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Comparison of measured and modelled uv indices for the assessment of health risks

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The World Health Organisation (WHO) and the World Meteorological Organisation (WMO) have jointly recommended that the UV Index (UVI) should be used to inform the public about possible health risks due to overexposure to solar radiation, especially skin damage. To test the current operational status of measuring and modelling techniques used in providing the public with UVI information, this article compares cloudless sky UVIs (measured using five instruments at four locations with different latitudes and climate) with the results of 13 models used in UVI forecasting schemes. For the models, only location, total ozone and solar zenith angle were provided as input parameters. In many cases the agreement is acceptable, i.e. less than 0.5 UVI. Larger differences may originate from instrumental errors and shortcomings in the models and their input parameters. A possible explanation for the differences between models is the treatment of the unknown input parameters, especially aerosols.

1. Introduction

The human health risk from solar ultraviolet (UV) radiation has become more important for two main reasons – one cultural and the other physical. In fair-skinned populations, a tan from UV exposure has become associated with good health and personal well-being; yet, due to stratospheric ozone depletion (SPARC, 1998), UV-B radiation (280–320 nm) may have increased. Overexposure of the skin to UV radiation, especially during childhood, significantly increases the risk of skin cancer (for example, see Moan & Dahlback, 1992; Ainsleigh 1993). It is also important to stress that apart from skin cancer, UV radiation also has negative effects on the skin associated with photoaging and photodamage (e.g. Lavker *et al.*, 1995; Frei *et al.*, 1998; Frei, 1999). Moreover, apart from the skin, negative effects of UV radiation on the eyes (cataract) and on the immune system have been documented as well (e.g. Taylor *et al.*, 1989; De Fabo *et al.*, 1990). The UV Index (UVI, see section 2 for its exact definition) is a means of informing the public about the strength of biologically effective, erythemal weighted UV radiation.

In many countries efforts are made to inform the public about these risks for human health reasons associated with concern about increasing UVB levels caused by ozone decrease. Mostly this is done by distributing forecast UVIs and warnings when the UVB levels are expected to be harmful. These UV intensity forecasts are based on the forecast of several input parameters (e.g. solar zenith angle, total ozone, surface albedo, and aerosol parameters) which are used in models to calculate the radiation levels. Different types of models are in use, from advanced multiple scattering radiative transfer models to simple regression models (which take only solar elevation and total ozone into account). Comparisons between different models and measurements of UVI are therefore important if we are to understand the influence of the different parameters. For public information purposes, it is necessary to have a uniform quality standard which can be applied across all countries. This is important given the fact that people travel a lot; the available information about UV radiation should be comparable everywhere, independent of the model used for the UVI forecast in the various countries. Investigations of different ways of obtaining UVI information are made in the framework of the COST (European Co-operation in the field of Scientific and Technical Research) Action 713. This Action co-ordinates the activities in different European countries with respect to the forecast of UVI. Mayer *et al.* (1997) made a comparison between measured UV spectra and model results under cloudless conditions. They found differences between measurements and models in the range of −11 to +2% with a statistical uncertainty of 2–3%. They showed that the agreement is very sensitive to the values of ozone content and the aerosol properties introduced as input parameter in the model. A case study by Pachart *et al.* (1997) revealed that, when aerosol optical depth and total ozone are known, an agreement within 5% between measurements with a well-calibrated instrument and results from a multiple scattering model can be obtained. Weihs & Webb (1997b) found differences of 5 to 10% between measurements and models when the aerosol properties are known. However, these parameters are not generally known.

Koepke *et al.* (1998) reported on a model benchmark to intercompare the performance of different models used for the prediction of UVIs based on information on aerosol and surface albedo as well as the total ozone content and the solar zenith angle. The agreement of the multiple scattering models was in the order of 5%, which shows the range of deviations due to the different calculation procedures, the assumed profiles and internal constants (e.g. temperature dependence of ozone absorption coefficients). The uncertainty of aerosol properties and albedo may have large effects on the modelled UVI (Schwander *et al.*, 1997). However with the current knowledge it is impossible to forecast regularly the aerosol optical depth at each site, and particularly its specific parameters such as the single scattering albedo and the asymmetry factor. Therefore, our study considers the albedo and aerosol parameters as part of the modelling, and consequently the set of given input parameters is restricted to those which are usually known or can be forecast at a site (solar zenith angle and total ozone) and the modellers had to decide what aerosol they should use based on their own knowledge.

Koepke *et al.* (1998) made no comparison with measured UVIs. The present study, initiated and carried out within the framework of the COST Action 713 of the European Commission, compares model results with routine observations in different environments. The goal is to test the actual status of the measurements and the models used for UVI calculations. Therefore the measurements as well as the models are treated as they are regularly used by their operators to derive UVI estimates for public dissemination. More information on the COST Action 713 can be found on the web page:
http://www.lamma.rete.toscana.it/uvweb/index.html

2. Method

The parameter to be compared is the UV index (UVI) because it is the aim of the COST Action 713 to produce a recommendation of methods to forecast and distribute UVIs. The (dimensionless) UVI is defined as:

$$UVI = \frac{40}{Wm^2} \int_{280\mathrm{nm}}^{400\mathrm{nm}} E(\lambda)A(\lambda)\mathrm{d}\lambda \qquad (1)$$

where $E(\lambda)$ is the irradiance at wavelength λ and $A(\lambda)$ is the (dimensionless) CIE action spectrum (McKinlay & Diffey, 1987; CIE, 1987).

For the comparison of the model results with measurements, data from different measuring stations taken under clear sky conditions during 1996 were considered. The selection of the clear days from the large station data sets was made by the persons responsible for each particular station. It should be noted that clear sky conditions in this context means no clouds *above* the observation point (at mountainous stations it is possible that there are clouds present at levels below the station level).

As total ozone is an important input parameter for all models, only stations that could provide concurrent total ozone measurements were selected. Since the goal of the exercise was to test the performance of the UVI models and not the quality of ozone forecasting schemes, the measured total ozone values were pro-

Table 1. *Stations and instruments providing measurements of UVI for this study.*

Station	Latitude	Longitude	Altitude (m)	Instrument	Type	Wavelength range (nm)	Days	Scans
Sodankylä	67.37°N	26.65°E	179	Brewer	single	290–325	8	176
Uccle	50.80°N	4.35°E	120	HD10 Jobin-Yvon	double	280–400	10	603
Thessaloniki	40.52°N	22.97°E	40	Brewer	double	286–366.5	11	247
Izaña1	28.30°N	16.49°W	2367	Brewer	single	290–325	15	578
Izaña2	28.30°N	16.49°W	2367	Brewer (FMI)	double	286–366.5	2	27

vided to the modellers. Since only clear days are used, the total ozone values are based on direct sun Brewer or Dobson observations. This means that the uncertainty in total ozone is less than 3% (Basher, 1982).

