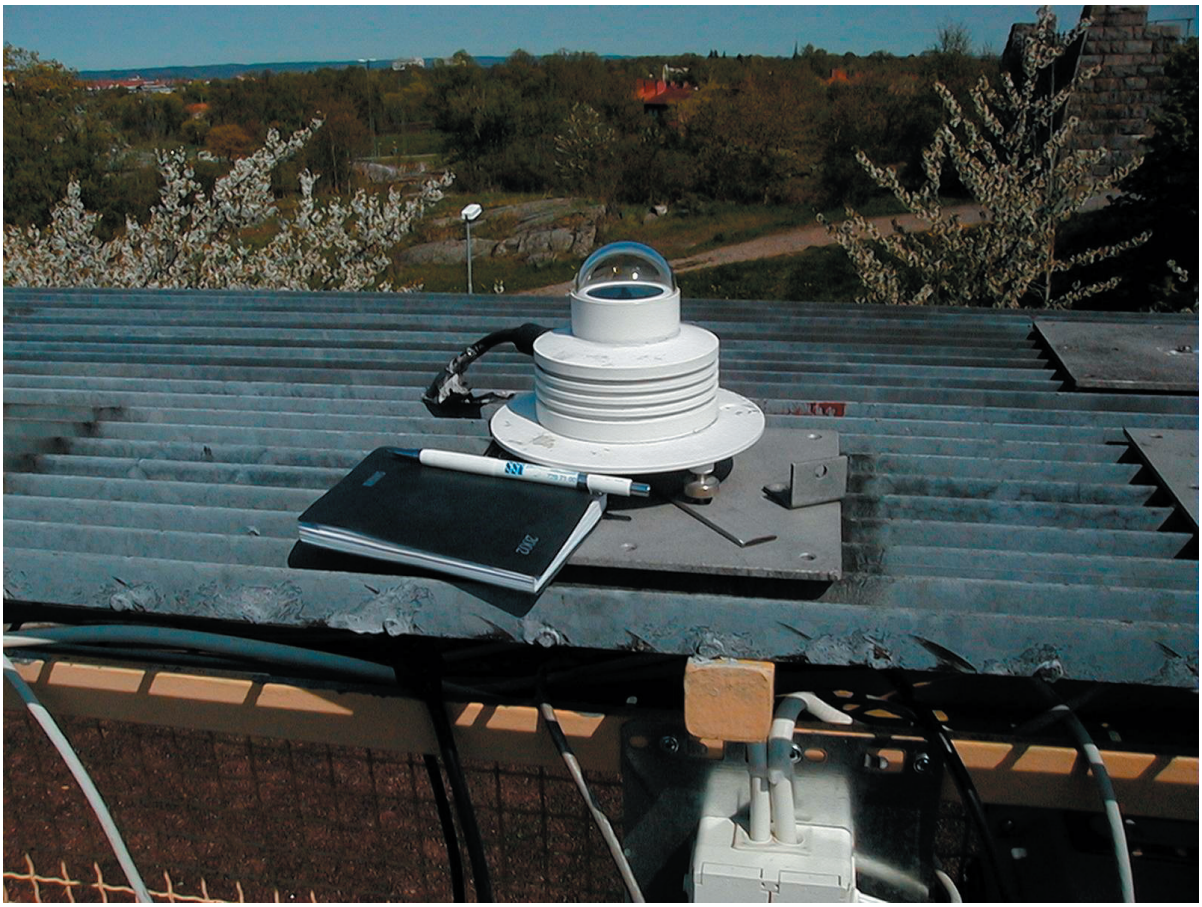
Nr 114, 2004

Meteorologi



UV-radiation measured in Norrköping 1983-2003.

Weine Josefsson

Cover: The Solar Light Model 501 instrument #922 on the platform at SMHI, Norrköping.

