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Reconstruction of erythemal UV-levels for two stations in Austria: a comparison between alpine and urban regions

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Abstract

The aim of this study is the reconstruction of past UV-radiation doses for two stations in Austria, Hoher Sonnblick and Vienna, using a physical radiation transfer model. The method uses the modeled UV-radiation under clear-sky conditions, cloud modification factors and a correction factor as input variables. To identify the influence of temporal resolution of input data and modification factors, an ensemble of four different modelling approaches has been calculated, each with hourly or daily resolution. This is especially important because we found no other study describing the influence of the temporal resolution of input data on model performance. Following the results of the statistical analysis of the evaluation period the model with the highest temporal resolution has been chosen for the reconstruction of the UV-radiation doses. This model (HMC) uses modelled UV-radiation under clear sky conditions, a cloud modification factor, both with hourly resolution, and a monthly correction factor. A good agreement between modelled and measured values of erythemally effective irradiance was found at both stations. In relation to the reference period 1976–1985 an increase in erythemal UV-irradiance in Vienna of 11 percent is visible in the period 1986–1995 and an increase of 17 percent in the period 1996–2005 can be seen. At Hoher Sonnblick an increase of 2 percent has been calculated for the yearly averages in erythemal UV for the period 1986–1995 and an increase of 9 percent for the period 1996–2005 in comparison to the reference period. For the different seasons the strongest increase in erythemal UV radiation has been found for winter and spring season at both stations.

1 Introduction

Since the detection of the Antarctic ozone hole in the early 1970s (e.g. Farman et al., 1985; Stolarski et al., 1991; Gleason et al., 1993) the interest in solar UV-B increased within the scientific community and the general public because of the link between reduced ozone concentrations and increased UV radiation doses (e.g. Calbó et al.,

2005). The UV part of the solar spectrum covers only a small part of the total energy of solar radiation, but its importance is explained by the high energy of the photons in this wavelength range (e.g. Gantner et al., 2000). Solar UV radiation covers the wavelength range of 200–400 nm and is subdivided in three spectral regions known as UV-C (200–280 nm), UV-B (280–315 nm) and UV-A (315–400 nm). The boundary between UV-A and UV-B is not clearly fixed, but most international agencies and consortia agree establishing the boundary at 315 nm (World Health Organization, 2002; European Union's action COST 713 (Vanicek et al., 2000); Commission Internationale de l'Eclairage, 1999; International Agency for research on Cancer, 1992).

Clouds, solar zenith angle and total ozone amount are the most important factors influencing UV radiation at ground levels (e.g. Burrows, 1997; Kerr, 2003). Stratospheric ozone is especially important because it is the major atmospheric absorber of solar UV-B (280–315 nm) radiation (e.g. Matthijsen et al., 2000; UNEP, 1998).

Long-term measurements of UV radiation are rare and datasets are only available for some locations. Also most of these measurements do not provide spectral information on the UV part of the spectra. Knowledge of past UV radiation levels is of increasing interest in order to estimate long-term biological effects (e.g. Reuder and Koepke, 2005). An increase in UV doses may lead to a broad variety of environmental and health effects (e.g. National Radiological Protection Board, 2002; UNEP, 1998; Slaper et al., 1996). The eye, the immune system and the skin are the three major organ systems of humans which are commonly exposed to sunlight and for all of them health effects regarding solar UV radiation have been documented (WHO, 2006; 1994; Longstreth et al., 1998). Among the most important biological effects of UV radiation are the development of skin cancer, pigmentation and erythema, aging effects and diseases related to the eyes like photokeratitis and photoconjunctivity. The erythema is probably the most widely experienced form of acute solar injury to the skin (Longstreth et al., 1998). Further various epidemiological studies have addressed the relative contributions of UV radiation to photocarciogenesis, in particular with regard to the development of melanoma (Setlow, 1974; Moan et al., 1999; Woodhead et al., 1999). A decrease in

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global ozone concentration of about 10 percent would lead to an increase in skin cancer cases of 300 000 per year (IPCS, 1994). Climate Change may also have an effect on future UV radiation doses reaching the earth's surface through changes in cloud amount, cloud properties and surface albedo (e.g. Lindfors and Vuilleumier, 2005).

Increased research activities in the field of UV radiation have led in the last years to worldwide monitoring of UV radiation levels (e.g. Seckmeyer et al., 1995), a better understanding of the atmospheric processes that influence the UV part of the spectra (e.g. Weihs and Webb, 1997a, b; Schwander et al., 1997) and the development of modelling approaches for the reconstruction of past UV radiation levels (e.g. Lindfors and Vuilleumier, 2005; Reuder and Koepke, 2005; Kaurola et al., 2000; Gantner et al., 2000).

Recent studies have shown that models may be able to reconstruct past UV levels with an accuracy between 5 and 15 percent (Fioletov et al., 2001; Kaurola et al., 2000; Reuder and Koepke, 2005). Most of them were based on daily values. A few studies however already use hourly meteorological input data (Reuder and Koepke, 2005; Den Outer et al., 2005). The exact improvement in accuracy by using hourly data has however not really been investigated. Only a few studies have given a statement on the exact magnitude of the meteorological factors influencing reconstructed UV levels (e.g. Lindfors and Vuilleumier, 2005; Reuder and Koepke, 2005).

During the last decade reconstruction studies for several regions in Europe, especially in Nordic and central European countries, have been performed (e.g. Lindfors et al., 2003; Lindfors and Vuilleumier, 2005; Reuder and Koepke, 2005; Den Outer et al., 2005). To the knowledge of the authors no study on the reconstruction of UV levels in a high alpine region above 3000 m has been performed. Lindfors and Vuilleumier (2005) reconstructed erythemal UV-radiation for the alpine station Davos, which is located on an altitude of 1850 m a.s.l., but this is still 1256 m lower than the station Sonnblick used in this study. During the present study the first reconstruction for an alpine site, located at more than 3000 m. a.s.l, was performed. The unique location of the mountain observatory at Hoher Sonnblick in Europe provides an opportunity to reconstruct solar UV

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for a high altitude alpine site and to investigate the influence of topography connected with high ground albedo and very low atmospheric pollution levels on UV trends.

The present study investigates first the influence of different temporal resolutions of input data on the reconstruction accuracy, it then performs a reconstruction for one high altitude alpine site and one low altitude site and investigates the contribution of the different meteorological parameters on the changes in UV. The investigation of changes in UV for the low altitude site of Vienna is especially of interest because this region is, with its 1.6 million inhabitants, the most populated one in Austria. These are to the knowledge of the authors new aspects in the domain of UV reconstruction.

2 Data

The Austrian national UV Monitoring network has been in operation since 1998 and has 12 stations all over the country. As already mentioned two stations out of this network have been selected to reconstruct past UV-levels. One station the Observatory Sonnblick (47°03′ N,12°57′ E) is located in the central alps at an altitude of 3106 m. The other one, Vienna (48°15′ N,16°26′ E), is located in the north-eastern part of the country at an altitude of 153 m. These two stations have been selected because of their significant differences in altitude, terrain and meteorological conditions. The data used in this study include UV erythemally weighted broadband irradiance, global irradiance, sunshine duration, snow height and snow cover as well as total ozone column.