One of the aims of this study was to test the validity of the UVI forecasting schemes under environments with different, but unknown, aerosol content. Presently, no methodology is available for synoptic aerosol forecasting, so the model operators were asked to make the best possible guess of the aerosols, and other relevant input parameters, to be used in their model.

The UVI is intended for distribution to the public. In this context, an agreement within 0.5 UVI units, on an absolute scale of differences, is considered to be adequate for international consistency. It must also be kept in mind that both models and measurements have their own uncertainties, and none of them must be considered as 'truth'.

2.1. The measurements

Table 1 gives an overview of the stations and instruments selected for use in this study. Of the 1,631 scans available for this study in 1996, a selection was made of cloudless cases that represent different latitudes, altitudes, total ozone contents and solar zenith angles (SZAs). As to the SZAs, the measurements closest to 80°, 60°, 50°, 40°, 30° and the smallest SZA were selected. Finally, a subset of 63 cases was obtained which related to four latitudes, five instruments, five groups of solar zenith angle and total ozone between 240 and 420 DU. The modellers were provided with files containing the latitude and longitude, time of observation, solar zenith angle and total ozone.

Most instruments do not measure the whole range of the integral in equation (1). In these cases, extrapolation is performed as follows. If the intensities are not measured down to 280 nm, they are assumed to be zero below the lowest observed wavelength (generally 290 nm or lower), which is a good approximation since the irradiance at these wavelengths is very low. If the longer (320–400 nm or UVA) wavelengths are not scanned, the average of the five last scanning points is calculated, and this value is taken as the constant for the rest of the spectrum. Since the action spectrum decreases by a factor of 25 in the wavelength range 310–325 nm and by another factor of 25 from 325 to 400 nm, reasonable estimates of the UVI are possible for clear skies, even when the scanning range is limited to the 290–325 nm interval, as with single monochromator Brewer instruments. This was further verified with model calculations for 30 cases with solar zenith angles between 30° and 70° and total ozone between 200 and 450 with an aerosol optical depth of 0.38 at 340 nm. The mean difference between the UVI determined from the complete spectrum and from the above described extrapolation was 0.8% with a standard deviation of 1.2%. For a typical summer situation (300–350 DU ozone and 30° zenith angle) this deviation is – 0.2%. The values increase towards higher ozone and lower sun. Other realistic values for the aerosol optical depth yield comparable differences. Also, the direct comparison of UVIs calculated from simultaneous scans from a single (290–325 nm) and a double (286–366 nm) Brewer (as shown in Figure 1) demonstrates that the error due to the estimate of UVA is smaller than the uncertainty of the absolute calibration level of the instruments, which will now be discussed.

The measurements at Sodankylä are performed with a single monochromator Brewer operated and maintained by the Finnish Meteorological Institute. The primary and secondary standards are traceable to NIST (National Institute of Standards). Every month the

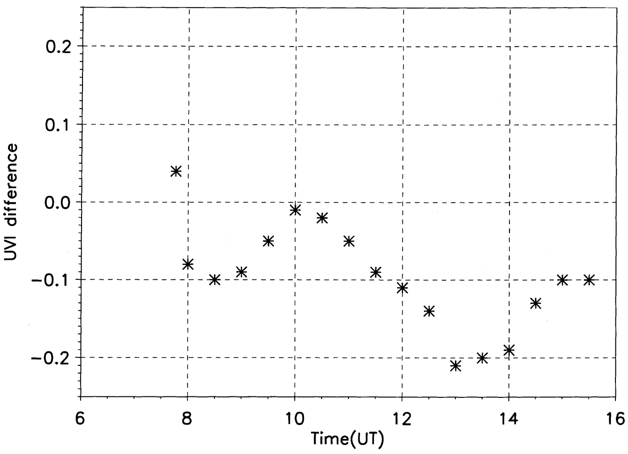


Figure 1. *Absolute differences between UVI measured with the single Spanish (Izaña1, 290–325 nm) and the double Finnish (Izaña2, 286–366.5 nm) Brewer monochromators at Izaña on 16 October 1996.*

stability is checked with 50 W lamps. The effect of stray light is reduced by subtracting the average signal below 292.5 nm. The data of this instrument have been completely recalculated (Masson *et al.*, 1998), and the new data used in this study were independently tested by reference to an intercomparison campaign at Izaña in 1996. The difference of the reprocessed data from the objective reference of the campaign (Slaper & Koskela, 1997) is ±0.06 UVI units at maximum, corresponding to 2–3% at noon. The wavelength accuracy of the Brewer, as analysed from the campaign data, was better than 0.03 nm. The station is located in a predominantly flat area, with snow cover from November to April, but this information was not communicated to the modellers.

At Uccle, measurements were performed with a Jobin-Yvon HD10 double monochromator, operated by the Belgian Institute of Space Aeronomy. During 1996 its calibration was checked three times against 1000 W, NIST-certified lamps in the laboratory. About every two weeks the stability of the instrument is tested with three 200 W lamps in a transportable lamp system, which allows a calibration without any displacement of the instrument. If deviations of more than 2% are found, a new full recalibration in the laboratory is scheduled. With this procedure the calibration stability of the instrument is estimated to be within 2–3%.

The UVI data for Thessaloniki were obtained from spectral measurements, in the region 286–366 nm, made with a double monochromator Brewer spectroradiometer, operated by the Laboratory of Atmospheric Physics at the Aristotle University of Thessaloniki. In 1996, the spectroradiometer was calibrated once every month with the use of a 1000 W, NIST-traceable source of spectral irradiance. From the calibration record, it appears that the calibration stability of the instrument was within about 2.5%. The measurements were corrected for the instrument's cosine response following the methodology described in Bais *et al.* (1998).