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Table of contents

1 Introduction

The purpose of this work is to homogenise a number of different data sets of daily values of UV-radiation to enable studies of the temporal variation of UV-radiation and atmospheric processes. Efforts are concentrated on the longest series measured using a Robertson-Berger and a Solar Light Model 501 radiometer. The lack of practical and reliable calibration standards have made measurements of UV uncertain. There are also several sources of uncertainty inherited in the designs of the instruments as well as uncertainties in the input data to the models used for corrections and for filling gaps of missing data.

The primary goal is to achieve a homogenous data set. The second goal is to mimic a true CIE-weighted irradiation, McKinley and Diffey (1987). The third goal is to be as close as possible to an absolute irradiance scale.

There are some factors that will prevent the achievement of these goals. These factors will introduce uncertainty in various fashions and affect the data differently. The applied corrections are assumed to remove systematic differences in a statistical sense. However, as will be discussed below, large differences may still remain in the hourly data.

For those not familiar with measurements in the UV spectral range it may seem surprising that UV data recorded by different instruments differ so much. This is partly due to the very large change (several orders of magnitude) in the solar spectrum combined with small differences in the spectral responsivity of the instruments in this range. Apparently small differences in spectral responsivity will produce relatively large variable differences in the output only by changing the solar elevation during the day or during the year. The yearly effect will be seen in the results below.

2 Measurements, instruments and data sets

The measurements are recorded at SMHI (Swedish Meteorological and Hydrological Institute) in Norrköping (58.58°N 16.15°E 43m), Sweden. The time period for this study encompasses the years 1983-2003. Data are measured to represent a horizontal surface. Note that all the radiometers have been operated at the same site (within 5 m distance) and with an almost free horizon. Maintenance, e.g. cleaning of domes, has been done at least every workday. Below, the different quantities and instruments are presented briefly. Abbreviations that will be used for each quantity/instrument are introduced.

Measurements from the Robertson-Berger Meter, *RB* #38, Berger (1976), are probably the most interesting UV-data in this study, as the instrument has been in operation only with a few interruptions since 1983. Unfortunately, there were some problems with the cable, caused by ageing, affecting data in an unpredictable manner during later years. After December 1997 data has not been digitised. In 1999 the instrument malfunctioned and was not repaired.

Starting in November 1992, a Solar Light Model 501, SL501 #922, was introduced. Since 1998 it has replaced the RB #38 as the instrument for broadband monitoring of UV. Contrary to the RB-radiometer this unit has been calibrated several times. This gives the opportunity to relate the measurements to a radiation scale (absolute level).

It is also valuable to have a relatively long period with overlap data between RB#38 and SL501#922. Unfortunately, there are some longer gaps in the record of this instrument.

Also used in the study are global radiation, sunshine duration and total ozone data. All these measurements are measured at the same site, within 5 m in addition there have also been two other UV-radiometers in operation. The oldest one is a dual band UW306 and UW360 meter, Wester (1983), and for a period there has also been a Solar Light Model 500 UV radiometer, Josefsson (1996, 1997). These data have not been analysed in this context.

Different acquisition systems have been used. Therefore, short-term data may be affected by small differences in the sampling frequency as well as in time-errors. This effect disappears when daily or longer time-periods are treated. In particular the Robertson-Berger meter has been a stand-alone system with its old printer unit producing printouts every half-hour. In the beginning this system was operated using local time +4 minutes, which is the time difference from middle European time for Norrköping. Usually the clock has been within 10 seconds but due to the laborious procedure for time setting larger offsets have occurred.

Global irradiance, G_h, data are taken from the regular network data. The quantity is measured using a Kipp and Zonen CM11-pyranometer, which is well calibrated by reference pyrheliometers and regularly compared to other pyranometers. These data are traceable to WRR (World Radiometric Reference). For the period of interest the stability, long-term precision, is probably within 1%. These data therefore give a platform for checking the long-term stability of the UV-radiometers.

The total ozone (column integrated) is observed using a Brewer spectroradiometer. From 1988 to mid 1996 the Brewer #6 was used. Since then the Brewer #128 has been in operation. These instruments are regularly calibrated by comparison to a travelling reference instrument. For the period prior to 1988 and also for periods of missing data, TOMS overpass data have been used. These instruments have also recorded spectral irradiance measurements in the UV-region. Data are available but they are not fully homogenised.

