Variability of UV-B at four stations in Europe

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Abstract. The variability of solar irradiance in the UV-B spectral region is studied at four stations operating well-calibrated spectroradiometers during the period 1991-96. It is confirmed that total ozone is the controlling factor in long-term changes of solar irradiance below 320 nm received at the ground. This result is supported by the similar long-term variability under clear sky and all sky conditions during the past five years. The study includes estimates of the amplitude of the annual cycle and estimates of long-term changes. An important result of this note is, that calculated changes in solar irradiance depend on the length of the observational period and that any speculations on its future changes should be treated always with caution. It is estimated that a 2.7% change per year in solar irradiance at 305 nm at Thessaloniki is a rate that could possibly continue in view of the expected continuation of the ozone decline resulting to an increase of 27% per decade, which is comparable to the amplitude of the annual cycle at that station.

Introduction

The observed and foreseen ozone depletion and its enlarged significance over the middle and high latitudes of both hemispheres is now well established [*Harris et al.*, 1997]. Because ozone is shielding the biosphere from the harmful UV-B radiation, research on this part of the solar spectrum has been intensified in the 90's. In the past, the perceived importance of the UV-B data has been often outweighed by the difficulties involved in collecting quantitative UV-B measurements, which have been confined mostly to campaign and short-term projects. Moreover, earlier analyses of UV-B erythemal levels, by *Scotto et al.* [1988] have shown decreasing UV-B levels over a small number of sites, in contradiction to the expected UV-B increases due to the declining of the ozone layer. This has been attributed to increases in the absorbing tropospheric aerosols, ozone and changes in meteorology [e.g. *Brühl and Crutzen,* 1989, *Justus and Murphy,* 1994]. Not only ozone but also clouds and haze are very important in determining UV-B levels at the ground [*Bais et al.*, 1993, *Estupinan et al.*, 1996, *Seckmeyer et al.* 1996a]. Other tropospheric minor constituents, such SO_2, and surface albedo are among the controlling factors of UV-B transfer through the atmosphere. Therefore changes in any or all of these factors may reduce, cancel, or even reverse the expected UV-B amplification caused by the ozone decline.

Blumthaler and Ambach [1990], found the erythemal dose increasing, at Jungfraujoch, a 3.6 km high mountain site in Switzerland, by about 1% per year in the 80's. An increase was also reported in the 90's from spectrophotometric observations in Toronto [*Kerr and McElroy,* 1993] and at Thessaloniki under practically cloudless skies and constant zenith angle [*Zerefos et al.*, 1995]. The opposition between short and long-term changes in total ozone and associated changes in the UV-B at the ground is well documented, particularly during periods of extreme ozone deficiencies, such as the case for 1992 and 1993, years of very low ozone [*Seckmeyer et al.*, 1994]. In this paper we discuss the European extent of updated spectral UV-B changes over 4 European stations in the 90's, which are well maintained and calibrated [*Bais et al.*, 1997], covering a wide range of latitudinal and environmental exposure conditions.

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Data

In this paper we used spectral UV measurements performed during the period 1991-1996 at four different sites in Europe, representing different latitudes and ozone climatology. Two stations are operated by LAP (Thessaloniki at 40°N and Reykjavik 64°N), one station by IASB (Uccle, 51°N) and one station by IFU (Garmisch-Partenkirchen, 47°N). Total ozone at Thessaloniki and Reykjavik, was measured by LAP with the Brewer instruments, whereas at Uccle was obtained by two co-located Brewer and Dobson instruments operated by KMI. Total ozone at Garmisch-Partenkirchen was calculated from spectral direct irradiance measurements which were evaluated by measurements of the nearby station of Hohenpeissenberg.