2.1 UV Data

In 1996, the setup of an Austrian UVB monitoring network was initiated by the Federal Department of Environment (Blumthaler and Schauberger, 2001). Now it consists of 12 broadband detectors for measuring erythemally weighted solar UV irradiance at locations between 153 m and 3106 m a.s.l.. All detectors are calibrated each year in the laboratory of the Division for Biomedical Physics, Innsbruck Medical University.

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The relative spectral response of each detector is determined and by comparison with a double monochromator spectroradiometer the absolute calibration function is derived in dependence on solar zenith angle and on total atmospheric ozone (Blumthaler, 2004). The uncertainty of the calibration is about ±7% (at 95% confidence level) for solar zenith angles <75°, which is dominated by the uncertainty of the calibration lamp for the spectroradiometer (±4%). During routine operation, the measurements of all detectors are transmitted in near real time to the laboratory and then converted to UV-Indices, the internationally agreed unit for erythemally weighted solar irradiance. The results are then published on the internet (http://www.uv-index.at) every 15 min., together with a regional map showing the distribution of the UV-Index over Austria by combining the information from the measurement detectors with cloud information from Meteosat Second Generation.

3 Input data

3.1 Total ozone

The total ozone content, usually given in Dobson Units (DU), is one of the most important parameters affecting UV-B radiation at the ground. Ground based measurements by Dobson (e.g. Dobson, 1931; Komyhr, 1980) and Brewer (e.g. Brewer, 1973; Kerr and McElroy, 1995) instruments are the most accurate and widely used method for the determination of atmospheric total ozone content. Because of the lack in local ozone data before 1994 at Hoher Sonnblick and the absence of ozone measurements in Vienna additional datasets from satellite, ground measurements as well as ozone model simulations have been used. The total ozone record from Arosa is the world's longest, dating back to 1926. This record has been homogenized and is discussed in detail by Staehelin et al. (1998a, b). In addition the simulated total ozone values over Europe have been calculated within the objectives of European Union's Action COST-

726 project (Krzyścin, 2008[1]). The ozone reconstruction model was trained on satellite data (NIWA assimilated total column ozone data base) over the period 1979–2004. The ozone values were reconstructed backward in time using the regression constants derived as a result of the training, time series of various atmospheric indices of the atmospheric circulation, and the meteorological variables. The quality of the data base is assured by a comparison of the modeled total ozone with the ground-based data taken at several Dobson stations which have been in operation since the early 1950s and 1960s.

A comparison against the measured daily total ozone over Arosa provides that the mean difference, [(Model – Observation)/Observation]*100%, is 1.5%±4.5% for the period 1976–2004. A high correspondence between the modeled and measured total ozone values over Arosa is also corroborated by Fig. 1a. The model estimates total ozone values at sea level pressure, thus an equivalent of measured total ozone at Arosa (site altitude ∼1600 m) should be lowered of ∼1.5% because of the altitude effects, i.e. ∼1%/km decrease of total ozone is approximated from an assumption that ∼10% of column ozone content is in the troposphere.

We compared the modeled daily total ozone values for Arosa and Vienna (or Hoher Sonnblick), to find a relation between the ozone values for these sites. The mean difference, [(Model_Vienna – Observation_Arosa)/Observation_Arosa]*100%, is 4.0%±6.5% and the correlation coefficient between the modeled values for Vienna and the observed ozone at Arosa is 0.92 (see also Fig. 1b). Moreover, the mean difference between modeled daily ozone values for Vienna and Arosa (the altitude effect is not included) is 2.5% for the period 1976–2004. Thus, the measured Arosa total ozone should be enlarged by 4.0% to be representative for Vienna. Similar calculations done for Hoher Sonnblick show that measured total ozone for Arosa corresponds to total ozone that would be expected over Hoher Sonnblick at altitude 3100 m (see also Fig. 1c) for a correspondence of modeled total ozone values for these sites). Moreover,

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[1]Krzyścin, J. W.: Statistical reconstruction of daily total ozone over Europe 1950 to 2004, J. Geophys. Res., submitted, 2008.

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the comparison of the measured monthly averages between the Austrian ozone data set and those from Arosa shows that the differences are not higher than ±3%. We may therefore use the measured total ozone at Arosa to cover the whole period for Austria. The ozone record of Arosa has some periods of missing data (see Staehelin et al.,
5 1998a, b) and for these periods missing values are filled up by the modeled COST-726 total ozone.

3.2   Cloudiness, global irradiance and sunshine duration

The use of cloud modification factors (CMFs), gained from information on global irradiance and sunshine duration, is a common method used by the scientific community to
10 describe cloud effects on solar UV radiation (e.g. Kaurola et al., 2000; Schwander et al., 2002; Koepke et al., 2006).

European Union's Action COST 726 identified global irradiance in combination with cloud modification factors (CMFs) as the best way to describe cloud attenuation and cloud effects on solar UV (Koepke et al., 2006). We therefore used global irradiance
15 data and sunshine duration only if global irradiance data were missing. Global irradiance and sunshine duration have been measured at both stations by the Austrian Central Institute for Meteorology and Geodynamics (ZAMG). The time series for global irradiance and sunshine duration at Hoher Sonnblick is dating back to the year 1972 while at Vienna information is available since the year 1960. The global irradiance time
20 series has some gaps at station Hoher Sonnblick (see Table 1). Sunshine duration was therefore used to fill the gaps. Sunshine duration was used to distinguish between clear-sky and cloudy conditions and to reconstruct global irradiance levels for some periods of the used time series. More information will be given in Sect. 4.3. Two have comparable time periods at both stations the period 1976–2005 has been chosen for
25 further analysis. A detailed overview of datasets used in this study is shown in Table 1.

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3.3 Ground albedo, snow depth and snow amount

Snow depth and snow amount are the most important factors influencing surface albedo in the UV range of the spectra and the relationship has been well studied (Blumthaler and Ambach, 1988; McKenzie et al., 1998; Weihs et al., 1999; Kylling et al., 2000; Weihs et al., 2001; Schmucki et al., 2002). The data on snow depth and snow amount used in our study were measured by the Austrian Central Institute for Meteorology and Geodynamics (ZAMG). At Hoher Sonnblick measurements on snow depth and snow amount are available since 1972 while in Vienna information is available since 1960. Snow cover is the most important parameter for the calculations of the surface albedo (see Sect. 4.1).

4 Methods

As already mentioned in Sect. 3.2., we used information on global irradiance instead of sunshine duration to calculate past UV levels. For the reconstruction an approach similar to the one described by Kaurola et al. (2000) has been used. The use of cloud modification factors (CMFs) to model erythemal UV irradiance for skies with broken cloudiness in combination with a clear-sky model is a commonly used method (e.g. Thiel et al., 1997; Schwander et al., 2002; Koepke et al., 2006; Kaurola et al., 2000).