At Izaña there are two data sources. A first set of measurements (referred to as Izaña1) is obtained with the single monochromator Brewer operated permanently at the site by the Spanish Meteorological Institute. Data used here were obtained in a period between two major calibrations (in 1995 and 1996) with 1000 W lamps. Routine checks of the 40 W lamp every two weeks during this period showed no deviations larger than 3%. The instrument participated in the Nordic intercomparison campaign in October 1996, where it deviated about 5–6% above the reference (Koskela *et al.*, 1997). This difference was only about 1% higher than a previous calibration in 1995, which indicates the stability of this instrument. However, the SUSPEN campaign (Bais, 1998) showed that the instrument was lower by about 10% than the cosine corrected reference. During the SUSPEN intercomparison a new calibration reference was used. Combined with the cosine correction of the reference, this can explain the different results between NOGIC and SUSPEN. For this study the data were adjusted to the SUSPEN calibration level. Straylight correction is done as usual for single Brewer instruments by subtracting the average counts of the wavelengths below 292.5 nm from the whole spectrum. Recently a new double monochromator Brewer was installed, and a preliminary intercomparison of five months of data (approximately 600 simultaneous scans) shows that the mean difference in UVI, derived from the two instruments and attributed to straylight, is about 0% (0.005%) with a standard deviation of 1%. The combined uncertainty on the UVI values from the stability of this instrument (3%), the estimate of UVA (1.2%), and the detected drift of 1% is about 5%.

Special attention should be drawn here to the location. The observatory is on a high mountain on an island. This may affect the local albedo, since the observing site is often surrounded by sea clouds below the observatory. It was shown by Dahlback (1997) that the presence of these lower level clouds may increase UV radiation by 10%. It should also be noted that the horizon of the Brewer is obstructed not only by small orographic obstacles but also by a dome to the south. Sometimes the site is affected by Sahara dust outbreaks. In the data used here the presence of light dust was reported for the summer observations. Days with heavy dust outbreaks were excluded from this analysis.

The second instrument at Izaña is a double monochromator Brewer of the Finnish Meteorological Institute (named Izaña2) which was used in the Nordic intercomparison campaign in October 1996. The primary calibration of this instrument is also traceable to NIST. Additional stability checks are performed every one to two weeks. Data originally collected as a blind test during the campaign are used here. The differences from the objective reference of the campaign (Slaper & Koskela, 1997) were always positive and amounted to 0.10 UVI units as a daily average and at maximum 0.18 UVI units at noon which was equivalent to 2–3% of the near noon readings. This overestimation is partly attributed to a small wavelength shift of +0.08 to +0.06 nm in the UV-B domain. The observing conditions are described by Cuevas & Dahlback (1994).

The regular calibration checks show that the stability of all instruments is about 3%. The uncertainty on the measurements is higher, since the uncertainty of the calibration standard, the error on the transfer of the calibration, and the error on the estimate of the UVA part of the spectrum must also be taken into account. This combined error may be estimated to be about 10% for all instruments.

2.2. The models

Most of the models also participated in the model intercomparison by Koepke *et al.* (1998) although, in some cases, newer versions of the algorithm are used in this study. However, no conceptual changes have been introduced. The institutes involved with the models examined are listed in Table 2. The acronyms in this table are used later in the text and in the figures to identify the models. The models, divided into different groups for convenience in the discussion, are described briefly below. As no information on the albedo and aerosol was provided (which is generally not available and the aim of this study was to simulate a real forecasting situation) each modeller had to make reasonable assumptions of these parameters. Overviews of the different albedo values and assumed aerosol optical depths are listed in Tables 3 and 4, respectively. Since the aim was to test the models as they are used operationally, the single scattering albedo and the asymmetry factor (if applicable to the particular model) have also been chosen by the modelling groups.

Group a: Spectral models – part 1

- The UNIB UV modelling has been performed with the radiative transfer model GOMETRAN (Rozanov *et al.*, 1997), including full multiple scattering and a parameterisation scheme for aerosols. The aerosol properties are estimated with the help of the GADS data set (Koepke *et al.*, 1997).
- The IMWM calculations are based on the UVSPEC model (Kylling, 1994) with different atmospheres for the different sites and seasons.
- The MIM results were obtained with STAR (Ruggaber *et al.*, 1994). Special attention was drawn to the aerosol content. The aerosol properties were taken from OPAC (Hess *et al.*, 1998) with respect to the meteorological conditions.

Group b: Spectral models – part 2

- The model NCAR1 is the UVSPEC model from the libRadtran package (Kylling & Mayer, 1998), a new and improved version of the original UVSPEC model (Kylling, 1994).
- UNBA calculations were done following the SMARTS2 model (Gueymard, 1995) with aerosol models adapted to the stations.
- Also FMI1 is the SMARTS2 model of Gueymard (1995).
- FMI2 is the SBDART (Santa Barbara Disort), based on a discrete ordinates radiative transfer module (Stamnes *et al.*, 1988) and low atmospheric transmission models with solar data from LOWTRAN7 (Kneizys *et al.*, 1988).

Group c: Tropospheric Ultraviolet and Visible (TUV) spectral models

- At KMI the TUV model version 3.0 (Madronich, 1993) was used.
- Also LAP used the Tropospheric Ultraviolet and Visible model (TUV 3.8) (Madronich, 1993).
- Model NCAR2 is the newer TUV 4 (Madronich, 1998).

Group d: Models without explicit use of aerosol or albedo

- The CHMI model is essentially the Canadian empirical model (Burrows *et al.*, 1994) with Czech

Table 2. *Models participating in the measurement–model comparison. The different groups of models correspond to those used in the figures.*

Model acronym	Institute	Country	Model	Type
Group a				
UNIB	University Bremen	Germany	GOMETRAN++	Radiative transfer
IMWM	Institute for Meteorology and Water Management	Poland	UVSPEC	Radiative transfer
MIM	Meteorological Institute München	Germany	STAR	Radiative transfer
Group b				
NCAR1	National Centre for Atmospheric Research	USA	libRadtran	Radiative transfer
UNBA	University Barcelona	Spain	SMARTS2	Radiative transfer
FMI1	Finnish Meteorological Institute	Finland	SMARTS2	Radiative transfer
FMI2	Finnish Meteorological Institute	Finland	SBDART	Radiative transfer
Group c				
KMI	Royal Meteorological Institute	Belgium	TUV3	Radiative transfer
LAP	University Thessaloniki	Greece	TUV3.8	Radiative transfer
NCAR2	National Centre for Atmospheric Research	USA	TUV 4	Radiative transfer
Group d				
CHMI	Hydrometeorological Institute	Czech Republic	Canadian	Empirical
ETHZ	Federal Institute of technology Zürich	Switzerland	Swiss	Empirical
IMPB	University Wien	Austria	Diffey	Radiative transfer