3 Problems and Methods

The starting point of the data correction is raw-data from the two instruments. The RB data were recorded on paper strips as printouts of counts once every 30-minutes. These counts were added to hourly sums that were digitised.

SL501 raw-data are 30-min integrated values with no constant applied. The instrument is supposed to have the detector stabilised at 25° C. Data are summed to hourly values.

The goal of this processing is to convert the raw-data to hourly values (sums), correct for known errors, adjust RB-data to SL501 data to get a data set that is homogenous and as close as possible to the CIE-weighted erythemal irradiation (Whm^{-2}). By multiplying these hourly values by the factor 40 ($W^{-1}m^{+2}$) UV-index is achieved.

The correct irradiance level is assumed to be traceable to the available comparisons (calibrations). For conditions not typical for comparisons adjustments have to be

done to the recorded values. The calibration factors derived from the comparisons have been based on references that have been cosine corrected. Thus, a cosine correction factor, CCF, is implicitly integrated in the found constant. Further cosine correction only needs to be done relative to the conditions prevailing at comparisons, see below. The constants from comparisons are based on data for solar zenith angles, SZA<45°. However, measurements are recorded for a much wider range of angles. It can be seen from Figure 3.2.1.2. that using a simple constant factor may only be justified for small SZA. At larger SZA the CIE erythemally weighted irradiance will be underestimated if a constant factor is used. Another complication arises from the fact that the spectral composition in the UV-B varies strongly with the amount of total ozone and with the SZA. To account for these factors a relative spectral responsivity correction function (relSCF) will be applied.

There are also other environmental factors, ground reflectance and aerosols, that have an influence on the spectrum and thus on the measured estimate of the CIE weighted irradiance. However, in this process they have been neglected assuming they are of a second order of importance.

3.1 List of error sources

UV-instruments are designed to have a responsivity that is proportional to the quantity of interest. However, there are always shortcomings. Typical ones for the RB- and the SL501-radiometers are listed in Table 3.1. They will be further interpreted in the following sections.

Table 3.1. Major sources of errors for UV-data recording using RB and SL501-meters in Norrköping 1983-.

Error sources
Non-CIE spectral responsivity
Non-perfect cosine responsivity
Temperature dependence
Long-term changes in responsivity
Time errors
Low resolution in data sampling
Missing data
Maintenance, humidity, snow, others
Absolute irradiance calibration

Some of these errors only affect short-term values or short periods. For example the time error, which normally is of the order of minutes, has effects on hourly but not on daily or longer integration times. Other errors, such as cosine and spectral uncertainties affect data on all time scales.

3.2 Approaches to correct for errors

3.2.1 Non-CIE spectral responsivity

The spectral responsivity of the instruments and the action spectrum for erythema adopted by CIE differ. In Figure 3.2.1.1 the wavelength dependencies of these are plotted in a linear and logarithmic presentation.