Spectral measurements of solar ultraviolet global irradiance are performed at the Laboratory of Atmospheric Physics of the Aristotle University of Thessaloniki, Greece (40°N, 22.9°E, 60m) with a MKII Brewer single-monochromator spectrophotometer, since 1989 [*Bais et al.*, 1993]. For the UV measurements, it uses a 35mm-diameter Teflon diffuser situated under a weather-protected quartz dome and records UV scans in the spectral region 290-330nm in steps of 0.5nm. The calibration of the instrument is maintained using a 1000-Watt source of spectral irradiance, traceable to the National Institute of Standards and Technology (NIST) standards, once every month. Its long-term stability is monitored in the field by a set of 50-Watt lamps, used once per week. The wavelength calibration of the spectrophotometer is ensured before each scan by using an internal mercury lamp. The observational program consists of several scans per day, made at least at local noon and at solar zenith angles of 50° and 63°. A comparison with a collocated double-monochromator Brewer [*Bais et al.*, 1996] showed that the absolute irradiance of the conventional Brewer may be overestimated by more than 10% below 300nm depending on wavelength and zenith angle. The overall accuracy of the measurement at 305 nm is of the order of 5% and improves as we move to 325 nm.

A single-monochromator Brewer MKIV spectrophotometer, maintained by LAP and hosted by the Icelandic Meteorological Office, operates at Reykjavik (64.13°N, 21.9°W, 60m) continuously since 1991 [*Bais et al.*, 1997). The instrument has similar characteristics with the Brewer operating at Thessaloniki and is subject to similar periodical calibration procedures. Global solar irradiance measurements are performed several times per day at Reykjavik depending on the duration of the daylight.

The core instruments of the main station at Uccle, a residential area in the Brussels suburbs (50°47'N, 4°21'E, 105m), consist of two double monochromators (modified HD10, Jobin Yvon) and operate since mid-March 1993 [*Gillotay*, 1996]. The first spectroradiometer is fitted with a Lambertian Teflon diffuser and measures with a 2π sr field of view the global solar irradiance from 280 to 600 nm. The second measures a fraction of the diffuse irradiance at the zenith, in a solid angle of 10°, and is mainly used to characterize the cloud layer optical homogeneity. The scans are taken once every 15 minutes, for SZA smaller than 100°. Periodical absolute calibration is performed in a dark room using five different NIST-FEL 1000-Watt standard lamps. Furthermore, stability is periodically checked by means of a Transportable Lamp System (TLS) developed specifically in IASB. With both 'standards' the uncertainties can be estimated to be less than ±5% in the whole wavelength range. This estimate was confirmed during the previous European intercomparison campaigns [Gardiner and Kirsch, 1995].

Global and direct irradiance measurements are performed at Garmisch-Partenkirchen (47°29'N, 11°04'E, 730m) with an automated Bentham DTM300. Although measurements were performed occasionally before 1994, continuous data sets are available since April 1994. The UV scans cover the spectral region 285-410nm with a bandwidth of 0.5 nm and a step of 0.25nm. The wavelength calibration of the instrument is performed with a low-pressure pen-ray mercury lamp. Field calibrations are done once per week with a 100W NPL-certified lamp, while in the laboratory a PTB-certified 1000-Watt FEL spectral irradiance standard is used. A detailed description of the instrument operation and calibration procedures can be found in *Seckmeyer et al.*[1996b].

The above instruments, except the one operating at Reykjavik, have participated in various intercomparison campaigns during the last five years and their performance and comparability is well documented [Gardiner and Kirsch, 1995]. The performance of the Brewer at Reykjavik was successfully tested during SESAME against a double-monochromator Bentham DTM150 [*Bais et al.*, 1997].

UV-B changes at four stations in Europe

Figure 1 shows the change in solar UV irradiance under low cloudiness (≤ 2/8 cloud cover) at Thessaloniki for 305nm, which is a good indicator for erythemal UV-B doses [*Bais et al.* 1993, *Zerefos et al.* 1995] and for 325 nm, which is least affected by ozone, together with the observed change in total ozone. The op-

