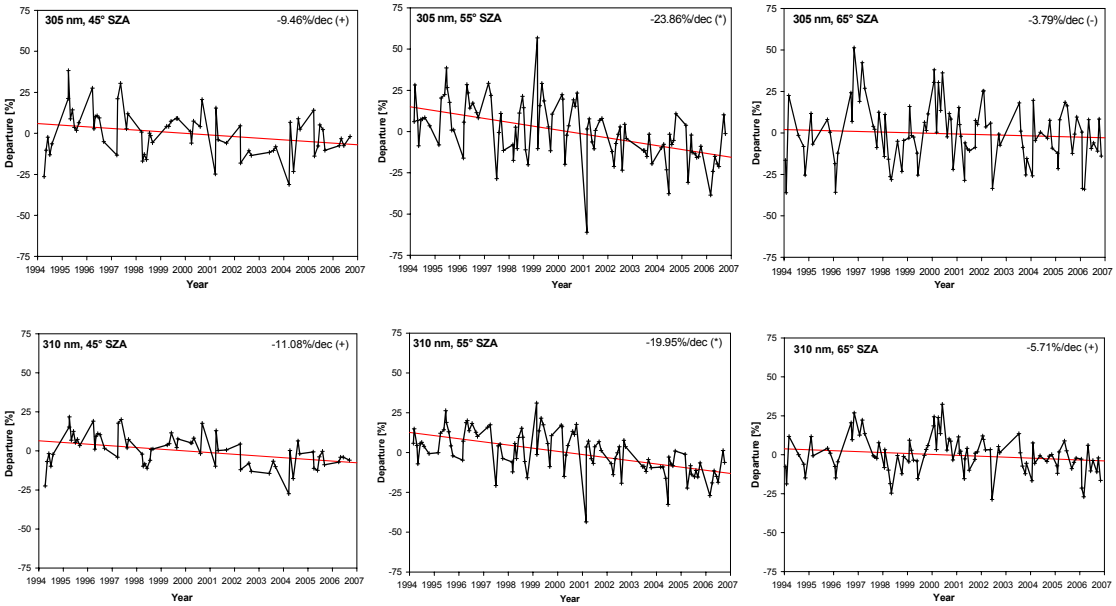

Fig. 8. Relative departures of UV irradiance from climatological monthly mean values, wavelengths of 305 nm (first row), 310 nm (second row), 324 nm (third row) and CIE (fourth row) are shown for solar zenith angles of 45° (first column), 55° (second column) and 65° (third column), data from 1994 to 2006 are approximated with linear regression lines using the Theil-Sen method, symbols in parenthesis indicate trend significance [(–): insignificant (α>0.1), (+): significant ($\alpha \leq 0.1$), (*): highly significant ($\alpha \leq 0.01$)].

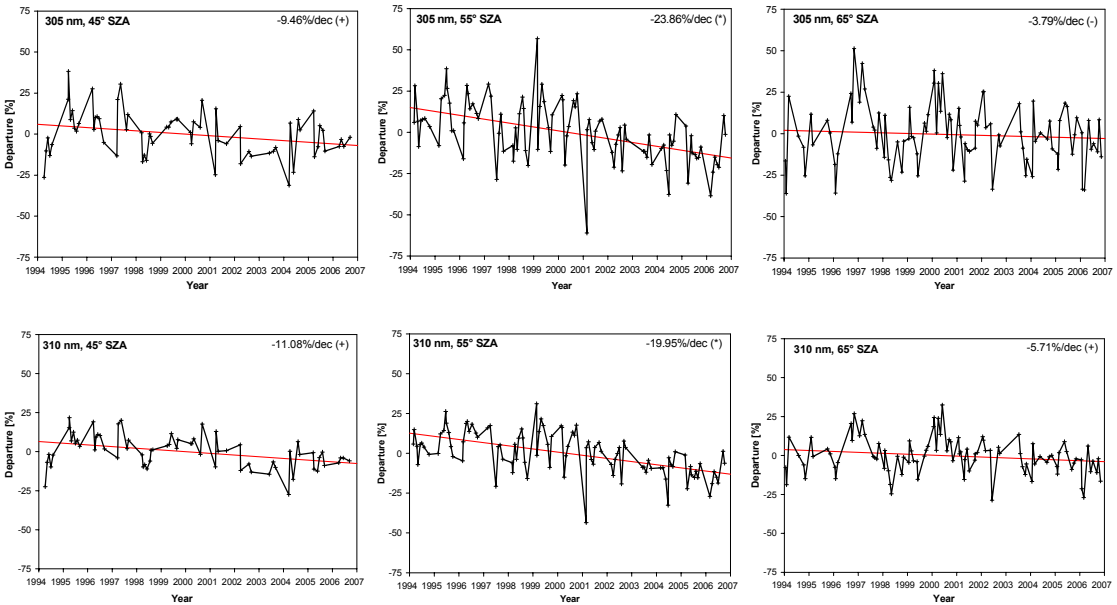

Fig. 8. Continued.

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