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Total solar radiation and the influence of clouds and aerosols on the biologically effective UV

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Abstract. Since clouds and aerosols contribute substantially to the attenuation of biologically effective UV at ground level it is important to consider their role in studies on UV climatology on earth. We describe a method to quantify this attenuation using spectral measurements of UV radiation at ground level and measurements of total solar radiation. The analysis presented gives a very good indication for a non-linear relation between the attenuation of biologically effective UV on the one hand and total solar radiation on the other. An UV-climatology can be calculated using the relations found.

Introduction

The reported worldwide decrease in the ozone layer thickness [*Stolarski et al.*, 1992] has triggered the concern about a possible increase in the amount of biologically effective UV radiation reaching the surface of the earth. Since long-term measurements of spectrally resolved UV are lacking, trend analyses consist mainly of radiation transfer model studies that relate the biologically effective UV on earth to the total ozone column [e.g. *Madronich*, 1992]. Other studies combine UV calculations with UV measurements for clear-sky conditions [*Zheng and Basher*, 1993].

A climatology of the biologically effective UV budget is needed to assess the consequences of this climatology for public health. The influence of the different parameters that determine the transmission of UV through the atmosphere should be treated separately in the analysis used. Besides solar zenith angle and ozone these parameters include attenuation of UV by clouds and (tropospheric) aerosol. Indeed, recent studies indicate the significance of aerosols [*Liu et al.*, 1991] and clouds [*Frederick and Snell*, 1990] for the effective UV budget.

Given the complexity of treating the radiation transfer in an atmosphere with realistic cloud properties, model studies of the influence of clouds have focused on homogeneous layers of clouds. These studies apply therefore only to overcast conditions [e.g. *Lubin and Frederick*, 1991]. Because of the uncertainties in the model description, the influence of fractional cloud cover can best be studied in an empirical way, i.e. relating measurements of UV with simultaneous observations of cloud properties [see e.g. *Frederick and Snell*, 1990; *Frederick et al.*, 1993; *Ilyas*, 1987 or *Webb*, 1991].

Empirical studies may help to clarify the relation between radiation transfer and such atmospheric composites as trace gases, aerosols and clouds. Fractional cloud cover can be related to the total solar (or global) radiation [*Dutton et al.*, 1991]. We will use this to present a method that accounts for the attenuation of the effective UV dose by clouds, taking measurements of total solar radiation as a measure for cloudiness. Since data on the total solar radiation is available for long-term periods and for many locations on earth this method may prove to be useful in the evaluation of effective UV doses in the past.

Method

The data, used to establish the method, were recorded by the UV spectrometer system of the R.I.V.M., Bilthoven, The Netherlands (52.1°N, 5.2°E). The system, which came into operation in april 1993, consists of two separate components: a scanning double monochromator with photoncounting detection and a spectrograph with a diode array for spectral UV measurements [see *Reinen et al.*, 1993 for details]. The data consist of UV irradiances measured using the scanning double monochromator only, with wavelength intervals of 1 nm between 285 and 355 nm. These scans of approximately 9 min were made every 20 min. The response function of the instrument has a FWHM of 0.35 nm. In addition to UV measurements, the total solar radiation is measured with a pyranometer every 60 s. The total solar radiation in the interval of (roughly) 300 to 3000 nm is determined by taking the mean value of the pyranometer readouts during the scan in the UV-B region of the double monochromator.

The effective UV dose is defined here as the integral in the wavelength interval between 285 and 345 of the UV spectrum weighted with an action spectrum typical for carcinogenesis in hairless albino mice [see *Slaper*, 1987 and *Sterenborg*, 1987].

A radiation transfer model is used to calculate the effective UV dose, taking the influence of the solar zenith angle, the ozone column and tropospheric aerosol into account. These calculations serve as a reference for clear-sky conditions. In contrast, the actual weather conditions (i.e. the conditions during the measurements) include clouds, additional aerosol loading of the atmosphere and other possible radiation shielding. In the analysis, the measured effective UV doses for actual cloud conditions are compared to these calculations.