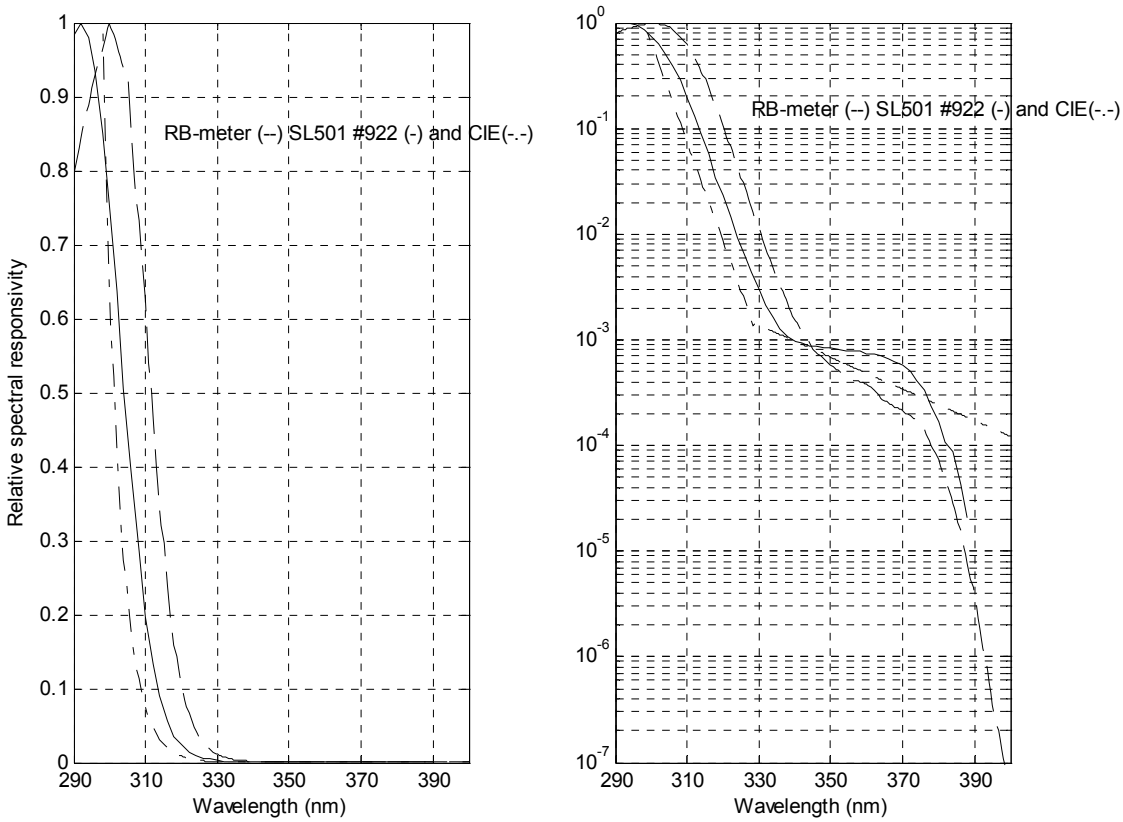

Figure 3.2.1.1 Spectral responsivity of RB-meter #27 (Berger personal communication and SL-meter 501 #922 and the CIE-action spectrum for erythema, McKinley and Diffey (1987).

<u>RB-meter</u>

The spectral responsivity of the specific RB-meter #38 has never been measured. Therefore, as a best guess a spectral responsivity from a RB-meter was retrieved from the Solar Light Co. (Berger personal communication).

To correct for the difference in the spectral responsivity from the idealised CIE-action spectrum a similar approach as for the SL501 (see below) was first initiated. But, as the true spectral responsivity of the RB-meter #38 is not known such an approach will not be sufficient to remove this uncertainty. There will without doubt remain an error that must be dealt with to get a homogenous series. Therefore, it was decided to apply another approach for dealing with the spectral problem as well as the homogenisation. For the overlap period a similar model is applied to minimise any differences between the RB and the SL501-meter.

So in practise the spectral responsivity of the RB-meter is not used. The uncertainty introduced by this factor and other are handled by the model (see section 3.3.2) to minimise the differences between the two types of instruments. This approach was selected to make the data set as homogenous as possible.

SL501-meter

The relSCF (relative spectral correction function) has been established by using 2198 spectra recorded at Norrköping by the Brewer #128 in the year 2003. The spectral responsivity function for the SL501 #922 meter measured in laboratory and the CIE ISO-2000 weighted action spectrum are applied on these spectra. By studying the ratio between these two weighted irradiances it is possible to establish the relative spectral responsivity correction function (relSCF), Figure 3.2.1.2, to account for major differences between the two action spectra. The relSCF is normalised to unity at SZA=50°. A polynomial fit is made for the data points grouped by the prevailing amount of total ozone. This can also be done by a modelling approach, see e.g. Leszczynski et al. (1995/1996), Leszczynski (1998).