Kaurola et al. (2000) used modelled clear-sky UV values, a cloud modification factor for global irradiance and a correction factor in their study (Eq. 1). Here UV_{REKO} is the reconstructed UV-radiation, UV_{MOD} is the modelled UV-radiation under clear-sky conditions, CMF_{SOL} is the cloud modification factor for global irradiance and C is a seasonal correction factor.

$$UV_{REKO} = UV_{MOD} * CMF_{SOL} * C \tag{1}$$

For our purpose we have modified this approach for different temporal resolutions which are discussed in detail in Sect. 4.4 of this paper.

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4.1 Calculating surface albedo values

Because of the altitude the influence of snow cover on ground albedo is more important at the alpine station Hoher Sonnblick than in Vienna. For the calculation of surface albedo values we used a multiple regression model (Simic et al., 2005), using snow height (SNOW), amount of fresh snow (NSNOW) and days since last snow fall (DAYS) at Hoher Sonnblick. The calculation for spring (March, April, May) and winter (December, January, February) is shown in Eq. (2) while the calculation for summer (June, July, August) and autumn (September, October, November) is given in Eq. (3).

$$Albedo = 0.156 + 2.27 * 10^{-4} * SNOW + 4.01 * 10^{-3} * NSNOW - 1.954 * 10^{-2} * DAYS \qquad (2)$$

$$Albedo = 0.138 + 6.99 * 10^{-4} * SNOW + 6.06 * 10^{-3} * NSNOW - 1.489 * 10^{-2} * DAYS \qquad (3)$$

In Vienna snow cover is less frequent and we used fixed ground albedo values for snow covered and snow free ground conditions. If a snow height of more than 5 mm was reported in Vienna we used a value of 0.4, if the snow cover was below this value we used a value of 0.03 to describe the surface albedo.

4.2 Modelling clear-sky UV-Values

To model clear-sky UV radiation the model SDISORT developed by Stamnes et al. (1988) has been used. This model needs information on date, time, location, altitude, solar zenith angle, total ozone column, surface albedo and aerosol optical depth as input parameters. Using SDISORT we calculated clear-sky UV levels on hourly resolution (UV_{MODEL}).

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4.3 Reconstruction of global irradiance

At station Hoher Sonnblick the global irradiance dataset had some gaps in the years 1973, 1981, 1983, 1984, 1988 and 1990. Global irradiance is needed to calculate the cloud modification factors for global irradiance. We modified an approach developed by Neuwirth (1979) for the reconstruction of monthly mean values of global irradiance (see Eqs. 4 and 5), whereas G_{OBS} is the observed global irradiance, G_{POT} is the potential global irradiance, a and b are correction factors, n is the observed sunshine duration and N is the potential maximum sunshine duration.

$$\frac{G_{OBS}}{G_{POT}} = a + b \left(\frac{n}{N}\right) \tag{4}$$

$$G_{OBS} = a + b \left(\frac{n}{N}\right) * G_{POT} \tag{5}$$

For our study we adapted the model for hourly values (Eq. 6). Where G_{MODEL} is the modelled global irradiance, G_{REF} is the reference global irradiance under clear-sky conditions, X is a correction factor dependent on observed sunshine duration and N is the potential sunshine duration.

$$G_{MODEL} = G_{REF} * X * N \tag{6}$$

Using this modelling approach 90% of the modelled global irradiance values agree within ±20% of the observed ones.

4.4 Calculation of cloud modification and correction factors

The cloud modification factor for global irradiance (CMF_{SOL}) is calculated as shown in Eq. (7) as ratio between observed (G_{OBS}) and reference global irradiance (G_{REF}) for each solar zenith angle (za).

$$CMF_{SOL} = \frac{G_{OBS_{(za)}}}{G_{REF_{(za)}}} \tag{7}$$

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Corresponding to the cloud modification factors for global irradiance a CMF for the UV part of the spectra (CMF_{UV}) has been calculated (Eq. 8). The CMF_{UV} is calculated as ratio between observed UV radiation (UV_{OBS}) and modelled clear-sky UV radiation (UV_{MOD}) for each solar zenith angle (za). The CMF values were stored in look up tables for a solar zenith angle range between 19° and 90° using 2 degree intervals.

$$CMF_{UV} = \frac{UV_{OBS(za)}}{UV_{MOD(za)}} \tag{8}$$

The correction factor C has been calculated as ratio between CMF_{SOL} and CMF_{UV} (see Eq. 9).

$$C = \frac{CMF_{SOL}}{CMF_{UV}} \tag{9}$$

4.5 Analysis of the influence of different temporal resolutions on the model performance

To analyse the influence of temporal resolutions of input data, cloud modification and correction factors, 4 modelling approaches with different temporal resolution were developed (Eqs. 10 to 13).

$$UV_{HMC} = UV_{MOD(H)} * CMF_{SOL(H)} * C_M \tag{10}$$

$$UV_{HSC} = UV_{MOD(H)} * CMF_{SOL(H)} * C_S \tag{11}$$

$$UV_{DMC} = UV_{MOD(D)} * CMF_{SOL(D)} * C_M \tag{12}$$

$$UV_{DSC} = UV_{MOD(D)} * CMF_{SOL(D)} * C_S \tag{13}$$

$UV_{MOD(H)}$ is modelled clear-sky UV radiation on hourly resolution, $UV_{MOD(D)}$ is modelled clear-sky UV radiation on daily resolution, $CMF_{SOL(H)}$ is a cloud modification factor for

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global irradiance on hourly resolution and $CMF_{SOL(D)}$ an average daily cloud modification factor for global irradiance, C_M is a monthly correction factor and C_S a seasonal correction factor.

For each station we defined two independent data sets: a 2 year development period and a 2 year testing period. The performance of our 4 models is quiet different throughout the year. Table 2 shows the correlation, root mean square error and bias between estimated and observed daily UV doses for the different seasons of the year for all 4 modelling approaches. At station Hoher Sonnblick the HMC-Model shows the best fit between estimated and observed UV doses for all 4 seasons. In Vienna the HMC-Model shows the best fit during the winter, spring and summer seasons while in autumn the reconstruction quality of the HMC, HSC and DMC are similar.

A more quantitative way to look on the performance of our reconstruction approaches for both stations can be seen in Table 3 (for Vienna) and Table 4 (for Hoher Sonnblick). It is obvious that the reconstruction quality significantly decreases with increasing temporal resolution of the input data. Altogether, most of the day-to-day variation is captured fairly well by our models and the results are comparable to those from other studies (Lindfors and Vuilleumier, 2005; Reuder and Koepke, 2005; Kaurola et al., 2000). The performance of the single models on monthly timescale is even better. The results in Tables 3 and 4 also point out that the performance of our reconstruction method is slightly better at Hoher Sonnblick than for Vienna. Possible reasons for that will be discussed later in this paper.

