EDUCE WP 2.1 - The influence of atmospheric variability on short- and long-term changes of spectral UV irradiance at two European stations

1. Introduction

There have been relatively few studies that have attempted to separate the effects of different UV affecting factors on the short- and long-term changes of UV radiation [e.g. *Krzyścin and Puchalski* [1998]; *Udelhofen et al.* [1999]; *Chubarova and Nezval* [2000]; *Fioletov et al.* [2001]]. The effect of ozone is fairly easily represented through radiation amplification factor (RAF) or by comparison of changes at two distinct wavelengths, one with strong and other with negligible ozone absorption. However, the effect of other factors is not as straight-forward. In this paper we represent a methodology that can account for the other effects as well.

To study what part of short- and long-term variability, as measured by spectral UV instrument of few selected European sites, is explained by each UV affecting factor we used radiative transfer modeling and measured time series of input parameters. The influence of inter-annual variability of atmospheric conditions hampers the detection of change in UV irradiance caused by a single factor, such as ozone. Our analysis allows one to evaluate and remove the effect of inter-annual variability of other factors than that of concern. Long-term irradiance changes at different wavelengths and contributions of each UV affecting factor are estimated for different seasons. It is also demonstrated that it is crucial to check and remove even small wavelength shifts, when the irradiance changes at single wavelength are studied.

We analyzed the spectral data of Sodankylä (67N), Finland and Thessaloniki (40N), Greece. Both have time series of about 11 years. In terms of typical atmospheric conditions, these the two sites differ from each other; Sodankylä has a rather continental climate, whereas climate of Thessaloniki is affected by Mediterranean. Regarding stratospheric meteorology, Sodankylä can be classified as an Arctic site, often lying beneath the middle or the edge of the stratospheric polar vortex and in the zone of polar stratospheric ozone depletion. Thessaloniki is located the in mid-latitude area, where the natural inter-annual ozone variability is smaller.

2. Methods and Data

We focused on both short- and long-term UV variability. In the former case, monthly CIE variability was studied, while in the latter case irradiance changes at single wavelengths were investigated. For this latter purpose, we selected those spectral measurements of both sites that had been performed at solar zenith angle (sza) range of 63-65 degrees. There are several advantages of this particular choice. First, the results are comparable, but with an extended data set, to those of *Zerefos et al.* [1998], who analyzed the irradiance changes at both 50 and 63 degrees of sza. Second, lower values of sza would have reduced the available measurements in the northern latitude site of Sodankylä. Now enough data were available from both sites, allowing interesting intercomparisons. Third, neither of the data sets contained cosine corrected data. Angular response of Brewer is such that the sensitivity of cosine correction factor (ccf) to the atmospheric conditions diminishes around sza of 55-60 degrees. When long-term changes are considered, the long-term stability is clearly one of the most crucial issues, so arguably the lack of cosine correction did not have any substantial effect on our analysis.

2.1. Spectral data of Sodankylä

The spectral UV measurements of Sodankylä and Thessaloniki were both recorded by Brewer ozone single spectrophotometers, which are used to measure global irradiance (UV), total ozone (O_3) and the sulphur dioxide column (SO_2).

The MK II Brewer at Sodankylä is situated on the roof of the Observatory, where the horizon is free up to very high solar zenith angles. The near surroundings are pine forest and swamp areas. The first UV measurements were made in 1990, since when the UV spectrum has been recorded every half hour in steps of 0.5 nm. The spectroradiometer has a single grating monochromator with a spectral range of 290-325 nm. One scan contains measurements from 290 nm to 325 nm and back. The total scanning time is around 8 minutes. The Brewer has a 35 mm-diameter Teflon diffuser which is protected by a weather-proof quartz dome. The temperature of the Brewer is recorded but not stabilized.

The daily performance of the spectroradiometer at Sodankylä is checked with lamp measurements. An internal mercury lamp test is performed several times a day in order to achieve as accurate wavelength settings as possible. The stability and performance is controlled by 50 W lamp measurements every second week on the roof and every second week in the laboratory. Every month the Brewer is calibrated in a laboratory darkroom, against 1000 W lamps traceable to the National Institute of Standards and Technology (NIST). The Brewer has participated in intercomparison campaigns organized by the Nordic Ozone Group (NOG) held at Izaña, Tenerife, in 1993 and 1996, and at Tylösand, Sweden, in 2000 (*Koskela* [1994]; *Kjeldstad et al.* [1997]). The long-term responsivity of the instrument over the period 1990 – 1997 has been calculated using 50 W lamp measurements, other independent lamp measurements and the results of the intercomparisons of 1993 and 1996. For the period 1998 – 2000 the response is calculated using the NIST irradiance scale via the laboratory of SP, the Swedish National Testing and Research Institute.

2.2. Spectral data of Thessaloniki

The measurements of spectral UV global irradiance at Thessaloniki have been performed at the Laboratory of Atmospheric Physics of the Aristotle University of Thessaloniki, Greece. The Brewer has measured since 1982 total ozone and columnar sulfur dioxide, and in addition to these, since 1989 also spectral UV global irradiance (*Bais et al.* [1993]). For global UV measurements the Brewer uses a Teflon diffuser of about 35mm diameter protected by a quartz dome, and records UV scans in the spectral region 290-330 nm in steps of 0.5 nm. The stability of the instrument is monitored every week outdoor using 50 W lamp measurements. The calibration is performed every month using a 1000 W lamp traceable to the NIST. A comparison of the Brewer to a collocated Brewer double monochromator has shown that the overall accuracy of the measurement at 305 nm is of order of 5% and improves towards 325 nm (*Bais et al.* [1996]; *Zerefos et al.* [1998]).