Table 3. *Albedo assumed by the different models. Where two values are given, the first is for summer, the second for winter.*

Model	Albedo			
	Sodankylä	Uccle	Thessaloniki	Izaña
Group a				
UNIB	0.05	0.05	0.05	0.05
IMWM	0.03/0.5	0.03/0.5	0.03	0.03
MIM	0.02/0.58	0.02	0.02	0.25
Group b				
NCAR1	0.05	0.05	0.05	0.05
UNBA	0.20	0.20	0.20	0.20
FMI1	0.05/0.8	0.05/0.8	0.05	0.05
FMI2	0.05/0.8	0.05/0.8	0.05	0.05
Group c				
KMI	0.05	0.05	0.05	0.05
LAP	0.05	0.05	0.05	0.05
NCAR2	0.05	0.05	0.05	0.05
Group d				
CHMI	Not applicable			
ETHZ	Not applicable			
IMPB	Not applicable			

Table 4. *Aerosol optical depths at 340 nm assumed by the different models. Where two values are given, the first is for summer, the second for winter. The model FMI2 used the visibility as turbidity parameter, with values of 50, 25, 25 and 50 km for Sodankylä, Uccle, Thessaloniki and Izaña respectively.*

Model	Aerosol Optical Depth			
	Sodankylä	Uccle	Thessaloniki	Izaña
Group a				
UNIB	0.08	0.25	0.25	0.17
IMWM	0.20	0.30	0.40	0.10
MIM	0.08/0.13	0.41–0.66/ 0.25–0.50	0.33/0.83	0.04
Group b				
NCAR1	0.30	0.30	0.50	0.10
UNBA	0.38	0.38	0.38	0.38
FMI1	0.46	0.45	0.45	0.42
FMI2	Not applicable			
Group c				
KMI	0.38	0.38	0.38	0.38
LAP	0.25	0.38	0.38	0.15
NCAR2	0.30	0.30	0.50	0.10
Group d				
CHMI	Not applicable			
ETHZ	Not applicable			
IMPB	Not applicable			

regression coefficients (Vanicek, 1997) and corrections for the altitude of Izaña.

- The ETHZ model is a statistical model (Renaud, 2000). The parameters were estimated from measurements at Davos (Switzerland). Correction for the differences in altitude between the actual stations and Davos are used.
- The IMPB model (Schauberger *et al.*, 1997) is essentially the model described by Diffey (1977) with the use of total ozone, solar elevation and altitude. The aerosol and surface albedo parameters are disabled.

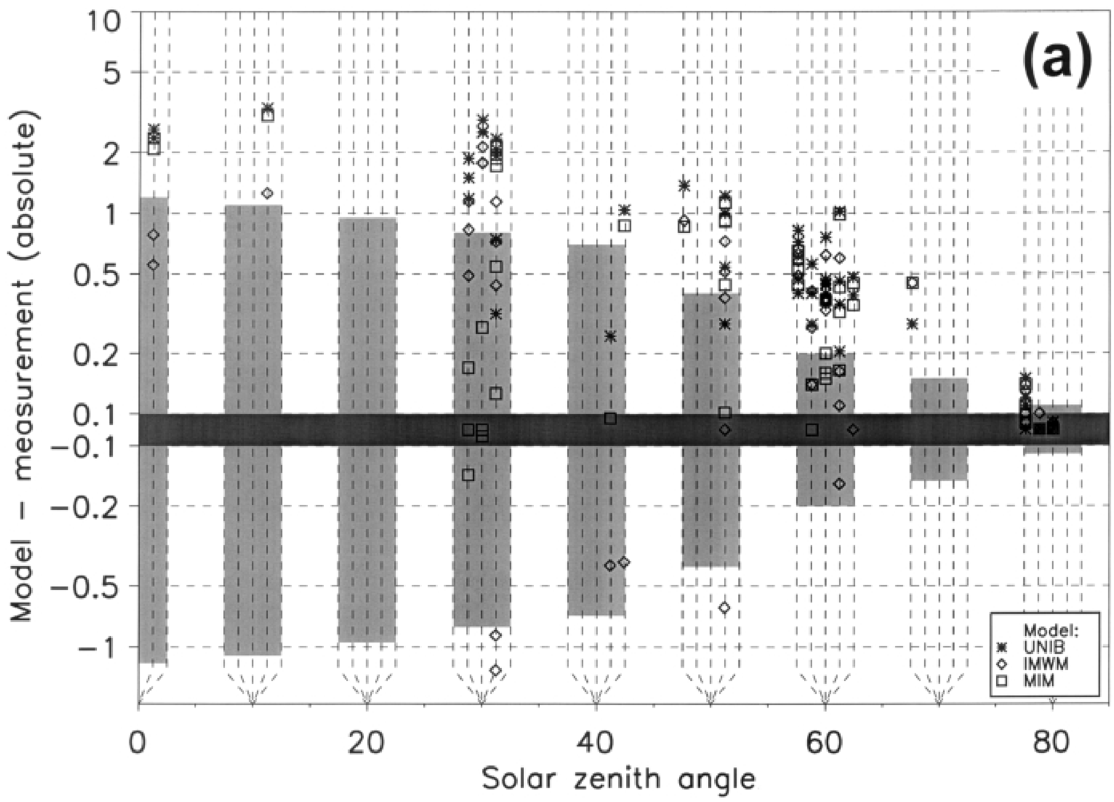
For the albedo, all modellers assumed similar summer values for all the different sites, while only three of them introduced higher winter values. This illustrates that parameters in models are often fixed, even when there is no physical basis for it. The high albedo value for Izaña used by MIM was taken to consider the effect of a cloud layer below the station, which was assumed to be present.

Of the aerosols' properties only the optical depth at 340 nm (AOD) is listed, without the other features available in some models (e.g. single scattering albedo, spectral behaviour, vertical distribution). Again the tendency to use fixed values for what are probably high variable parameters is apparent. Only MIM uses individually adjusted aerosol properties, according to the prevailing weather conditions during the observation. It may also be noted that some models assume very clean atmospheres for Sodankylä and Izaña, while the values for the urban sites of Uccle and Thessaloniki are generally higher.