4.6 Performance of the HMC-Model

Figures 2 (Sonnblick) and 3 (Vienna) show the correlation between observed and modelled UV irradiance for the testing period using the HMC-Model for the different seasons. The results show a good agreement throughout the year. The correlation coefficient for all seasons is between 0.96 and 0.98 at Hoher Sonnblick and 0.96 and 0.99 at Vienna. The Bias is between −8 and +1 percent at Hoher Sonnblick and between −1 and +7 percent in Vienna. The values of the root mean square error are between +18

and +11 percent at Hoher Sonnblick and between +26 and +13 percent in Vienna.

5   Results

The results of the statistical analysis of the testing period (Sect. 4.5) showed that the model with the highest temporal resolution (HMC) shows the best agreement between observed and modelled UV values. Using the method described above, the hourly and daily erythemal UV doses at Hoher Sonnblick and Vienna were estimated for the last decades. The following comparison concentrates on the period 1976–2005 in order to have a comparable 30 year period of data at both stations.

Figure 4 shows the yearly averages of estimated UV doses compared with the strato-spheric total ozone content since 1976 for both stations. In comparison to the reference period 1976–1985 we found an increase in the yearly averages of erythemal UV radiation for the period 1986–1995 of 11% in Vienna and 2% at Hoher Sonnblick and for the period 1996–2005 of 17% in Vienna and 9% at Hoher Sonnblick. Figure 5 shows the yearly averages of estimated UV doses and relative sunshine duration since 1976 for both stations. The results of the calculated averages of erythemal UV radiation and atmospheric total ozone content are plotted in Fig. 6a–d for each season separately. The plots of the seasonal averages of erythemal UV radiation compared to the relative sunshine duration are shown in Fig. 7a–d.

5.1   Total ozone column

Compared with the reference period 1976–1985 we found for the total ozone column during the period 1986–1995 an average reduction of 5% for winter, 4% for spring and 2% in summer and autumn. For the period 1996–2005 an average reduction in the ozone content of 4% for the winter months, 6% for spring, 4% for summer and only 1% for autumn was found. For the yearly averages we found a reduction in total ozone of 4% for the period 1986–1995 and of 5% for the period 1996–2005 in comparison to the

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reference period.

5.2 Relative sunshine duration

For the period 1986–1995 in Vienna we found an increase in relative sunshine duration of 20% in winter, 2% in spring, 11% in summer and 2% in autumn in comparison to the reference period 1976–1985. For the second period 1996–2005 we found in comparison to the reference period 1976–1985 an increase of 10% in winter, 13% in spring, 14% in summer and no change in autumn. At Hoher Sonnblick we found an increase in relative sunshine duration of 18% in winter and 5% in summer for the period 1986–1995 in comparison to 1976–1985. For the same period we found a decrease in relative sunshine duration of about 2% in spring and 6% in autumn. For the period 1996–2005 we found an increase in relative sunshine duration of 17% in winter, 10% in spring and 8% in summer in comparison to the reference period. In the same time interval the dataset for autumn shows a decrease of 3% in comparison to the reference period. For the yearly averages of relative sunshine duration we found an increase during the period 1986–1995 of 4% in Vienna and 3% at Hoher Sonnblick while we found an increase of 7% at both stations for the period 1996–2005 in comparison to the reference period 1976–1985.

5.3 Erythemal UV-radiation

For the period 1986–1995 we found an increase in erythemal UV-radiation in Vienna of 29% in winter, 9% in spring and autumn and 12% in summer in comparison to the period 1976–1985. During the period 1996–2005 the erythemal UV-radiation increases in Vienna at about 18% in winter, 20% in spring, 15% in summer and 11% in autumn. During the 1986–1995 period the erythemal UV-radiation at Hoher Sonnblick increases about 14% in winter and 7% in spring. Within the same time interval a small reduction of only 1% can be stated for autumn. Also during 1996 to 2005 there is remarkable increase of the erythemal UV-radiation at about 22% in wintertime, 19% in the spring

months and 10% in autumn. Surprisingly there is no change during the summer within both periods related to the reference time.

5.4 Influence of ozone and sunshine duration on erythemal UV-radiation

To identify the influence of total ozone content and sunshine duration on the erythemal UV-radiation doses we performed model simulations holding atmospheric ozone content and sunshine duration fixed at 1960s levels. We calculated the influence of changes in total ozone content on erythemal UV following Eq. (14) and the influence of changes in cloud cover following Eq. (15).

$$M\_TOC = \frac{UV_{KSD}}{UV_{REKO}} * 100 \tag{14}$$

$$M\_SD = \frac{UV_{KTOC}}{UV_{REKO}} * 100 \tag{15}$$

Where M_TOC is the change in erythemal UV through the influence of total ozone, M_SD is the change in erythemal UV through the influence of changes in cloudiness, UV_{REKO} is the reconstructed UV under observed conditions, UV_{KSD} is reconstructed UV holding cloudiness constant on 1960s levels, UV_{KTOC} is reconstructed UV holding total ozone concentration fixed on 1960s levels.

Using this technique we found out that changes in the atmospheric total ozone content play in most cases the dominant role in influencing erythemal UV-radiation changes at both stations (Tables 6 and 7). In Vienna during the period 1986–1995 for winter, summer and autumn more than 60% of the changes in erythemal UV result from changes in atmospheric ozone concentration. During spring season about 88% of the changes in erythemal UV result from the decrease in stratospheric ozone content. For the period 1996–2005 we found similar results. Here about 60% of the changes in erythemal UV arise from changes in total ozone concentration during spring, summer and autumn. During winter we found that 70% of the changes in erythemal UV result

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from changes in total ozone and only 30% arise because of the increase in relative sunshine duration. At Station Hoher Sonnblick during the period 1986–1995 an equal influence of changes in stratospheric ozone content and sunshine duration during winter and summer was found. Half of this increase in erythemal UV occurs through a decrease in total ozone content, the other one through the increase in sunshine duration. During springtime the decrease in stratospheric ozone is the major influencing factor on erythemal UV-radiation. The small decrease in sunshine duration shows almost no effect on the erythemal UV dose. In autumn the small decrease in erythemal UV-radiation results only from decrease in relative sunshine duration. In the period 1996–2005 during winter, 60% of the changes in erythemal UV-irradiance result from decreasing stratospheric ozone concentrations. For spring and summer, change in the erythemal UV is due to changes in cloudiness and changes in stratospheric ozone content. For autumn the control run shows a decrease in erythemal UV resulting from the decrease in cloudiness. Because of that the decrease in total ozone concentration is the main cause for the overall increase in erythemal UV. The results for the different periods of the year are summarized for both stations in Table 6. About 66% of the changes of the yearly averages of the erythemal UV radiation results from changes in the total ozone concentration, whereas 34% are caused through changes in cloudiness. The changes in yearly averages of erythemal UV at Hoher Sonnblick during the period 1986–1995 are partly caused by decreasing atmospheric ozone concentrations and partly by changes in cloudiness. For the period 1996–2005 we found that the major influence on the average change in erythemal UV was total ozone. Here 78% of the changes in erythemal UV are caused by decreasing atmospheric ozone concentrations. These results are summarized in Table 7.