2.3. Radiative Transfer Model Calculations

Radiative transfer (RT) model simulations were carried out to separate the impacts of ozone, snow albedo, aerosols and clouds in UV variability. We used LibRadtran 0.15 package and UVspec disort version. The input data to the RT model allowed the spectral measurements to be reproduced. When observed variations are introduced to any single factor, while the others follow the mean annual cycle, the influence of each factor can be estimated separately.

Measured irradiance depends mainly on the following factors: solar zenith angle (sza), total column ozone (O_3), effect of clouds, effect of aerosols and surface albedo (α). There are additional environmental factors that are predictable such as the Earth-sun distance and the elevation of the site of interest. In other words, in order to be able to estimate the spectral irradiance at any particular site, appropriate input data for sza, ozone, clouds, aerosols and surface albedo are needed. If only the varying input parameters are considered, we can write,

$$I_\lambda = f(sza, O_3, \tau_c, \tau_a, \alpha), \tag{1}$$

where τ_c is cloud optical depth (COD) and τ_a is aerosol optical depth (AOD). Of course irradiance depends on other optical properties as well, aerosol (or cloud) single scattering albedo and aerosol (or cloud) asymmetry factor. However, we assumed that the optical depth was the variable and other optical properties in RT model simulations were fixed, but as realistic as possible.

We want to emphasize that our analysis is based on irradiance measurements and the RT model is a tool to estimate the effects of UV affecting factors on observed irradiance variability. The estimation of each effect was possible, since the input data for RT model could be used to reconstruct the measurements, i.e. they are such that the equation 1 is valid. In the following sections each input parameter is explained in more detail.

2.4. Input Data for radiative transfer model

2.4.1. Ozone.

Time series of daily data of total column ozone were available for Sodankylä and Thessaloniki. For both sites the daily mean of ground based Brewer total ozone value in Dobson units (DU) were used. The Brewer instrument uses five wavelengths (306.3, 310.1, 313.5, 316.8 and 320 nm) to calculate total ozone. The gaps in the time series were filled by linear interpolation. In practice the total ozone can vary within a day, but for the purpose of long-term change studies the daily averages were used.

2.4.2. Albedo.

The regional albedo of snow-covered surface was a function of snow depth and 3% for snow-free conditions. This methodology follows the idea of *Arola et al.* [in preparation], who developed a snow albedo algorithm for satellite UV retrieval method. Their algorithm was based on TOMS 380 nm reflectivity measurements during cloud-free and snow-covered conditions. The requirement of clear-sky conditions is very essential, since TOMS 380 nm reflectivity measurement cannot distinguish snow from clouds. However, when the clear-sky and snow-covered cases were selected, these measurements were essentially surface reflectivity measurements. A relation between TOMS reflectivity and snow depth was estimated globally for each TOMS pixel of gridded data. In the current analysis we used SYNOP observations of cloudiness and snow depth in Sodankylä, while the analysis of *Arola et al.* [in preparation] was based on Era-15 data of European Center for Medium Range Weather Forecasts. The actual analysis resulted in a simple relation:

$$R = 0.13612 \times SD^{\frac{1}{3}}, \tag{2}$$

where R is the regional surface albedo, SD is snow depth in cm, for instance SD of 70 cm gives a regional albedo of 0.56.

Figure 1 shows the albedo in Sodankylä for the year 1997.

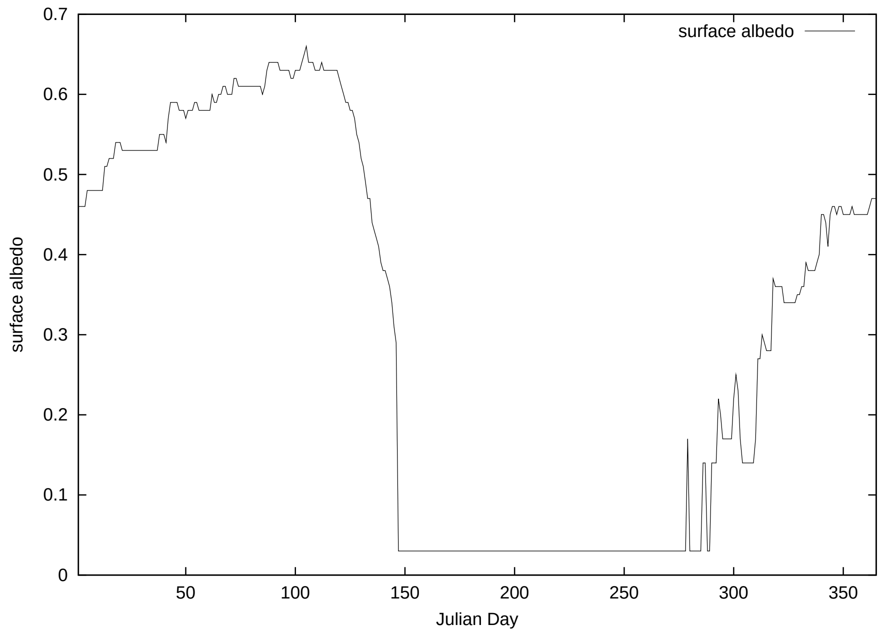

Figure 1. The daily surface albedo of 1997 in Sodankylä.

2.4.3. Aerosols.

There were no measurements of aerosol properties available for either of the sites. The visibility data of Sodankylä were used to take into account the amount of aerosols. Other aerosol related parameters in UVspec was chosen representative for Sodankylä.

The treatment of aerosols in Thessaloniki was more problematic. Since, on one hand, aerosols were assumed to have a stronger effect on the UV variability than in Sodankylä; *Zerefos et al.* [1998] speculated about the negative trend in air pollution in Thessaloniki. On the other hand, visibility data for Thessaloniki were not available.