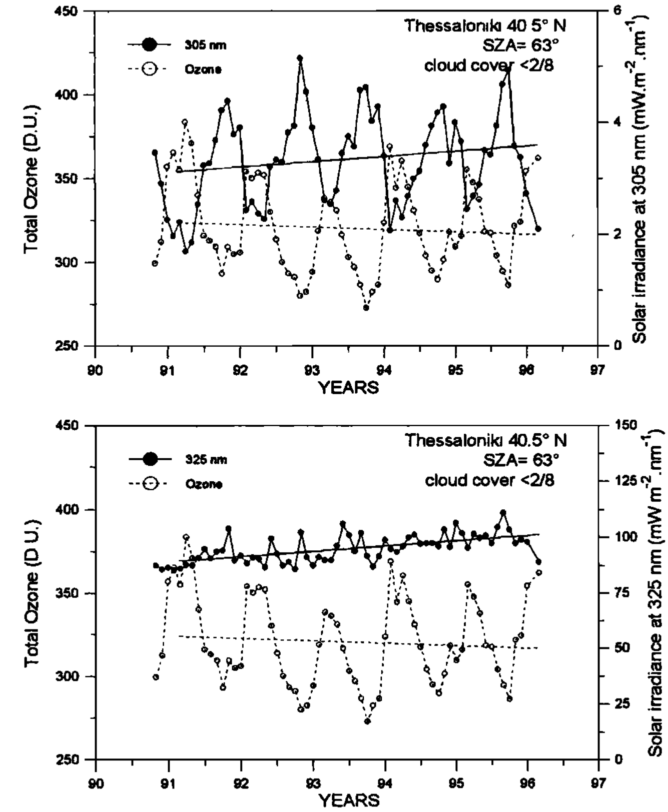

Figure 1. Monthly mean values of solar UV irradiance (solid circles) at 305 nm (upper panel) and at 325 nm (lower panel) measured at 63°SZA under clear skies, and total ozone (open circles) at Thessaloniki during the period November 1990 to March 1996. Straight lines represent linear regression lines on the monthly mean data.

position is remarkable, dominated by the seasonal change in total ozone which explains more than 80% of the total variance of the solar irradiance at 305 nm, but less than 10% at 325 nm, as it is shown by the anti-correlation coefficients between total ozone and the solar irradiance at these wavelengths in Table 1. For the wavelengths between 305 nm and 325 nm the anti-correlation coefficients are in-between those for 305 nm and 325 nm, as it results from the measurements performed at Thessaloniki not shown here. The mean total ozone at Thessaloniki is 318±2 D.U. with amplitude of the annual cycle of about 9% of the mean and a declining change between 1991 and 1996 of -0.46% per year. During this five years period the corresponding mean solar irradiance at 305 nm is 3.3±.5 mW m^{-2} nm^{-1} with amplitude of the annual cycle of about 25% of the mean and a rate of change between 1991 and 1996 of about +2.7% per year. These results should be compared with earlier findings of much larger changes discussed in the introduction. Table 2 shows the calculated spectral UV-B changes for four different time intervals (1991-93, 1991-94, 1991-95 and 1991-96) at Thessaloniki

Table 1. Correlation Coefficient (r) and Explained Variance (r^2 x 100%) between Total Ozone and Solar UV Irradiance

Station	r	r^2
Thessaloniki 305 nm (clear skies)	-0.94	88
Thessaloniki 305 nm (all data)	-0.91	82
Brussels 305 nm (all data)	-0.85	72
Reykjavik 305 nm (all data)	-0.81	65
Garmisch-Partenkirchen 305 nm (all data)	-0.77	59
Thessaloniki 325 nm (clear skies)	-0.25	6

Table 2. Mean Values and Percent Change per Year of UV and Total Ozone at Thessaloniki during Four Different Periods

Period	305 nm		325 nm		Total ozone	
	Mean	%	Mean	%	Mean	%
03/91 - 03/93	3.27	19.2	91.4	0.2	322	-7.2
03/91 - 03/94	3.34	8.4	92.7	1.8	319	-3.4
03/91 - 03/95	3.35	4.2	94.3	2.6	319	-1.5
03/91 - 03/96	3.36	2.7	95.3	2.4	320	-0.5

for cloud cover less than 2/8. As it appears from Table 2 the observed increase of the UV-B solar irradiance in 1993, is mainly a large perturbation of the UV-B field, caused by the extreme ozone deficiencies which occurred in that year [*Balis et al.*, 1997] and it would be wrongly characterized as "trend". This is because the 19% change of solar irradiance at 305 nm during the first 3-year period (1991-93) became about 4% per year when we added two more years of data and 2.7% per year by adding 3 more years of data (1991-96). This result shows exactly how delicate are these long-term changes with respect to the period chosen and the need for long-term, carefully calibrated, spectral measurements before assessing any tendencies in UV-B.