6   Summary and discussion

In our study we performed the first reconstruction for erythemal UV irradiance in Austria for one alpine and one urban region. A method developed by Kaurola et al. (2000)

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was adjusted to our meteorological stations. The method, which is fairly simple uses modelled clear-sky UV-radiation, cloud modification factors and correction factors and enables the estimation of UV radiation at Hoher Sonnblick and in Vienna for the last decades. For the modelling of clear-sky UV radiation we used SDISORT developed by Stamnes et al. (1988), which needs information on date, time, location, altitude, solar zenith angle, ground albedo, total ozone column and optical thickness of the atmosphere as input parameters. Further we analysed the influence of temporal resolution of input data, cloud modification factors and correction factors on the model performance. The improvement in modelling accuracy by changing the time resolution could therefore be estimated. The results of the testing period show clearly that those modelling approach using input data and modification factors with the highest temporal resolution shows the best fit between estimated and observed UV doses. The improvement of the accuracy achieved with hourly resolution varies with the seasons. In average the use of hourly resolution improves the accuracy of the reconstruction by 4% in Vienna and 8% at Hoher Sonnblick. For the different seasons we gain an improvement in the reconstruction quality in Vienna of 1% in winter and summer, 3% in autumn and 11% in spring. At Hoher Sonnblick the use of hourly data with monthly correction factors improves the reconstruction quality by 6% in autumn and 8% in the other seasons in comparison to the use of daily datasets.

The estimated UV doses using the HMC-Model were found to be in good agreement with measurements and the results are comparable to those from other studies. Especially the modelled monthly values are in good agreement with the observed ones. At Hoher Sonnblick all cases can be found within ±15% of the observed ones while at Vienna 96% of the cases can be found within ±15% of the observed values. It is important to note that the agreement between estimated and observed values is higher at station Hoher Sonnblick which might be due to the determination of surface albedo using a regression model while in Vienna fixed values depending on the presence or absence of snow cover have been used to describe the surface albedo. This has to be done because there have been only a few measurements of surface albedo under

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snow cover in the UV part of the spectrum in Vienna.

In addition aerosol loading was assumed constant during the period of our study. Since aerosol concentration is much higher in Vienna than at Sonnblick it may have larger effects on calculation uncertainty in Vienna than at Sonnblick. The measured CMF in the short wave length range may partly take into account the turbidity but it may be insufficient to characterize the full aerosol effects in the UV. But aerosol optical thickness has fortunately not increased much in central Europe since 1980 (Tegen et al., 2000). Another source of uncertainty was the lack of total ozone data in Vienna and at Hoher Sonnblick before the year 1994. Alternative ozone data from Arosa (CH), satellite data and ozone data obtained from modelling (see Sect. 3.1.) had therefore to be used. We compared the monthly means of total ozone concentration between Hoher Sonnblick and Arosa and there we found that the difference in the period 1994–1998 did not exceed ±3 percent. Through the results of a careful statistical analysis we finally believe that the alternative ozone dataset used in periods with missing total ozone observations over Arosa should not be a major source of uncertainty because on the one hand atmospheric ozone concentrations are spatially quite homogeneous and on the other hand we developed our correction factors with data obtained with the alternative dataset of total ozone (COST-726 total ozone data base providing high quality daily ozone data covering whole Europe since January 1950, Krzyścin, 2007) and adjusted so our modelled UV doses.

The analysis of our reconstructed time series shows a clear signal of increasing UV radiation in the last two decades in Austria. A higher increase in UV was calculated for the winter and spring season, and this is explained by a larger decrease in atmospheric ozone concentration in combination with an increase in sunshine duration. The results from our control run show that generally changes in atmospheric ozone concentrations have influenced erythemal UV more than changes in cloudiness. This study provides important information for epidemiological studies and for future required medical care in Austria, knowing that erythemal UV radiation is one of the major causes for development of skin cancer.

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Table 1. Overview of the datasets used in this study. * The global irradiance record at Hoher Sonnblick had some gaps in the years 1973, 1981, 1983, 1984, 1988 and 1990.

Station	Coordinates	Data	Period
Sonnblick	47.03° N, 12° 57′ E 3106 m a.s.l.	global irradiance sunshine duration UV irradiance total ozone snow depth	1972–2005* 1972–2005 1998–2005 1994–2005 1972–2005
Vienna	48° 15′ N, 16° 26′ E 153 m a.s.l.	global irradiance sunshine duration UV irradiance snow depth	1960–2005 1960–2005 1998–2005 1960–2005
Arosa	46.8° N, 9.7° E 1850 m a.s.l.	total ozone	1960–2005

Table 2. Statistical numbers of the 4 modelling approaches for the stations Vienna (VIE) and Hoher Sonnblick (SON), showing correlation R^2, bias and root mean square error (RMSE) between model results and data. HMC = model with hourly resolution and monthly correction factor C, HSC = model with hourly resolution and seasonal correction factor C, DMC = model with daily resolution and monthly correction factor C, DSC = model with daily resolution and seasonal correction factor C.

Station/Model	R^2				BIAS				RMSE			
	winter	spring	summer	autumn	winter	spring	summer	autumn	winter	spring	summer	autumn
VIE-HMC	0.96	0.96	0.96	0.99	+4	+3	+7	−1	26	16	13	18
VIE-HSC	0.96	0.96	0.95	0.99	+5	+7	+7	+1	28	18	14	19
VIE-DMC	0.94	0.90	0.94	0.99	−5	−2	+7	+1	28	27	14	19
VIE-DSC	0.94	0.90	0.95	0.99	−8	−2	+7	+7	27	27	14	22
SON-HMC	0.96	0.96	0.97	0.98	−2	−2	+1	−8	18	15	11	18
SON-HSC	0.96	0.96	0.97	0.98	−2	−3	+1	−7	21	16	12	19
SON-DMC	0.91	0.93	0.94	0.98	−2	−7	−3	−13	25	22	18	24
SON-DSC	0.91	0.94	0.94	0.98	+2	−12	−3	−13	26	23	19	24

Table 3. Distribution of the estimated UV doses in comparison to the observed ones for the testing period in Vienna. HMC= model with hourly resolution and monthly correction factor C, HSC= model with hourly resolution and seasonal correction factor C, DMC= model with daily resolution and monthly correction factor C, DSC= model with daily resolution and seasonal correction factor C.