Following approach was adopted to produce the input data for aerosol properties for the 11-year time series of Thessaloniki. Hourly data of total cloudiness were available. This data were used to select those spectral measurements when the nearest hourly cloudiness was zero both before and after the spectral scan. In other words, clear-sky spectra were selected. It was assumed that the unknown aerosol parameter is AOD and the single scattering albedo and asymmetry factor do not change over time. Values of single scattering albedo and asymmetry factor were set as representative as possible for Thessaloniki. *Kazantzidis et al.* [2001] used spectral irradiance measurements and radiative transfer modeling to estimate the daily course of single scattering albedo during specific days in Thessaloniki. Mainly based on their work and on some other similar studies (e.g *Kylling et al.* [1998]), we selected 0.9 for single scattering albedo and 0.7 for asymmetry factor. Since clear-sky spectra were selected and in Thessaloniki a constant value of 0.03 for the regional albedo could be assumed, equation 1 can be simplified as follows:

$$I_\lambda = f(sza, O_3, \tau_a), \tag{3}$$

We adopted a look-up table (LUT) approach, in which irradiance values for all the wavelengths were tabulated as a function of sza, ozone and AOD (assuming single scattering albedo and asymmetry factor as explained above). Now, for any clear-sky spectra, we can estimate AOD for any wavelength, since sza, ozone and the

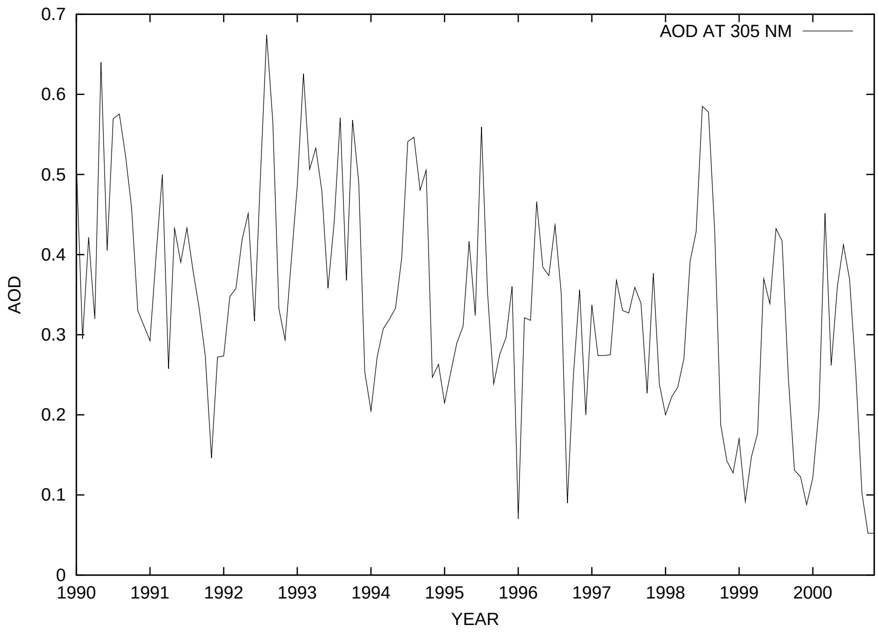

Figure 2. The mean monthly AOD in Thessaloniki.

measured irradiance are known. We did not tabulate the irradiance values of a given wavelength only, but we considered the adjacent wavelengths as well. The irradiance values of any wavelength λ were tabulated as follows:

$$\tilde{I}_\lambda = 0.5 * I_{\lambda-0.5} + I_\lambda + 0.5 * I_{\lambda+0.5}, \tag{4}$$

where $\lambda - 0.5$ and $\lambda + 0.5$ are the irradiance values 0.5 nm before and after the wavelength λ, respectively. The idea of this approach was to reduce the sensitivity of this methodology to the measurement uncertainty, to the occasional errors at a single wavelength and also to rapid changes in spectra. Finally, daily means of the estimated AOD values were calculated and interpolated between clear-sky measurements to provide a time series of daily AOD values.

Admittedly it is a simplification to use constant values for single scattering albedo and asymmetry factor, in reality both change even within one day, as shown by *Kazantzidis et al.* [2001]. However, our main focus was on the long-term changes and the effect of any particular UV affecting parameter on these changes. Therefore, arguably the long-term changes in aerosol properties are well represented, particularly since the total effect of aerosols is considered, not the effect of AOD or single scattering albedo separately. Moreover, we want to stress that the values of single scattering albedo and asymmetry factor are very representative in average sense at the site.

Figure 2 shows the mean monthly AOD in Thessaloniki for the entire data period, revealing a decreasing long-term change.

2.4.4. Cloudiness.

The estimation of input data for cloud effect was very similar to that used for aerosols in Thessaloniki. To estimate COD time series, again LUT of irradiance values for each wavelength was generated by UVspec. Now the full equation 1 had to be considered (surface albedo has high variability in Sodankylä due to the seasonal snow cover), i.e. the tables had five dimensions, *sza*, ozone, COD, AOD (or visibility in Sodankylä) and albedo.