Moving back to the annual cycle of spectral solar irradiance at 305 nm we see in Figure 2 the opposing annual cycles of monthly mean irradiance and of monthly mean total ozone at all four stations under study. The data are chosen to correspond to measurements near 63° solar zenith angle, which is the limit zenith angle at the southern most station of Thessaloniki in the winter solstice. Data refer to all sky conditions and yet we can easily see that the remarkable ozone opposition to UV-B explains in all cases more than 59% of the total variance of the UV-B irradiance levels at 305 nm. The correlation coefficients between total ozone and solar irradiance at 305 nm measured at the four stations are shown in Table 1. Interesting to note on the amplitude of the annual cycle in solar UV irradiance is that it seems to follow roughly the annual amplitude of total ozone caused by its latitudinal distribution, which is larger in the arctic circle than at 40°N. Moreover the annual cycle curves display a high anti-correlation with total ozone, as it can be easily seen in

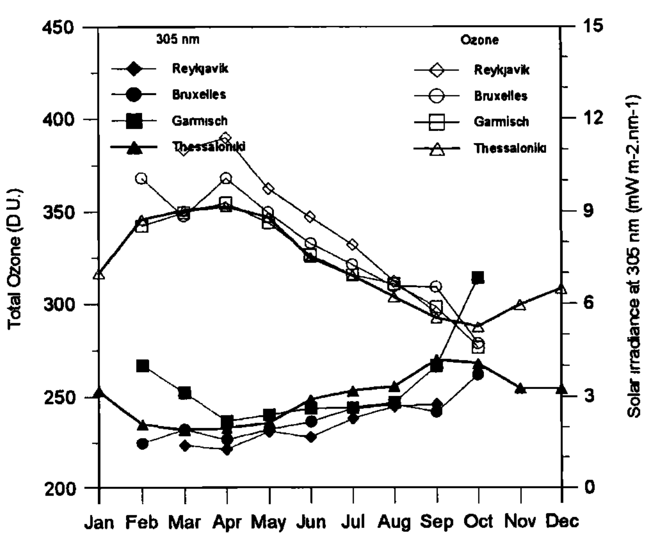

Figure 2. The annual variation of the solar irradiance at 305 nm measured at 63°SZA and the corresponding annual variation of total ozone under all sky conditions, for Reykjavik (diamonds), Brussels (circles), Garmisch-Partenkirchen (squares) and Thessaloniki (triangles).

Figure 2, irrespective of the well-known differences of exposure in different environments. As it appears from this figure there is rather similar amplitude of the annual variation of solar irradiance at 305 nm at all middle-latitude stations. Because of the limitations imposed by the accuracy at low solar zenith angles and the absence of any light during winter at high latitudes, no quantitative estimate of these spectral measurements can be given concerning the annual cycle except that they are in the right order. At Garmisch-Partenkirchen strange high values (based however on only two years of data) appear, which for February and March could have been influenced by the higher albedo from snow cover, but this cannot be the case in October. The high values in October are due to the weather conditions at Garmisch-Partenkirchen. October has usually many days with cloudless skies and in October 1995, there was an exceptionally high number of cloudless days. This example shows that cloud conditions cannot be neglected for the determination of monthly averages of UV-B irradiation.

On longer time scales, Figure 3 shows monthly means of solar irradiance at 305 nm for all sky conditions, at the four stations under study. With the exception of Reykjavik, where coincident total ozone and UV-B measurements are not always possible due to either the low solar zenith angles in winter or the increased cloud cover, at all stations the total ozone observations coincide with the measurements of solar irradiance. The decline rates of the total ozone range between 0.4% per year at Thessaloniki (1991-96) and 1.5% per year in Brussels (1993-96), for different periods, however. The corresponding changes in UV-B irradiance are about 3% per year at Thessaloniki and 9% per year in Brussels. As mentioned before no comparative conclusions can be drawn because of the short interval of the available data and of the different periods of available records at each site. The long-term ozone/UV-B opposition is clear also in Reykjavik, where ozone between 1992 and 1996 has not changed much (increased in this sample by about 0.5% per year) resulting to a 3% per year decrease of solar irradiance at 305 nm at this site. The reader is cautioned that this result is based on data between March and October only.