3. Results and discussion

The comparison was a blind test, which means that the measured UVIs were not available to the modellers. Figure 2 shows the absolute differences between modelled and measured UVIs as a function of SZA. The y-axis of these figures consists of two logarithmic parts (for positive and negative differences). All cases where the absolute value of the differences is smaller than 0.1 UVI units are plotted in the central dark grey zone. The purpose of this particular scale is to show in one and the same plot the detailed aspects as well as the large range of the differences observed. Absolute differences are given since in most cases the UVI is disseminated to the public with one decimal, and percentage differences would emphasise the differences at low UV irradiance (UVI less than 2), where the biological effect is less important. In interpreting the plots, note that the UVI is typically about 0.5, 2, 6–10 and 10–13 at 80°, 60°, 30° and 10° SZA, respectively. The corresponding 10% uncertainties of the measurements are shown by the vertical light grey bars in Figure 2.

As stated above, differences of less than 0.5 can be considered as sufficient agreement for UVI public information. If the total uncertainty of the measurements (which is about 10% for well-calibrated and well-maintained instruments) is taken into account, differences of 10% (i.e. about 1 UVI unit at 20° SZA) are to be considered acceptable. The figures clearly show that even in this intercomparison (based on measured – not forecast – ozone data), larger discrepancies are found. The



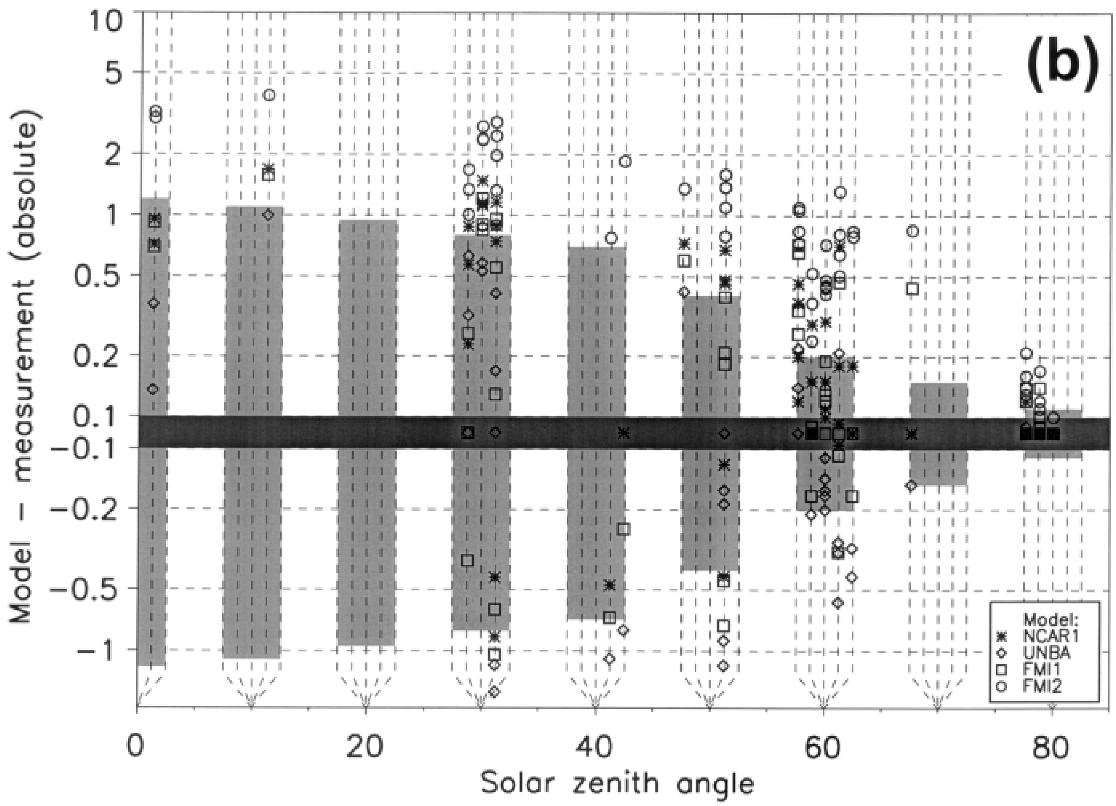


Figure 2. *Absolute differences in UVI units between model and measurements results for (a) Group a models, (b) Group b models, (c) Group c models and (d) Group d models as a function of SZA. The different symbols refer to the different models as shown in each key. The results are shown for each ten degrees SZA interval from left to right for Sodankylä, Uccle, Thessaloniki, Izaña1 and Izaña2. The light grey vertical bars show the estimated uncertainty of the measurements (10%).*