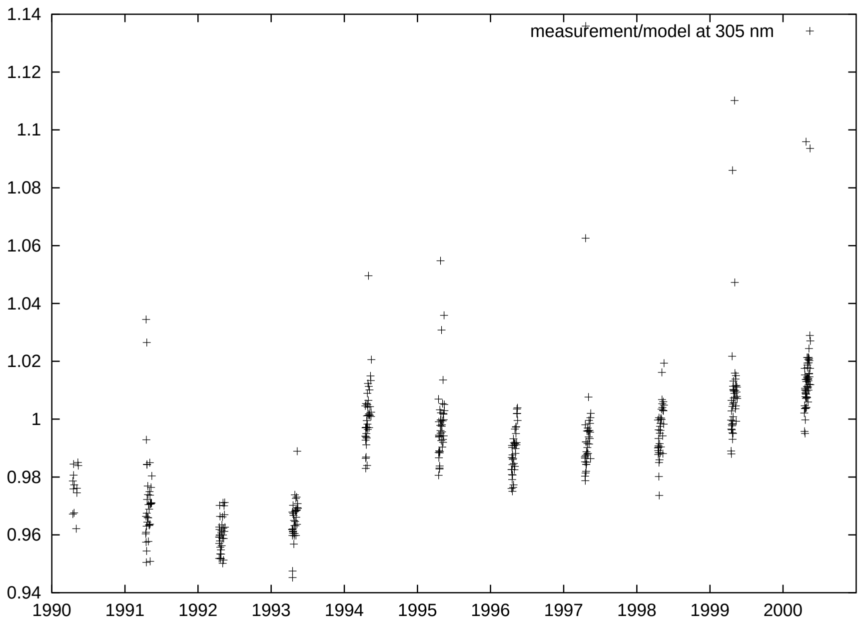

Figure 3. The ratio of measurement to model simulated irradiance value at 305 nm for the data of Sodankylä, no correction for wavelength shifts.

The other cloud optical properties than COD were assumed to be constant; single scattering albedo of 0.999 and asymmetry factor of 0.85 were selected based on the typical values in literature, appropriate to the UV wavelengths. Irradiance values calculated for the tables were again values of a narrow spectral band according to the equation 4.

2.5. Reconstructed irradiances

When all the input data for RT model were constructed, it was checked that they really reproduce the actual irradiance measurements, according to the equation 1. This revealed an interesting phenomena with the data of Sodankylä. Figure 3 shows the ratio of 305 nm irradiance measurement to the corresponding simulated value for the entire 11-year data for one month period in spring (April 15 to May 15) of each year and the sza range is 63-65 degrees. Slit function of the instrument is taken into account in the RT simulations. There is a stepwise change in the ratio after year 1993. Since in the figure the irradiance values of 305 nm are shown, while the COD was estimated by taking into account the adjacent wavelengths i.e. equation 4, the most likely explanation is the change in wavelength alignment. The change in absolute irradiance levels would have only resulted in changes in COD (which is a kind of tuning variable that guarantees that the measurements can be reproduced). Other variables are independent measurements, except for AOD in Thessaloniki, but it follows similar approach to COD estimation and the clear-sky requirement is based on hourly measurements. Due to this behavior of the measurement to model ratio, we checked and corrected all the spectra for possible wavelength shifts using the package called SHICrivm developed by Harry Slaper and his colleagues in RIVM, Netherlands (*Slaper et al.* [1995]).

Figure 4 shows the wavelength shift corrected data. It is apparent that the shift is removed, actually the typical value before 1994 was -0.06 nm and 0.01 nm thereafter. These are rather small values, if wavelength integrated doses are considered, they probably would not have had any noticeable effect on CIE doses or dose rates. It is often assumed that Brewer instrument has only minor problems with the wavelength alignment. However, when

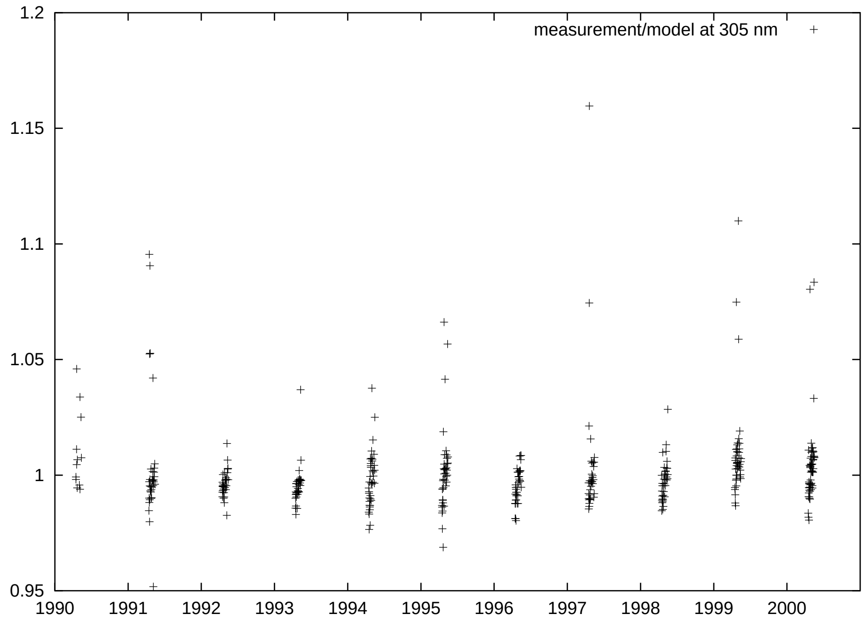

Figure 4. The ratio of measurement to model simulated irradiance value at 305 nm for the data of Sodankylä, wavelength shifts corrected by SHICrivm.

the variability of irradiance at a single wavelength is studied it is very crucial to check and remove even small wavelength shifts. Otherwise, one might wrongly interpret the irradiance variability and long-term changes.