Range	Station/Model	±5%	±10%	±15%	±20%	±25%	±30%	±35%	±40%
Daily data	VIE-HMC	22%	45%	62%	75%	86%	91%	93%	97%
	VIE-HSC	20%	41%	58%	74%	83%	88%	92%	96%
	VIE-DMC	17%	39%	53%	69%	75%	80%	85%	89%
	VIE-DSC	17%	35%	49%	62%	73%	80%	87%	89%
Monthly data	VIE-HMC	50%	67%	96%	96%	100%			
	VIE-HSC	33%	67%	88%	88%	96%	100%		
	VIE-DMC	42%	67%	88%	92%	100%			
	VIE-DSC	42%	46%	75%	92%	100%			

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Table 4. Distribution of the estimated UV doses in comparison to the observed ones for the testing period at Hoher Sonnblick. HMC= model with hourly resolution and monthly correction factor C, HSC= model with hourly resolution and seasonal correction factor C, DMC= model with daily resolution and monthly correction factor C, DSC= model with daily resolution and seasonal correction factor C.

Range	Station/Model	±5%	±10%	±15%	±20%	±25%	±30%	±35%	±40%
Daily data	SON-HMC	36%	62%	76%	86%	93%	95%	98%	99%
	SON-HSC	31%	53%	71%	82%	90%	95%	97%	98%
	SON-DMC	19%	39%	49%	60%	69%	76%	81%	84%
	SON-DSC	20%	37%	50%	58%	69%	75%	78%	84%
Monthly data	SON-HMC	67%	96%	100%					
	SON-HSC	54%	75%	92%	92%	100%			
	SON-DMC	42%	58%	71%	96%	96%	100%		
	SON-DSC	25%	42%	79%	88%	92%	100%		

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Table 5. Trends of the estimated UV doses, total ozone concentration (TOC) and relative sunshine duration (SD) for the periods 1986–1995 and 1996–2005 in comparison to the reference period 1976–1985.

Station	Season	UV 1986–1995	1996–2005	TOC 1986–1995	1996–2005	SD 1986–1995	1996–2005
Vienna	Winter	+29%	+18%	−5%	−4%	+20%	+10%
	Spring	+9%	+20%	−4%	−6%	+2%	+13%
	Summer	+12%	+8%	−2%	−4%	+11%	+14%
	Autumn	+10%	+10%	−2%	−1%	+2%	±0%
Sonnblick	Winter	+14%	+22%	−5%	−4%	+18%	+17%
	Spring	+7%	+19%	−4%	−6%	−2%	+10%
	Summer	±0%	±0%	−2%	−4%	+5%	+8%
	Autumn	−1%	+10%	−2%	−1%	−6%	−3%

Table 6. Influence of changes in total ozone concentration (TOC) and of changes in relative sunshine duration (SD) on the seasonal averages of erythemal UV-irradiance during the periods 1986–1995 and 1996–2005 in comparison to 1976–1985.

Station	Season	1986–1995 TOC	SD	1996–2005 TOC	SD
Vienna	Winter	60%	40%	70%	30%
	Spring	88%	12%	55%	45%
	Summer	66%	34%	60%	40%
	Autumn	64%	36%	65%	35%
Sonnblick	Winter	43%	57%	60%	40%
	Spring	100%	0%	53%	47%
	Summer	50%	50%	50%	50%
	Autumn	0%	100%	100%	0%

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Table 7. Influence of changes in total ozone concentration (TOC) and of changes in relative sunshine duration (SD) on the yearly averages of erythemal UV-irradiance during the periods 1986–1995 and 1996–2005 in comparison to the reference period 1976–1985.

| Station | 1986–1995 | | 1996–2005 | |
	TOC	SD	TOC	SD
Vienna	66%	34%	50%	50%
Sonnblick	66%	34%	78%	22%
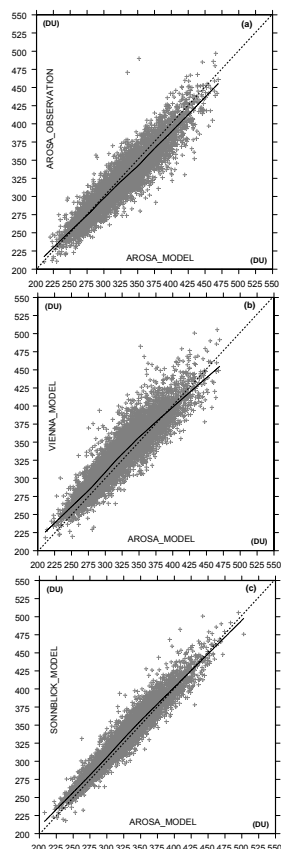
Fig. 1. Modeled versus observed daily mean total ozone values for Arosa **(a)**, modeled daily ozone values for Vienna versus corresponding values for Arosa **(b)**, modeled daily ozone values for Hoher Sonnblick versus corresponding values for Arosa **(c)**. The results are presented for the 1976–2004 period. Solid curve represents smoothed pattern of the differences calculated by LOWES low pass filter. Dashed straight line shows a diagonal of the square.

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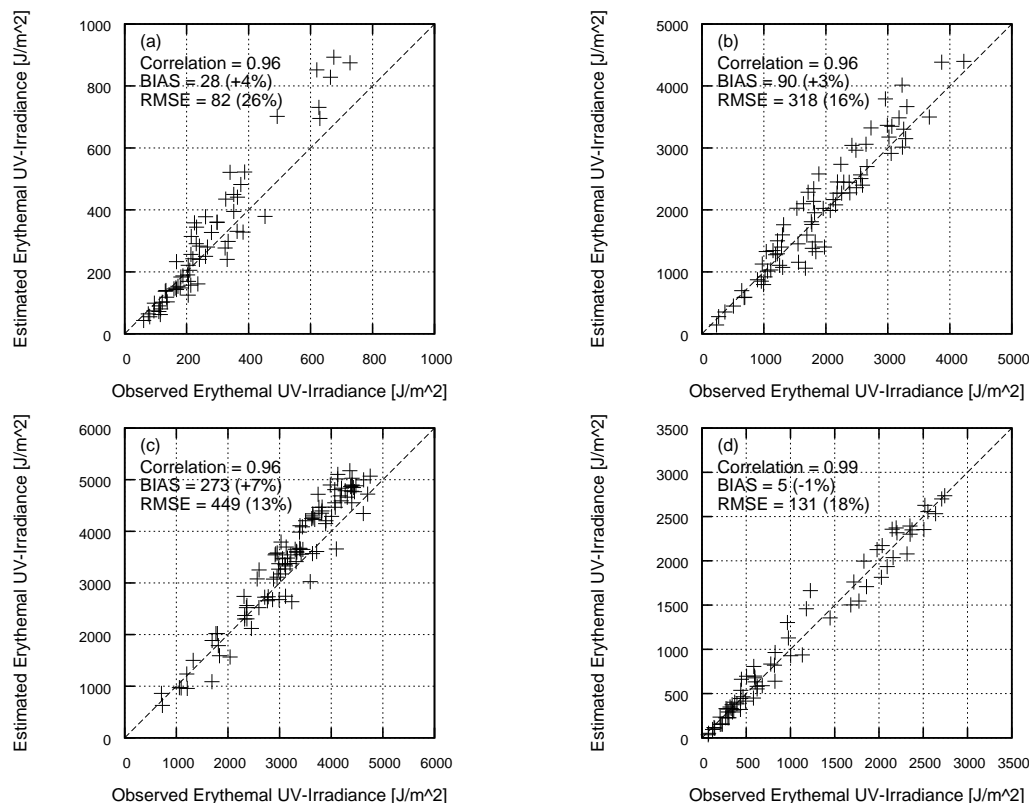
Fig. 2. Observed versus estimated daily erythemal UV doses calculated with the HMC-Model for the testing period in Vienna. The Root Mean Square Error (RMSE) and the bias of the estimated UV doses compared to the observed ones are also shown, as well as the correlation coefficient between estimated and observed UV doses. **(a)** shows the comparison for Winter, **(b)** for Spring, **(c)** for Summer and **(d)** for Autumn. Winter is December–February, spring is March–May, summer is June–August and autumn is September–November.