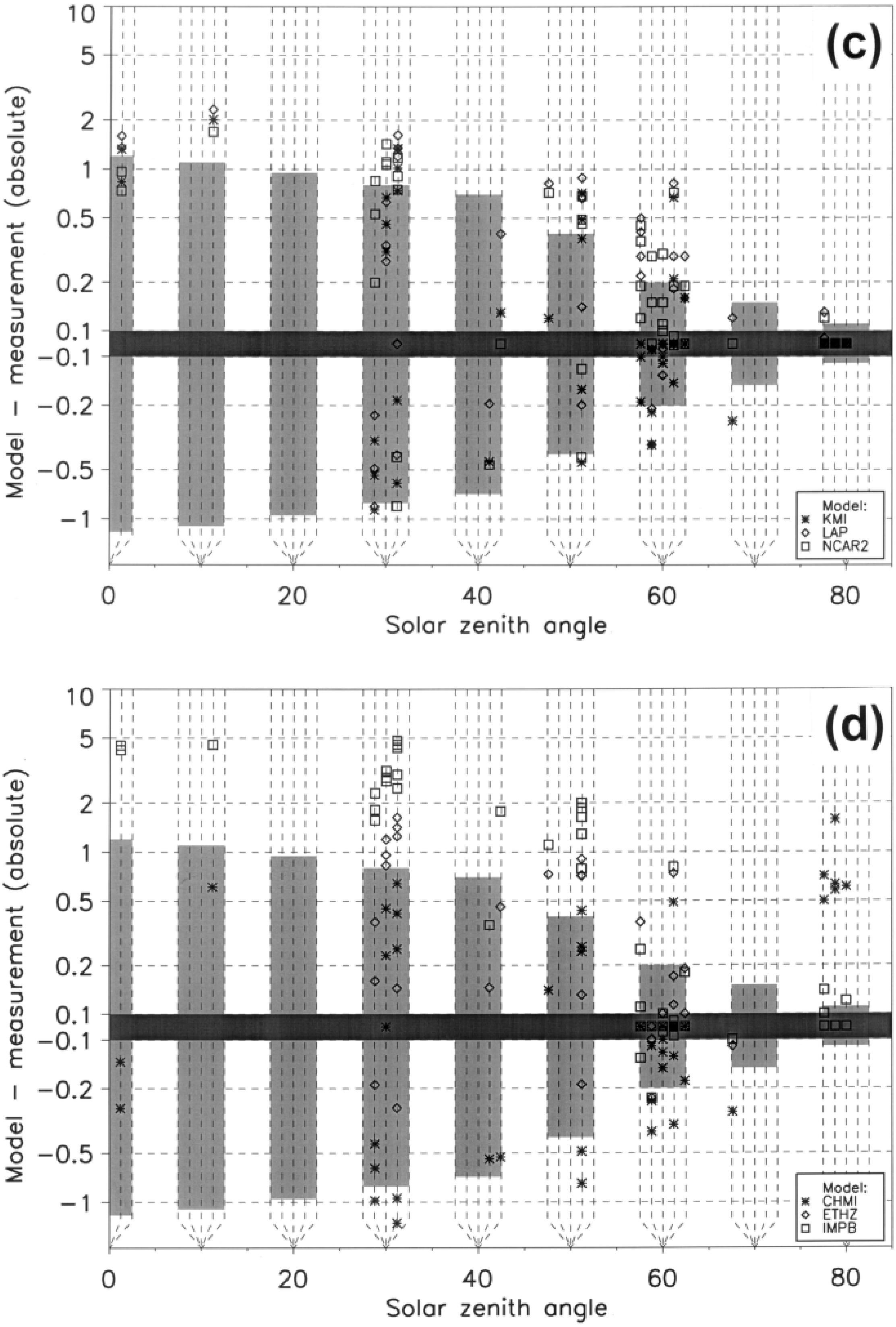


Figure 2. *Continued*

following sections discuss the differences in some detail.

3.1. Comparison between models

A previous model intercomparison (Koepke *et al.*, 1998) showed that differences between multiple scattering models are within 5% if the input data are specified in sufficient detail. In our investigation, only location, solar zenith angle and total ozone were provided. The other parameters (albedo and aerosol optical properties) had to be estimated by the modeller for each model run. The different estimating methods explain the larger differences between the model results compared with those of Koepke *et al.* (1998). As expected, the UVIs calculated with multiple scattering models for the different stations and solar zenith angles decrease with increasing optical depth. This effect is superimposed on the model properties discussed by Koepke *et al.* (1998). For example, the empirical models produce larger deviations at low sun (e.g. CHMI at 80° SZA; ETHZ did not give estimates for these SZA).

It is remarkable that the regression models (CHMI and ETHZ) are generally within the range of the other models, even when regression coefficients obtained at one site are applied to another location. Extrapolation of the models outside the SZA range that was used to determine the regression coefficients gives only a rough estimate. The IMPB model results, neglecting aerosol and albedo effects, give the highest model results.

It is interesting to see the different results obtained by the same model (SMARTS2) implemented by different groups (UNBA and FMI1). The different treatment of the unknown input parameters leads to quite different results. While UNBA results are generally low compared to the other models, the FMI1 results are close to the mean of all models. This illustrates the importance of the estimate of the input parameters.

The results of the TUV models (KMI, LAP and NCAR2) are very close for Uccle and Thessaloniki, but differ more for the other locations, especially for Izaña. This may be due to the difference in the selected aerosol optical depths (Table 4). Here again, the lower AODs of NCAR2 produce the higher UVIs. Other reasons for the discrepancy between the TUV model results may be the use of different choices for selectable input data such as the extra-terrestrial spectra or the ozone absorption cross-sections.

3.2. Comparison between models and measurements

The dominant feature of the plots is that in general the models give higher UVI values than the observations. If the data are plotted as a function of total ozone (not shown here) no clear dependence on total ozone is seen. The systematic difference may be caused, for example, by an underestimation of aerosol extinction or an overestimation of surface albedo by the models, or by the uncertainty of the measurements. One of the measurement errors is an uncorrected cosine error, which generally leads to an underestimation of the measured irradiances, varying between 3% and 7% (Bais *et al.*, 1998).

The best agreement between models and measurements is reached at Thessaloniki and Uccle. For these stations all the modellers, who had to provide aerosol input, have chosen a high aerosol load. It may also be noted that these stations operate double monochromators. It is worth mentioning that the results of the model where efforts were made to include specific aerosol information (MIM) give the smallest differences. This implies that most models can probably be improved if better aerosol estimates are applied. It has also been shown by Kylling *et al.* (1998) that UVB irradiance may change by 2 to 35% if the aerosol optical depth varies between 0.2 and 1 at 355 nm. Similarly Reuder & Schwander (1999) found a reduction of 25% of UV irradiances between clean (AOD = 0.1, Single Scattering Albedo SSA = 0.95 at 400 nm) and turbid (AOD = 0.8, SSA = 0.88 at 400 nm) atmospheres. Although the empirical models do not include an explicit treatment of aerosols, their relatively good correspondences can be explained by the fact that the regression technique implicitly takes aerosols into account. Therefore this type of model will work best for the location where the regression data originated.

Although in Sodankylä a single monochromator Brewer is in use, it seems that the results of the comparison are mostly within 1 UVI unit. It must be noted, however, that due to the high latitude, observations are only possible at relatively high SZA, and thus the UVI is always lower than 4 in this data set. For these low absolute values the model results generally overestimate the UVI. Possible explanations for this are the uncertainty of models at low sun, an underestimation of the turbidity of the atmosphere (models generally assume low AODs for Sodankylä), or an overestimation of the albedo. The latter may be true during winter, when the snow cover is not complete, but does not hold during summer. Of course the uncertainty of the measurement must also be taken into account.