As stated earlier, those irradiance measurements from both sites were selected that were performed at a given sza range of 63 to 65 degrees. It was found that even a rather narrow window of 2 degrees can introduce an effect that hampers the trend detection. This was the case in the data of Thessaloniki in particular, since sza of the selected measurements during the early part of the data period were in average close to 63 degrees, but increased later most likely due to the changed measurement schedule. If this effect of sza was not removed, there was an erroneous signal, decreasing the estimate of the long-term change. In other words, if the long-term variability in spectral UV data are estimated, it is important to remove the effect of sza and normalize all the measurements to some exact sza value. This was done in our study, since we carried out all the simulations for constant sza of 64 degrees.

3. Results

3.1. Short-term variability

In order to study the year-to-year variability and relative influence of each particular factor on UV doses, we made several model simulations. Monthly CIE doses of each year were compared to the doses of same month of all the other years. For instance, the monthly CIE dose of April 1994 was compared to monthly CIE doses of April 1991, April 1992 and so on. Spectral data were simulated at 1 hour time step using the input time series described in the previous section and then time- and wavelength integrated daily CIE doses were calculated. Simulations differed in terms of input data, as an example Figure 5 shows the effect of ozone and albedo on the difference of CIE monthly dose of April 1994 and April 1997. The percent difference is shown, i.e. $[dose97 - dose94]/dose94$, when $dose94$ is simulated with the input data of 1994 (that reproduce the measurements) and $dose97$ is simulated so that the input data of a single factor only (ozone or albedo) is from 1997, while other input data are that of 1994. It can be seen that lower ozone in 1997 induces higher daily UV doses. Similarly, in 1997 there was more

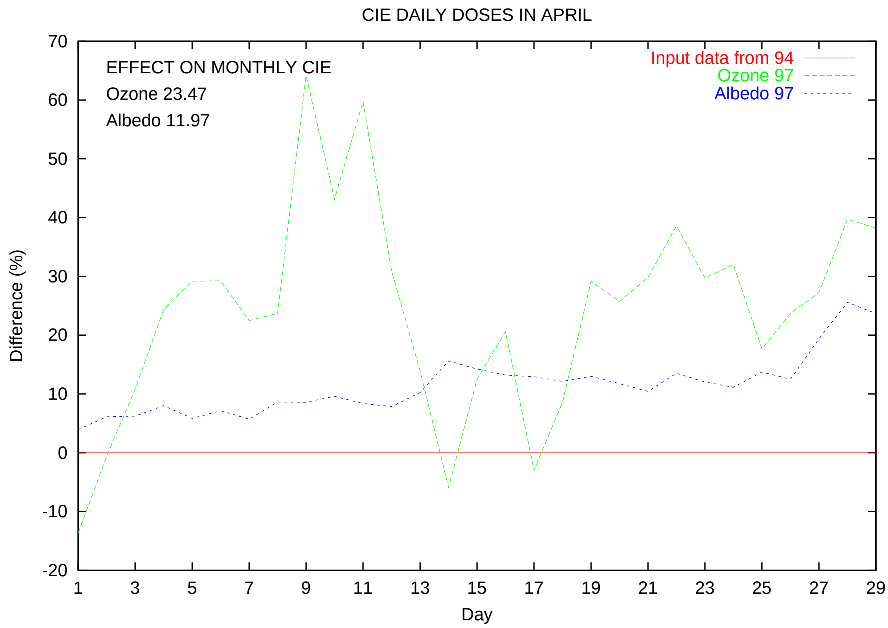

Figure 5. The simulated CIE daily doses of April 94 and 97 compared in Sodankylä. The effect of ozone and albedo. The statistics of monthly doses shown in the upper left corner.

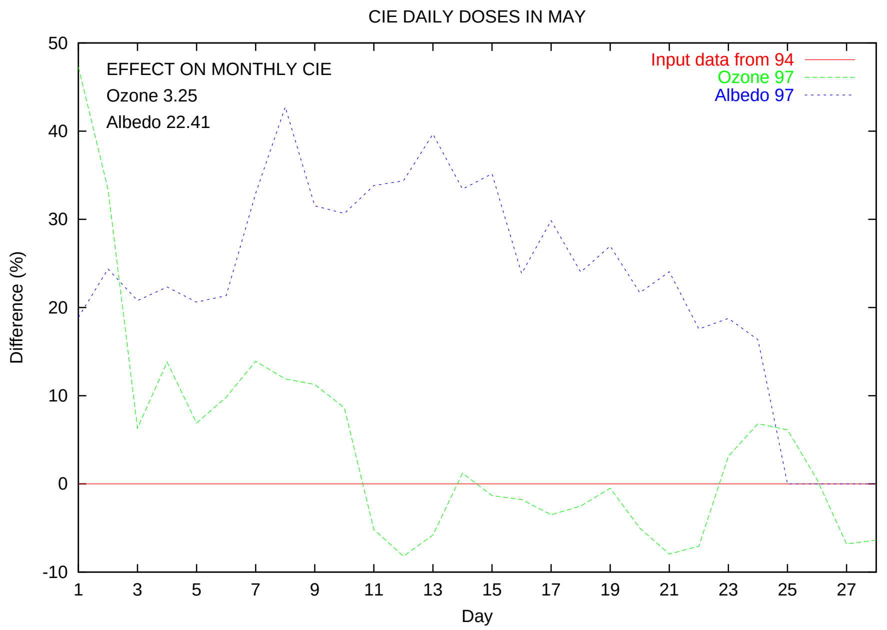

Figure 6. The simulated CIE daily doses of May 94 and 97 compared in Sodankylä. The effect of ozone and albedo. The statistics of monthly doses shown in the upper left corner.

snow and it persisted longer in Sodankylä, thus higher albedo resulted in increased UV levels if compared to 1994. In the upper left corner the percent differences are shown for CIE monthly doses.

Figure 6 shows the data of May. It is evident that the effect of ozone is reduced, while the albedo is dominating. Snow melts typically in Sodankylä during May, in 1997 snow stayed until the end of month.