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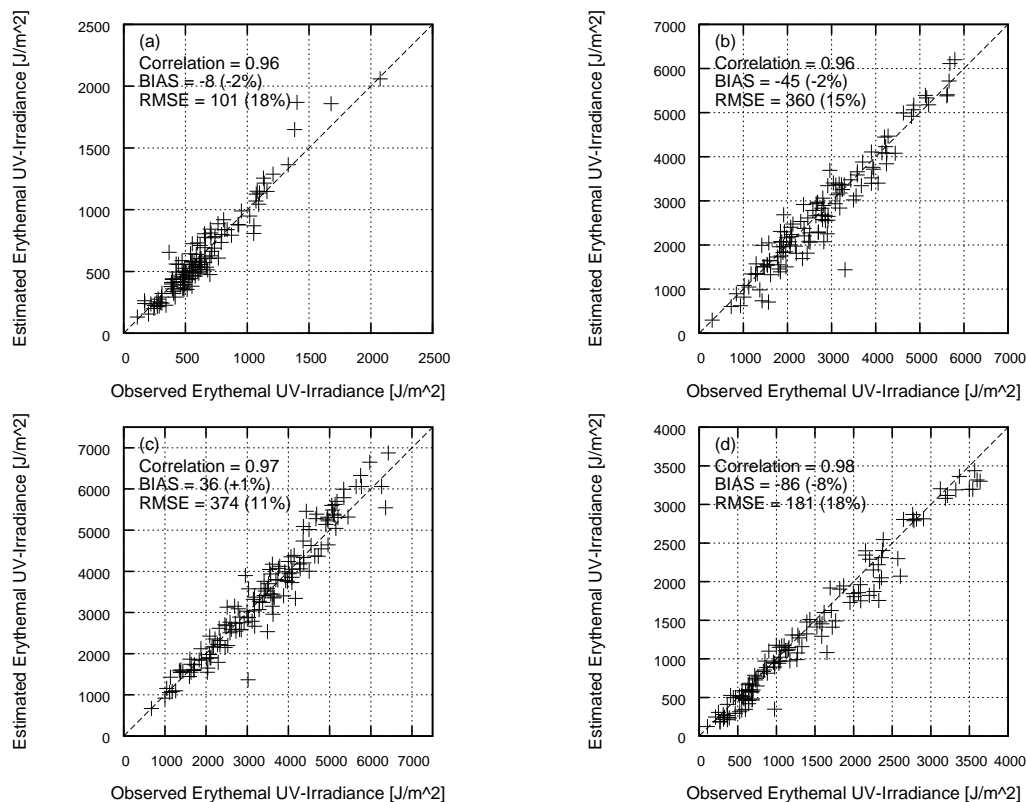
Fig. 3. Observed versus estimated daily erythemal UV doses calculated with the HMC-Model for the testing period at Hoher Sonnblick. The Root Mean Square Error (RMSE) and the bias of the estimated UV doses compared to the observed ones are also shown, as well as the correlation coefficient between estimated and observed UV doses. **(a)** shows the comparison for Winter, **(b)** for Spring, **(c)** for Summer and **(d)** for Autumn. Winter is December–February, spring is March–May, summer is June–August and autumn is September–November.

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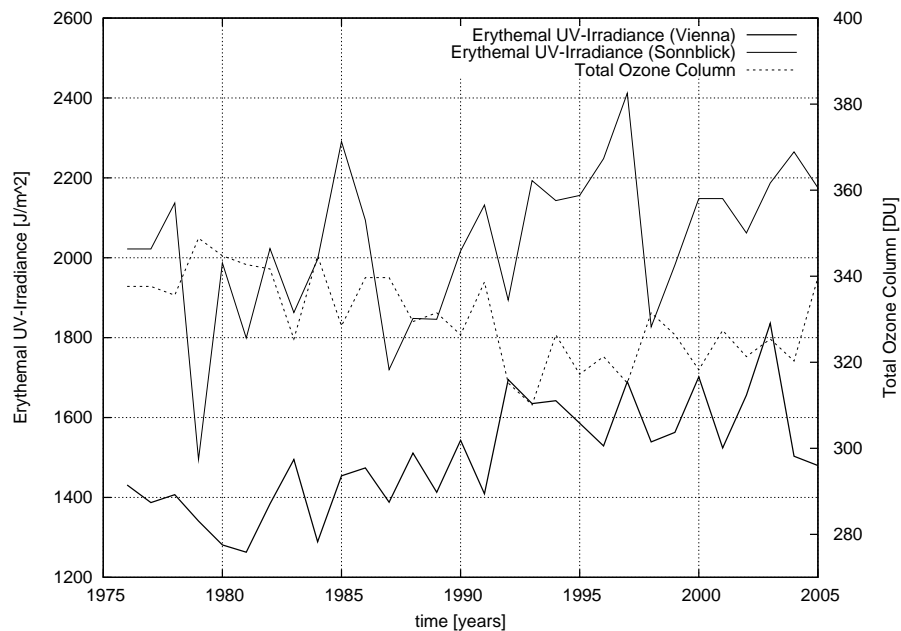
Fig. 4. Yearly averages of estimated UV, compared to total ozone column at Hoher Sonnblick and Vienna from 1976–2005.