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The model applied uses a two-stream approximation to calculate the UV spectrum at the earth's surface [*de Leeuw*, 1988]. The model atmosphere consists of homogeneous layers of increasing thickness with altitude. The direct solar flux is reduced by absorption of ozone, Rayleigh scattering, and scattering of aerosol in each layer. Absorption cross sections for ozone are taken from *Molina and Molina*, [1986]. The equations for the diffuse flux are solved in an iteration procedure starting from a solar spectrum taken from *Mentall et al.*, [1981] and *Neckel and Labs*, [1984]. The model calculates UV irradiances in the range of 250-350 nm with a spectral resolution of 1 nm. The model takes into account a mean ozone profile [*Demerjian et al.*, 1980], an urban aerosol profile [*Diermendjian*, 1969] and a lambertian reflecting earth surface with an albedo value typical for land. Ozone column data are taken from daily mean values measured by a Brewer spectrometer at the KMI in Uccle, Belgium (50.5°N, 4.2°E), [*de Backer*].

Clear-sky values of the total solar radiation (TS_C) are calculated from the parametrization given in *Kasten and Czeplak*, [1980]:

$$TS_C = \alpha_1 cos(\theta) + \alpha_2 \tag{1}$$

where θ is the solar zenith angle and α_1 and α_2 are fit parameters. As distinct from [*Holtslag et al.*, 1983] this parametrization is taken here to represent the *maximum* value instead of the *mean* value for clear-sky conditions, in order to quantify the attenuation relative to true clear-sky conditions. We found that $\alpha_1 = 1100$ and $\alpha_2 = -60$. The analysis presented was limited to data taken at zenith angles smaller than 80° since the results of the calculations of both the effective UV and the total solar radiation are doubtful for larger angles.

Results

Measurements at the end of 1993, together with calculations for this period, are used to quantify the attenuation of UV radiation. This is done with the use of reduction factors (R), which are defined as the ratio of the measured radiation for actual weather conditions over the calculated radiation for clear-sky conditions. For the effective UV dose and total solar radiation they are R_{UV} and R_{TS}, respectively:

$$R_{UV} = \frac{UV}{UV_C}, \quad R_{TS} = \frac{TS}{TS_C} \tag{2}$$

where UV and TS denote the measured values and UV_C and TS_C denote calculated clear-sky values. As an example, Figure 1 shows the diurnal variation of both the measured and calculated effective UV dose on a day with clear-sky conditions. For this day the calculations reproduce the measured values within 6% for solar zenith angles smaller than 70°; for larger zenith angles the uncertainty is larger (up to 20% at 83°).

In Figure 2, R_{UV} is plotted against R_{TS} for data taken at zenith angles smaller than 87°. This figure shows a non-linear relation between R_{UV} and R_{TS}. The distribution of data points in this figure has therefore been fitted to the exponential relation:

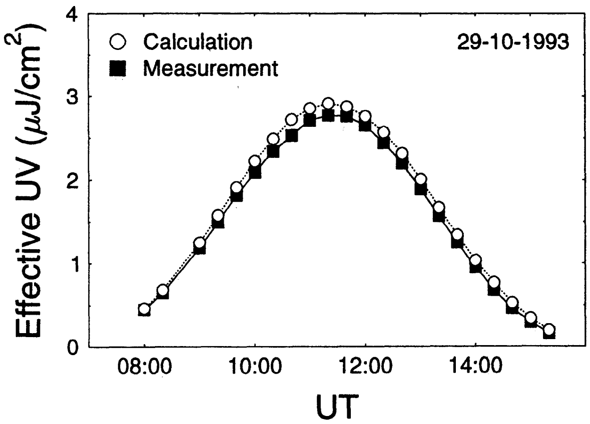

Figure 1. Diurnal variation under clear-sky conditions of the effective UV dose for both measurements (squares) and calculations (circles) on 29-10-1993.

$$R_{UV} = A(1 - e^{BR_{TS}}) \tag{3}$$

where A and B are fit parameters. For the individual data the fit parameters have the following values, $A = 1.0$ and $B = -2.7$.