Figure 7 illustrates similar comparisons in August. There exists some ozone induced variability, but the cloudiness has clear effect as well.

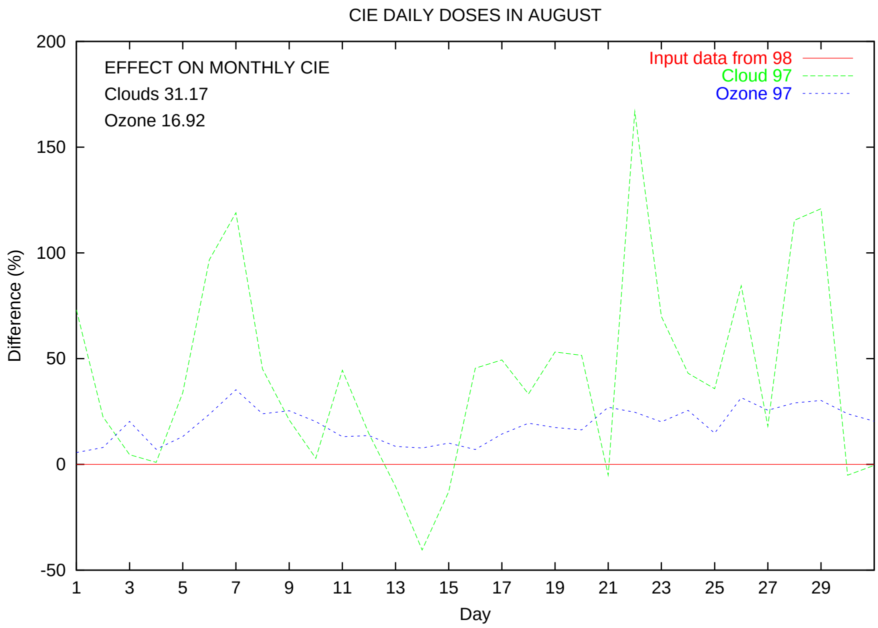

Figure 7. The simulated CIE daily doses of August 96 and 98 compared in Sodankylä. The effect of ozone and cloudiness. The statistics of monthly doses shown in the upper left corner.

All the years were inter-compared and the most prominent cases were illustrated above. The findings can be summarized by concluding that ozone, snow albedo and cloudiness can have effect in short-term variability in monthly CIE doses, which is very similar in magnitude, 25% to 30%. These results agree with *Kylling et al.* [2000], who analyzed the data of Tromsø and concluded that the clouds reduce the monthly doses by 20-40% and snow can increase the doses by 20%.

3.2. Long-term variability

Spectral measurements at *sza* range of 63-65 were selected and they were simulated for the entire 11-year period at both sites. When the actual input data were used, the measured spectral data were reproduced by the RT model. When the input data were varied with a consistent manner, the effect of each UV affecting factor on the observed variability could be estimated.

Mean annual cycle of daily input data for each variable were calculated from the 11-year daily data. If the effect of ozone, for instance, is estimated in the observed long-term UV variability, the spectral irradiance values are estimated for the entire period, allowing ozone vary according to the actual daily measurements, while the other factors follow their mean annual cycle.

Figure 8 shows the RT simulations for the 305 nm irradiance in Sodankylä for the data of April 15 to May 15. Ozone induced long-term changes should be most detectable in short wavelengths, due to the stronger ozone absorption. On the other hand, the measurement uncertainty increases with decreasing wavelength, due to stray light problem of single Brewers. Thus, wavelengths around 305 nm were considered as being most interesting to carry out detailed analysis of long-term changes. They are simulated with different sets of input data; label "Measured" means that the actual input data are used, i.e. the Brewer measurements are reconstructed by the model. In the run labeled "Ozone" the ozone had measured day-to-day and year-to-year variability, while visibility, COD and albedo had their mean annual cycle of daily values. Simulations were carried out spectra

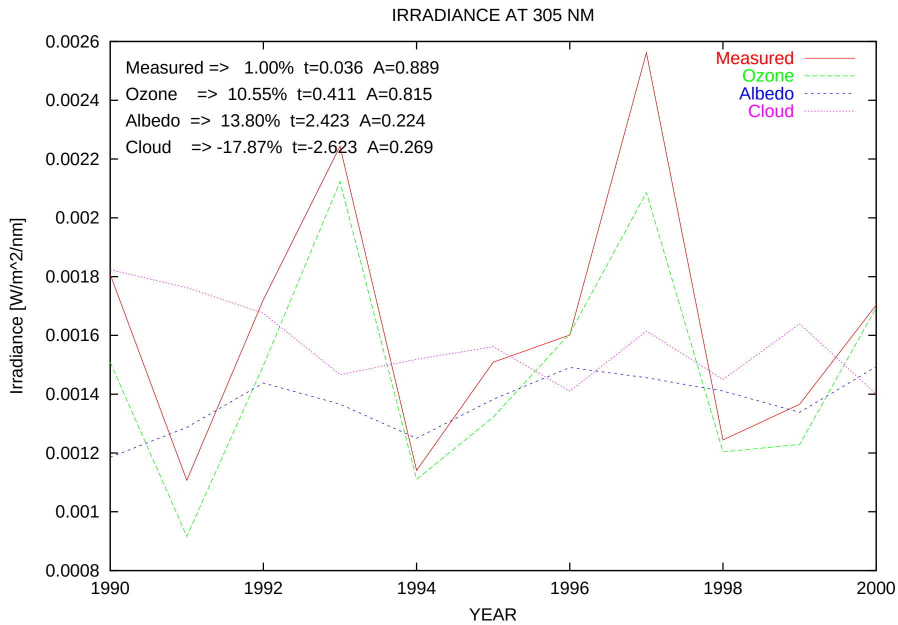

Figure 8. The simulated irradiance values at 305 nm in Sodankylä for April 15 to May 15 of the period of 1990 to 2000. The effect of different UV affecting factors.