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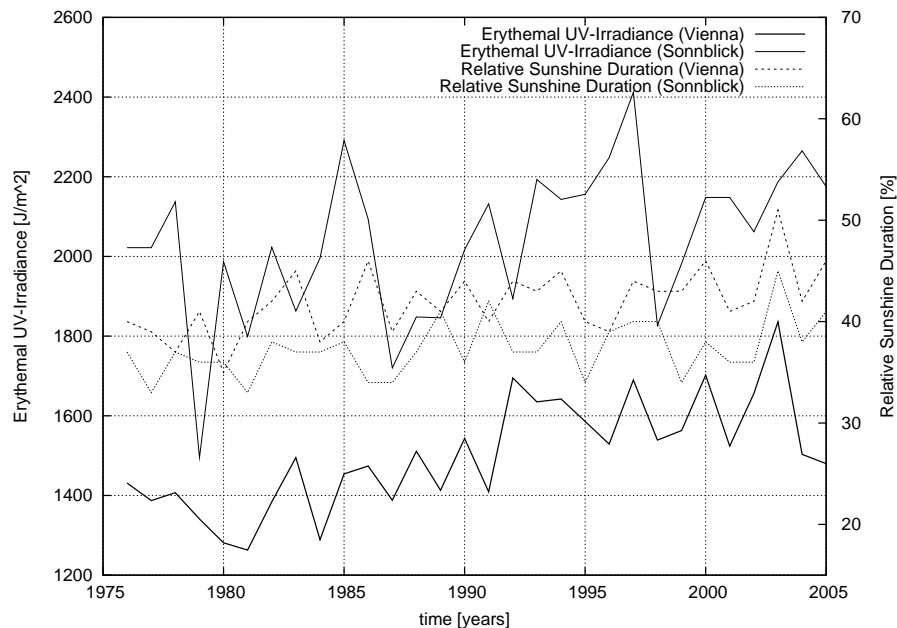
Fig. 5. Yearly averages of estimated UV, compared to relative sunshine duration at Hoher Sonnblick and Vienna from 1976–2005.
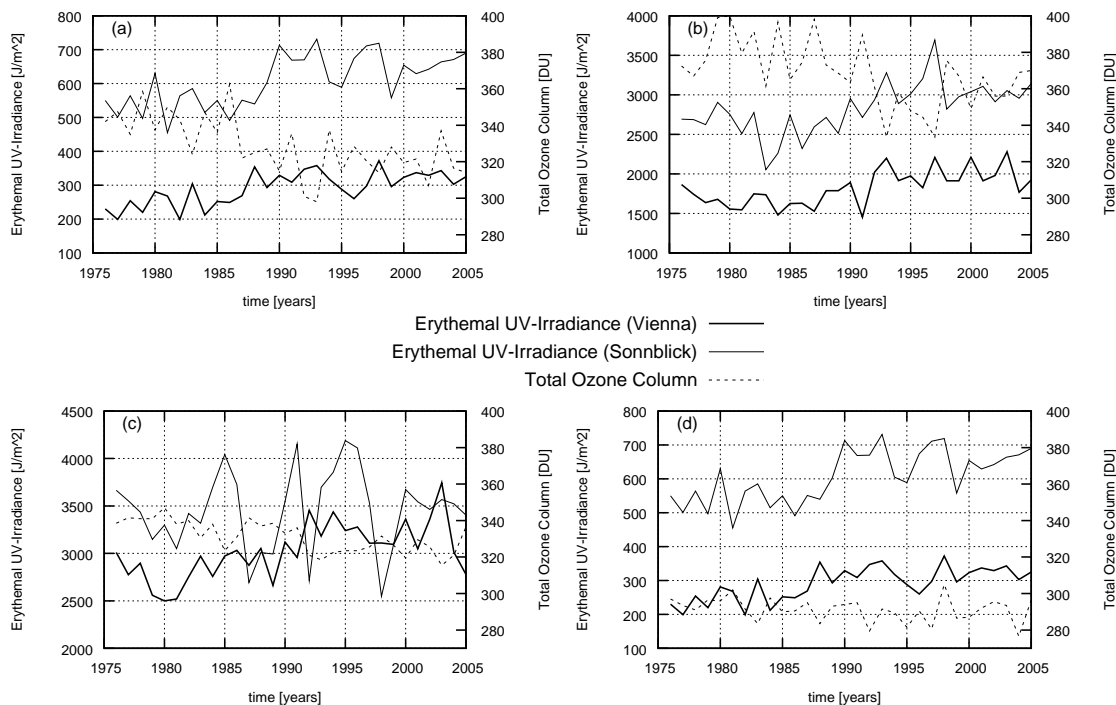
Fig. 6. Time series of estimated UV and total ozone column for the different seasons at the stations Hoher Sonnblick and Vienna from 1976–2005. Winter **(a)** is December–February, spring **(b)** is March–May, summer **(c)** is June–August and autumn **(d)** is September–November **(e)**.

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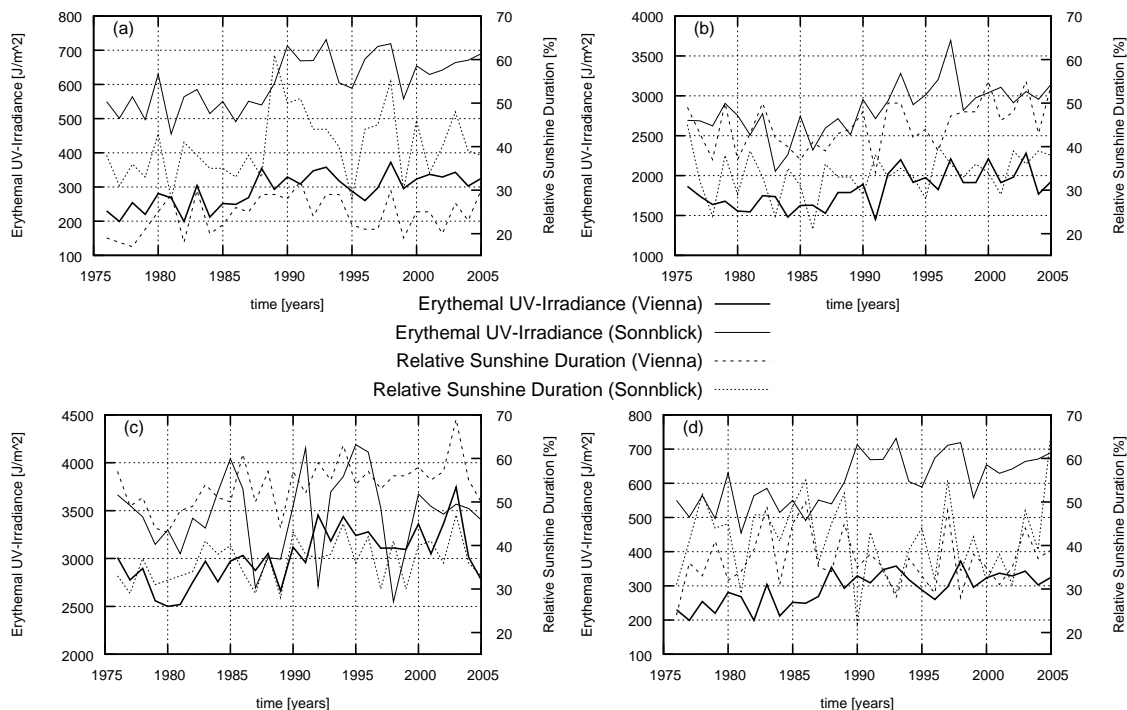
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Fig. 7. Time series of estimated UV and relative sunshine duration for the different seasons at stations Hoher Sonnblick and Vienna from 1972–2005. Winter **(a)** is December–February, spring **(b)** is March–May, summer **(c)** is June–August and autumn **(d)** is September–November.

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