At Izaña most model results are higher than the measurements (well over 10% on some occasions) for both Brewers. Given the careful maintenance of these instruments, the cause of the differences must be found elsewhere. Dust blown from the Sahara, for example, may explain part of the differences. As mentioned before, the presence of light dust was reported on three of the four observing days during summer. On these days a maximum difference of about 2 UVI units between the KMI model and the measurements was found, while on the summer day without reported dust, this was about 1 UVI unit.

4. Conclusions

Differences between modelled and measured UVIs under different environments have been discussed. It was found that the main differences between models can be attributed to different assumptions for unknown input parameters, of which the aerosol content is probably the most important. Model investigations by different groups (Mayer *et al.*, 1997; Kylling *et al.*, 1998; Reuder & Schwander, 1999; Weihs & Webb, 1997a) also indicate that large uncertainties (amounting to 5–8% at 380 nm and even higher at 305 nm) in model results are caused by uncertainties in the assumed aerosol properties of the atmosphere.

Since comparisons of measurements with models, when aerosol information is available, revealed discrepancies of 5 to 10% (see Pachart *et al.*, 1997; Weihs & Webb, 1997a), we can consider in our study, where the model input parameters had to be estimated, differences of 10% as very satisfactory. The occasionally large discrepancies between models and measurements of more than 2 UVI units at Izaña, representing large differences in health risk from UV radiation, may be partly due to Sahara dust outbreaks. Except in these special conditions, the agreement between models and measurements is not too bad, considering the usual measuring uncertainty and the fact that several atmospheric parameters were estimated. It may also be noted that the model predictions tend to overestimate UVI values, which is less dangerous for health than underestimation would be. Nevertheless, to produce more accurate information for the public, discrepancies of more than 10% which are also larger than 1 UVI unit need further study.

Which model is most appropriate for a certain application will depend on the aims, and the available resources. To produce a UVI forecast in the absence of information on specific atmospheric conditions, a simple empirical model may be sufficient. To take advantage of the more complex models, additional input information on the state of the atmosphere is necessary. For the study of the effect of aerosols, a complete radiative transfer model is required, together with a complete set of observations describing the atmospheric properties (ozone, albedo, aerosols).

Part of the uncertainty comes from the inability to describe, with sufficient accuracy, the characteristics of the expected aerosol contents of the atmosphere. Therefore, this issue will be studied in more detail in the future. At present it can already be concluded that simple average aerosol values, adapted to individual locations, will improve the model results. A further step in the COST Action 713 aimed at evaluating forecasted UVIs will be the validation of ozone forecasts and finally the comparison of real forecasted UVIs with measurements.

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References

Ainsleigh, H. G. (1993). Beneficial effects of sun exposure on cancer mortality. *Prev. Med.*, **22**: 132–140.

Bais, A. F. (Ed.) (1998). Standardisation of Ultraviolet Spectroradiometry in Preparation of a European Network (SUSPEN), *Final Report, European Commission Dir. Gen. XII*, Luxembourg.

Bais, A. F., Kazadzis, S., Balis, D., Zerefos, C. S., & Blumthaler, M. (1998). Correcting global solar ultraviolet spectra recorded by a Brewer spectroradiometer for its angular response error. *Appl. Optics*, **37**: 6339–6344.

Basher, R. E. (1982). Review of the Dobson spectrophotometer and is accuracy, *WMO Global Ozone Research and Monitoring Project, Report No. 13*, WMO, Geneva.

Burrows, W. R., Vallee, M., Wardle, D. I., Kerr, J. B., Wilson, L. J. & Tarasick, D. W. (1994). The Canadian operational procedure for forecasting total ozone and UV radiation. *Meteorol. Appl.*, **1**: 247–265.

CIE (1987). A reference action spectrum for ultraviolet induced erythema in human skin. *CIE-Journal*, **6**: 17–22.

Cuevas, E. & Dahlback, A. (1994). Location and conditions. In *Final Report of The Nordic Intercomparison of Ultraviolet and Total Ozone Instruments at Izaña from 24 October to 5 November 1993*, edited by T. Koskela, Finn. Meteorol. Inst., Meteorological Publications No. 27, ISBN 951-697-412-0, 23–26.

Dahlback, A. (1997). Clouds and UV radiation. In *Final Report of the Nordic Intercomparison of Ultraviolet and Total Ozone Instruments at Izaña, October 1996*, edited by B. Kjeldstad, B. Johnsen and T. Koskela, Finn. Meteorol. Inst., Meteorological Publications No. 36, ISBN 951-697-475-9, 173–178.

De Fabo, E. C., Noonan, F. P. & Frederick, J. E. (1990). Biologically effective doses of sunlight for immune suppression at various latitudes and their relationship to changes in stratospheric ozone. *Photochemistry and Photobiology*, **52**: 811–817.

Diffey, B. L. (1977). The calculation of the spectral distribution of natural ultraviolet radiation under clear day conditions. *Phys. Med. Biol.*, **22**: 309–316.

Frei, Th., Dummer, R. & Gehrig, R. (1998). Die UV-Belastung in der Schweiz: Abhängigkeit von Ort und Zeit und ihre Bedeutung für die Haut. *Praxis*, **88**: 1023–1029.

Frei, Th. (1999). Die Stärke der ultravioletten Strahlung in verschiedenen Höhenlagen der Schweiz und ihre Bedeutung für die Gesundheitsvorsorge. *Prävention und Rehabilitation*, **11**: 28–36.

Gueymard, C. (1995). SMARTS2, A simple model of the atmospheric radiative transfer of sunshine: algorithms and performance assessment. *Florida Solar Energy Center, Rep. FSEC-PF-270-95*, 83 pp, Florida.

Hess, M, Koepke, P. & Schult, I. (1998). Optical properties of aerosols and clouds: the software package OPAC. *Bull. Am. Meteorol. Soc.*, **79**: 831–844.

Kneizys F. X., Shettle, E. P., Abreu, L. W., Chetwynd, J. H., Anderson, G. P., Gallery, W. O., Selby, J. E. A., & Clough, S. A. (1988). LOWTRAN 7. *AFGL-TR-88-0177, Envir. Res. Papers*, No. 1010.

Koepke, P., Hess, M., Schult, I. & Shettle, E. P. (1997). Global Aerosol Data Set. *Report No. 243, Max-Planck-Inst. Meteorol., Hamburg, Germany*, 44 pp.