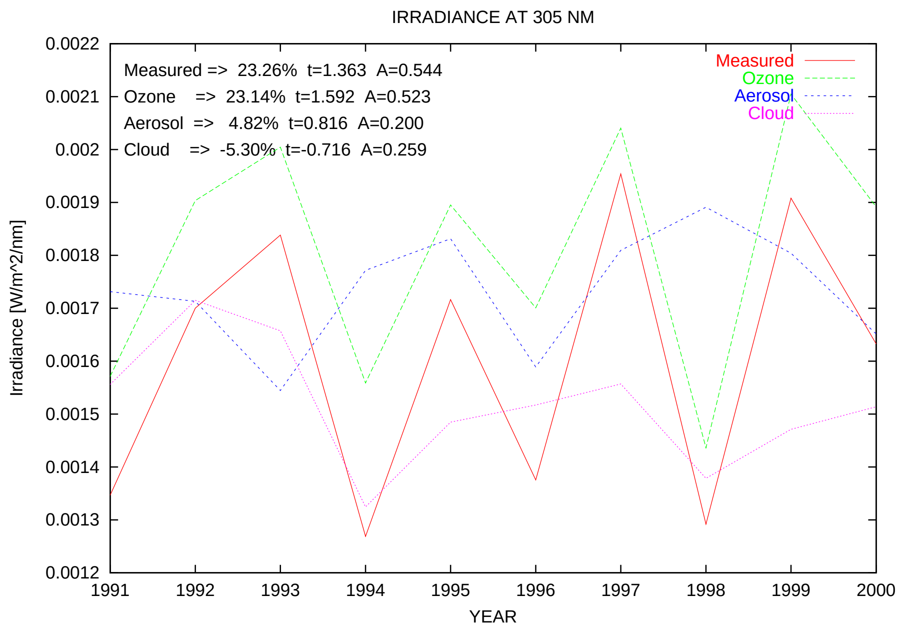

Figure 9. The simulated irradiance values at 305 nm in Thessaloniki for April 15 to May 15 of the period of 1990 to 2000. The effect of different UV affecting factors.

by spectra and the time series of monthly mean values are shown. Figure 9 shows the results for Thessaloniki. Similarly summer data of July for both sites are shown in Figure 10 and Figure 11.

It is interesting to inter-compare both sites and also the typical behavior of each factor in different seasons. In the upper left corner of each figure some statistics are printed; first the increase over the mean irradiance (as percent per decade) is shown, followed by a student t-test value. Peak-to-peak amplitude of the variability induced by each factor is also shown (A), which is calculated as follows: [max-min]/mean of irradiance values.

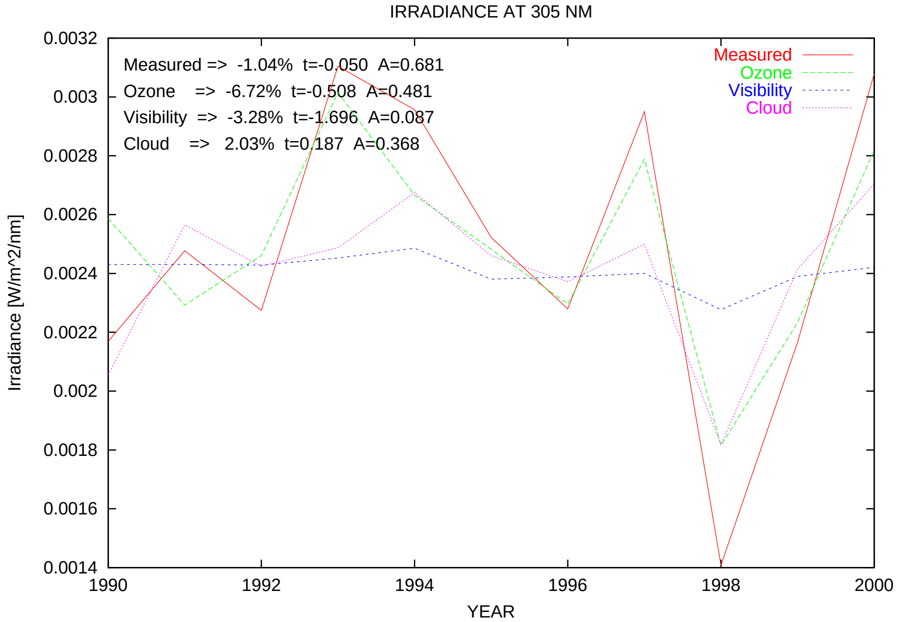

Figure 10. The simulated irradiance values at 305 nm in Sodankylä for July of the period of 1990 to 2000. The effect of different UV affecting factors.