Conclusions

The results presented here from a set of well-calibrated spectroradiometers operating in Europe provide further evidence on the opposition between total ozone and solar UV-B irradiance on long-term scales. The study confirms that total ozone is the dominant factor in long-term changes of solar irradiance below 320 nm at ground level. This result is supported by the similar long-term variability under clear sky and all sky conditions at Thessaloniki during the past 5 years. The authors do not wish to comment on the observed large increases of UV-B in Europe in the 90's, because it has been shown (Table 2) that calculated changes in solar irradiance (in % per year) critically depend on the length of the period of study. A few years are not enough for any reliable conclusions on long term changes. For example conclusions drawn from the first 3 years of data from Table 2, would mean that the expected increase in UV-B, would be 190% per decade, i.e. exceeding by more than 7 times the amplitude of the annual cycle at that station. In spite of these reservations, the authors do not underestimate the important changes seen in this study. The 2.7% change per year in solar irradiance at 305 nm at Thessaloniki is comparable to the amplitude of the annual cycle at this station and is a rate that could possibly continue in the years to come, in view of the expected continuation of the ozone decline.

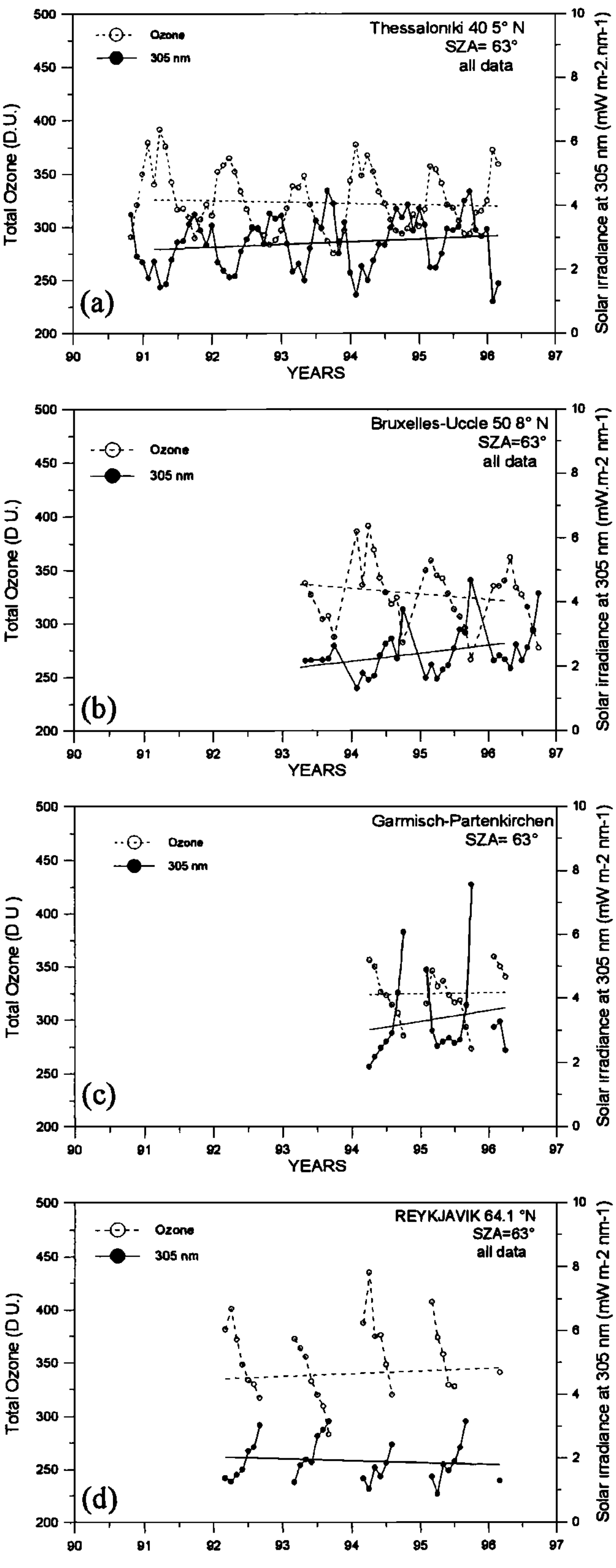

Figure 3. Time series of monthly mean values of solar UV irradiance at 305 nm (solid circles) measured at 63°SZA under all sky conditions, and total ozone (empty circles) at (a) Thessaloniki, (b) Brussels, (c) Garmisch-Partenkirchen and (d) Reykjavik. Straight lines represent linear regression lines on the monthly mean data.

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