Koepke, P., Bais, A., Balis, D., Buchwitz, M., De Backer, H., de Cabo, X., Eckert, P., Eriksen, P., Gillotay, D., Koskela, T., Lapeta, B., Litynska, Z., Lorente, J., Mayer, B., Renaud, A., Ruggaber, A., Schauberger, G., Seckmeyer, G., Seifert, P., Schmalwieser, A., Schwander, H., Vanicek, K. & Weber, M. (1998). Comparison of models used for UV index-calculations. *Photochemistry and Photobiology*, **67**: 657–662.

Koskela, T., Johnsen, B., Bais, A., Josefsson, W. & Slaper, H. (1997). Spectral sky measurements. In *Final Report of the Nordic Intercomparison of Ultraviolet and Total Ozone Instruments at Izaña, October 1996*, edited by B. Kjeldstad, B. Johnsen and T. Koskela, Finn. Meteorol. Inst., Meteorological Publications No. 36, ISBN 951-697-475-9, 109–148.

Kylling, A. (1994). UVSPEC, a program for calculation of diffuse and direct UV and visible fluxes and intensities at any altitude. Available on http://www.libradtran.org

Kylling, A. & Mayer, B. (1998). libRadtran – A library for radiative transfer calculations. Available on http://www.libradtran.org

Kylling, A., Bais, A. F., Blumthaler, M., Shreder, J. & Zerefos, C. S. (1998). UV irradiances during the PAUR campaign: comparison between measurement and model simulations, *J. Geophys. Res.*, **103**: 26051–26060.

Lavker, R. M., Gerberick, G. F., Veres, D., Irwin, C. J. & Kaidbey, K. H. (1995). Cumulative effects from repeated exposures to suberythemal doses of UVB and UVA in human skin. *J. Am. Academy of Dermatology*, **32**: 53–62.

Madronich, S. (1993). UV radiation in the natural and perturbed atmosphere, in M. Teveni (ed.) *Environmental Effects of Ultraviolet Radiation*, Lewis: Boca Raton, 17–69.

Madronich, S. (1998). TUV 4, *Anonymous ftp to acd.ucar.edu, /user/sasha*.

Masson, K., Kyrö, E. & Savijärvi, H. (1998). Long-term responsivity of Sodankylä's Brewer Spectrophotometer. In *Abstracts of The European Conference on Atmospheric UV Radiation, Helsinki, Finland, June 29–July 2, 1998*, 80–81.

Mayer, B., Seckmeyer, G. & Kylling, A. (1997). Systematic long-term comparison of spectral UV measurements and UVSPEC modeling results. *J. Geophys. Res.*, **102**: 8755–8767.

McKinlay, A. F. & Diffey, B. L. (1987). A reference action spectrum for ultraviolet induced erythema in human skin. *CIE Journal*, **6**: 17–22.

Moan, J. & Dahlback, A. (1992). The relationship between skin cancers, solar radiation and ozone depletion. *Brit. J. Cancer*, **65**: 916–921.

Pachart, E., Lenoble, J., Brogniez, C., Bocquet, J. L. & Wang, P. (1997). Modelling of UV-B irradiance complementarity with measurements. In *Proceedings of the International Radiation Symposium* (*IRS '96*) *on Current Problems in Atmospheric Radiation* (eds. W. L. Smith & K.Stamnes) Fairbanks, Alaska, 19–24 August 1996. A.Deepak, Hampton, USA, 857–860.

Renaud, A., Staehelin, J., Fröhlich, C., Philipona, R. & Heimo, A. (2000). Influence of snow and clouds on erythemal UV radiation: analysis of Swiss measurements and comparison with models, *J. Geophys. Res.*, **105**: 4961–4969.

Reuder, J. & Schwander, H. (1999). Aerosol effects on UV radiation in nonurban regions, *J. Geophys. Res.*, **104**: 4065–4077.

Rozanov, V. V., Diebel, D., Spur, R. J. D. & Burrows, J. P. (1997). GOMETRAN: A radiative transfer model for the satellite project GOME – The plane parallel version. *J. Geoph. Res.*, **102**: 16683–16695.

Ruggaber, A., Dlugi, R. & Nakajima, T. (1994). Modeling of radiation quantities and photolysis frequencies in the troposphere. *J. Atmosph. Chem.*, **18**: 171–210.

Schauberger, G., Schmalwieser, A. W., Rubel, F., Wang, Y. & Keck, G. (1997). UV-Index: Operationelle Prognose der solaren, biologisch-effektiven Ultraviolett-Strahlung in Österreich. *Zeitschrift für Medizinische Physik*, **7**: 153–160.

Schwander H., Koepke, P. & Ruggaber, A. (1997). Uncertainties in modeled UV irradiance due to limited accuracy and availability of input data. *J. Geoph. Res.*, **102**: 9419–9429.

Slaper H. & Koskela, T. (1997). Methodology of intercomparing spectral sky measurements. In *Final Report of the Nordic Intercomparison of Ultraviolet and Total Ozone Instruments at Izaña, October 1996,* edited by B. Kjeldstad, B. Johnsen and T. Koskela, Finn. Meteorol. Inst., Meteorological Publications No. 36, ISBN 951-697-475-9, 89–108.

SPARC/IOC/GAW (1998). Assessment of trends in the vertical distribution of ozone. *SPARC report no. 43*, Sparc Office, Verrières-le-Buisson.

Stamnes, K., Tsay, S. C., Wiscombe, W. & Jayaweera, K. (1988). Numerically stable algorithm for discrete ordinate method radiative transfer in multiple scattering and emitting layered media. *Appl. Opt.*, **27**: 2501–2509.

Taylor, H. R., West, S. K., Rosenthal, F. S., Munoz, B., Newland, H. S., Abbey, H. & Emmet, H. (1989). Effect of ultraviolet radiation on cataract formation. *New England J. Med.*, **319**: 1429–1433.

Vanicek, K. (1997). Relation between total ozone and erythemal solar radiation on clear days in Hradec Kralove. In *Proc. of the Workshop on Monitoring of UVB Radiation on Total Ozone, Poprad, 24–26 April 1996*, Slovak Hydrometeorological Institute.

Weihs, P. & Webb, A. R. (1997a). Accuracy of spectral UV model calculations: 1. Consideration of uncertainty in input parameters. *J. Geoph. Res.*, **102**: 1541–1550.

Weihs, P & Webb, A.R. (1997b). Accuracy of spectral UV model calculations: 2. Comparison of UV calculations with measurements. *J. Geoph. Res.*, **102**: 1551–1560.