The concentration of data around (R_{TS}, R_{UV}) = (1,1), where no reduction of both the effective UV dose and the total solar radiation occurs, shows that as expected for clear-sky conditions, the measured values are equal to the calculated values. The horizontal extent of this concentration means that even when the total solar radiation is attenuated down to 80%, the effective UV dose is equal to the clear-sky value. The concentration of data points in the lower left corner of the figure correspond to measurements with overcast skies when the total solar radiation as well as the effective UV dose are strongly attenuated. This concentration shows an almost linear behavior. The other data points show a large scatter connected to varying cloud conditions. The reduction factors have values up to 1.3. This

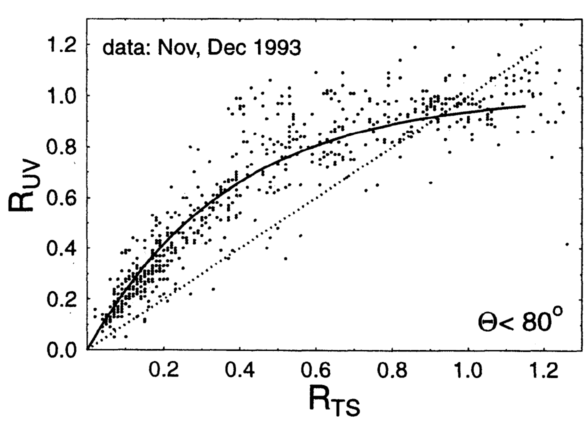

Figure 2. Reduction factors of total solar radiation measured simultaneously with UV. The solid line indicates the non-linear behaviour, the dotted line a one to one relation.

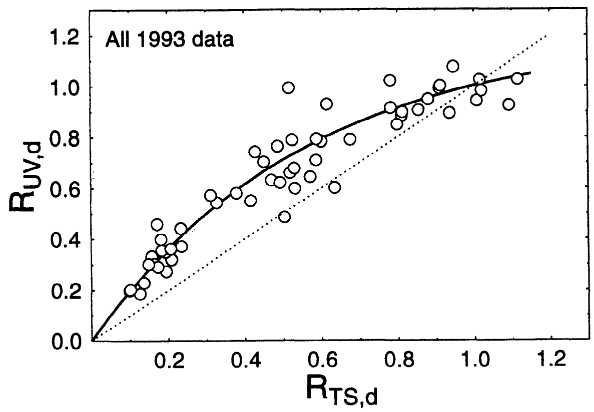

Figure 3. Reduction factors of total solar radiation measured simultaneously with UV. The solid line indicates the non-linear behaviour, the dotted line a one to one relation.

could be due to the reflection of solar radiation at the vertical edges of cumulus clouds or to very thin cirrus clouds that act as an UV greenhouse [*Madronich*, 1987].

The data for the individual measurements were also used to calculate the daily mean effective UV dose. The daily mean value of the reduction factors ($R_{UV,d}$), is calculated from the individual reduction factors weighted with the clear-sky calculated effective UV dose:

$$R_{UV,d} = \frac{\sum_i^N R_{UV} UV_C}{\sum_i^N UV_C} = \frac{\sum_i^N UV}{\sum_i^N UV_C} \qquad (4)$$

where the index i runs over all N measurements for a single day and the subscript d indicates daily mean values.

An analogous formula holds for the daily mean of the total solar radiation. In the calculation of the daily mean reduction factor representative for a whole day, only data from days with at least 10 measurements were taken. The daily mean reduction factors for data taken in 1993 are plotted in Figure 3. Bearing in mind the exponential behavior found for the individual data, the data of the daily mean reduction factors have also been fitted to eq. (3). The fit parameters are: $A_d = 1.2$ and $B_d = -1.8$. It is apparent from this figure that the presence of clouds may reduce the effective UV dose by a factor 2 to 5 on a daily basis. This emphasizes the relevance of quantifying the effects of clouds and aerosol in trend analyses of the UV budget.