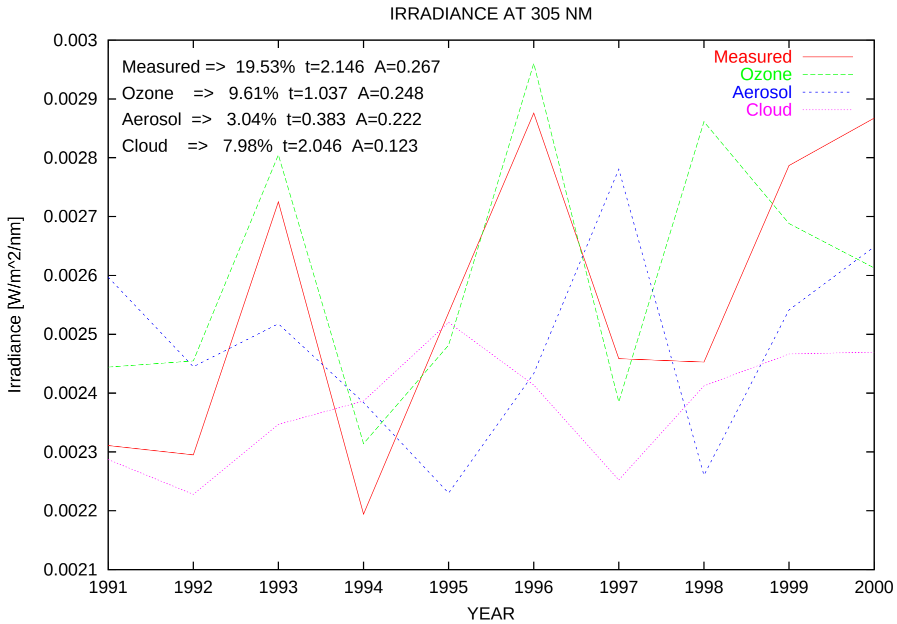

Figure 11. The simulated irradiance values at 305 nm in Thessaloniki for July of the period of 1990 to 2000. The effect of different UV affecting factors.

Quasi-biennial oscillation (QBO) and solar cycle have some effect on the amplitude values, *Zerefos et al.* [1998] estimated that the peak-to-peak amplitude of QBO in 305 nm irradiance in Thessaloniki is about 21%, while the signal of solar cycle is substantially less. Both effects have clearly reduced influence in the northern latitudes, i.e. the time series of spectral measurements of Sodankylä are less affected. These effects are not taken into account in the long-term increase estimates, which is justified by the fact that the data length of both sites is about one solar cycle and is very close to five cycles of QBO. Therefore it is argued that, although our main focus is not to estimate the trends themselves and their significance, the estimated values are not affected much by periodic signals, such as QBO and solar cycle. We want to strongly emphasize, however, that the periods investigated are very short to make any definite conclusions about long-term trends. *Fioletov et al.* [2001], for instance, studied the long-term UV changes over Canada with more than 30 years of data and it was evident that very different trend estimates can be obtained from 10-20 year data period if compared to the entire length. This is also theoretically supported by *Weatherhead et al.* [1998]. There is an additional point to note, which influences the long-term changes and their significance; Pinatubo eruption had a significant effect on low ozone values in 1992 and, particularly in 1993, (*Gleason et al.* [1993]; *Kerr and McElroy* [1993]), thus increasing the variance within this 11-year period.

If the model simulations of Sodankylä and Thessaloniki are compared it is apparent that the amplitude in the irradiance time series caused by ozone is much stronger in Sodankylä both in spring and summer, so longer time series is needed to detect any possible trend. Nevertheless, there was no significant ozone induced increase in Thessaloniki irradiance data either. The amplitude caused by cloudiness is very similar between these sites, while the effect of aerosols is stronger in Thessaloniki.

In the summer data of Thessaloniki there is a long-term increase, which is mainly caused by a negative trend in cloudiness. The impact of ozone in this long-term change supports the total effect, although it was found that in most cases additional variable only increases the variance, thus reducing the level of significance caused by a single factor. In other words, the observed increase in UV irradiance may have a very small significance, although some factor, such as cloudiness, can have a stronger signal embedded. The increase in the summer data of Thessaloniki agrees with *Ziemke et al.* [2000], who analyzed the Nimbus-7 global UV data for trends. They studied the period of 1979-1991 and estimated the global and seasonal trends in monthly erythemal UV. Spring season did not indicate trends in Europe and Mediterranean, however July and August exhibited significant increases. They speculated about the effect of decrease in cloudiness, which is supported by our study.

4. Conclusions

The results can be summarized as follows:

1) It is crucial to check the spectral data for any possible wavelength shift, if the long-term variability at a single wavelength is studied.

2) If the irradiance measurements of a given sza range are selected, even a rather narrow band of 2 degrees can introduce an effect that hampers the trend detection. In other words, it is important to remove the effect of sza and normalize all the measurements to some exact sza value, as was done in our study.

3) The methodology presented herein offers a way to to separate the effect of single factor, e.g. ozone, cloudiness, aerosols and albedo, in short- and long-term UV variability, using measurements of spectral irradiance. It is argued that although the absolute values of AOD at any given day, for instance, may not be very accurate, at the average

sense they are. Therefore, in long-term changes, when the long-term stability of the data is very important issue, their effects are captured.

4) If the effects of ozone, snow albedo and clouds are considered in short-term variability in monthly CIE doses, they can be very similar in magnitude, 25% to 30%.

5) The amplitude of the long-term variability caused by ozone is much stronger in Sodankylä than in Thessaloniki, so longer time series is needed to detect any possible trend. Nevertheless neither in Thessaloniki time series there was significant ozone caused increase. The amplitude caused by cloudiness is very similar between these sites, while the effect of aerosols is stronger in Thessaloniki.

6) In the summer data of Thessaloniki there is a long-term increase, which is mainly caused by cloudiness. The impact of ozone in this long-term change supports the total effect, although in most cases additional variable only increases the variance, thus reducing the level of significance. In other words, the observed trend in UV irradiance may have very small significance, although some factor, such as cloudiness, can have a more significant impact embedded. The increase in the summer data in Thessaloniki agrees with *Ziemke et al.* [2000], who analyzed the Nimbus-7 global UV data for trends. They speculated about the effect of decrease in cloudiness, which is supported by our study.

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