Discussion and Conclusion

In this paper we have presented a method that quantifies the reduction of the UV budget due to clouds and aerosol in Bilthoven. The method combines measurements of total solar radiation with radiation transfer calculations using an isotropic two-stream model. The model uses actual ozone column data from Uccle. Since this site is geographically close to the R.I.V.M., these data are considered to be representative for Bilthoven.

In Figure 4 the effective UV doses calculated with this method are compared to values from actual measurements in 1993, i.e. including summer and fall data. Part of these data (October and November) were used to set up the method as described above. Perfect agreement between measured and calculated values would result in the dotted line. In the figure it can be seen that although not all data points coincide with this line, the agreement between measurement and calculation is good. The figure demonstrates the usefulness of this method in calculating UV doses under realistic atmospheric conditions.

The method presented is based on UV measurements during the fall, i.e. those with relatively large solar zenith angles. The good agreement found in Figure 4 shows that the method can also be applied to summer data. However, the parameter values found in the analysis might show some dependence on atmospheric conditions. Data taken during the summer will be used, firstly, to investigate the influence of different atmospheric conditions along with smaller zenith angles (the analysis of data taken during the summer of 94 is now being done) and secondly, to investigate possible year to year variations.

In *Frederick et al.*, [1993] a linear relation rather than an exponential one in a figure similar to Figure 3 is reported on, using data taken in Chicago. In that analysis Robertson-Berger UV measurements, and radiation transfer model calculations with ozone climatology data, are used. In contrast, we used spectrally resolved UV spectra together with actual ozone column data. Thus the ozone dependence of the UV dose is taken into account better. This separates the influence of ozone on UV radiation on the one hand, and of clouds and aerosol on the other more properly. The discrepancy in the results, however, stresses the importance of examining not only temporal dependencies but also the possible influence of location.

Ito et al., [1993] present an empirical equation that also relates the total solar radiation to standard UV radiation. The equation, solely based on measurements, is applied to estimate past UV-B irradiances. In the

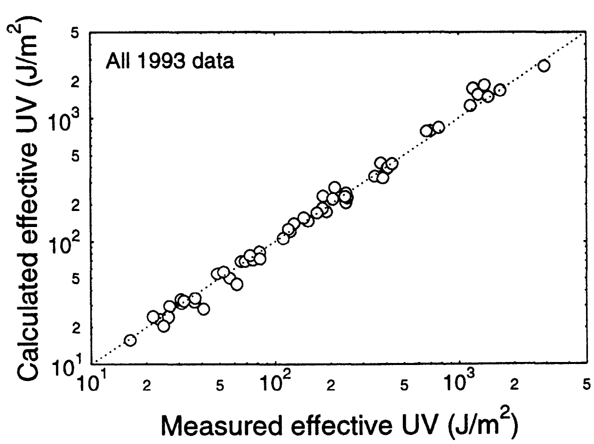

Figure 4. Comparison of the diurnal effective UV doses based on measurements and calculations using the method presented.

analysis presented we used model predictions relative to measurements, as expressed by the reduction factors in eq. (2), to remove the ozone and solar angle dependence in the relation of total solar radiation and effective UV. As a result, eq. (3) describes the influence of only clouds and aerosol on the effective UV. This nonlinear relation shows the non-similarity of the influence of clouds and aerosol on total solar radiation on the one hand and effective UV on the other. This non-similarity is due to the share of diffuse irradiance in UV radiation being larger than in total solar radiation. However, further study is needed to clarify the exact nature of the physical processes involved in this non-similarity.

Taking into account the above considerations, numerical results of the present method for calculating effective UV doses under realistic atmospheric conditions have to be regarded with some care. Despite the numerical uncertainty, the method presented here with the cited parameter values is useful in trend analyses since all available data on total solar radiation is treated in the same way. Such an analysis is necessary in assessing long-term risks of possible changes in UV radiation at ground level. It may therefore be concluded that the first results indicate the usefulness of the method in health research and will support further study.

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