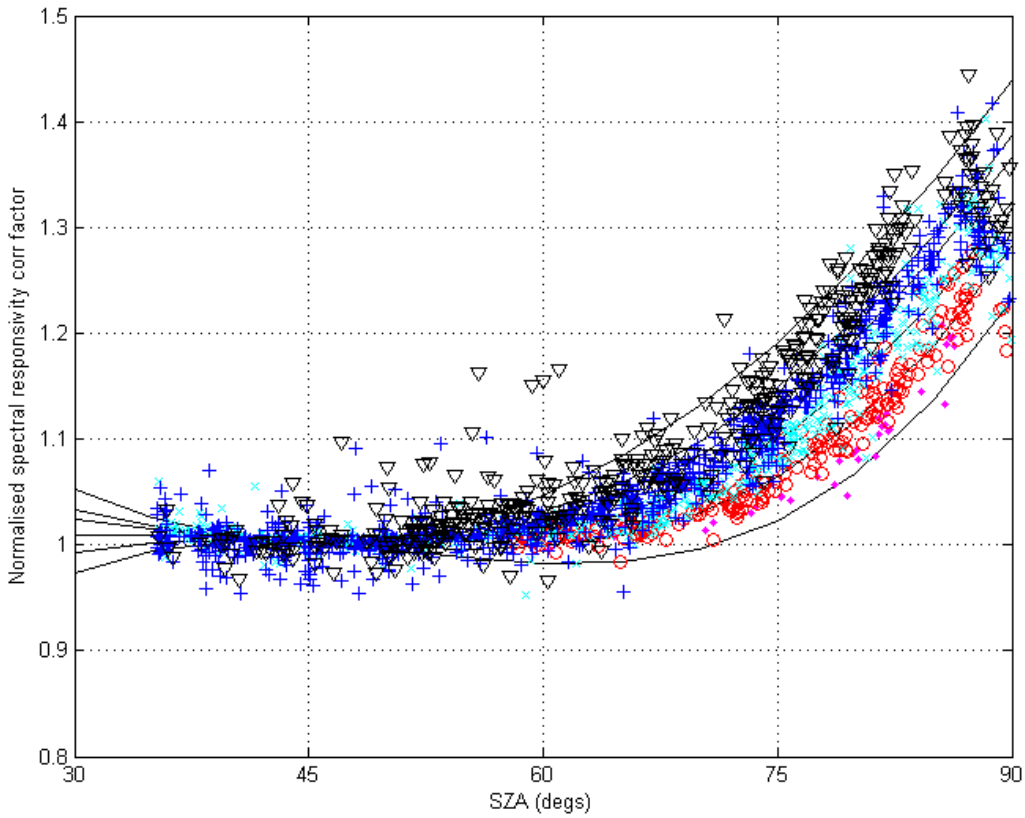

Figure 3.2.1.2 The ratio, normalised at SZA 50°, between CIE-weighted and SL501 #922 weighted irradiance based on 2198 spectra measured with the Brewer spectroradiometer. Data are grouped by amount of total ozone, various symbols. Polynomial fitting is applied to each group.

Based on the data in Figure 3.2.1.2 the following algorithm was deduced.

relSCF = 1 for SZA<= 50°

and

$$\begin{aligned} relSCF = & (-2.6016845*10^{-8} * TOZ + 1.1930454 * 10^{-5}) * SZA^3 + \\ & (5.122013*10^{-6} * TOZ - 2.123956 *10^{-3}) * SZA^2 + \\ & (-2.996299*10^{-4} * TOZ + 0.1169616) * SZA + \\ & (5.481172 *10^{-3} *TOZ - 1.046723) \end{aligned}$$

for SZA>50°

where SZA is, as before, the solar zenith angle in degrees and TOZ is the total ozone in DU. If the total ozone is not available the average (340 DU) valid for Norrköping is used. The algorithm is specific for the spectral responsivity of the #922 instrument. The algorithm is based on a limited data set of spectral data. As mentioned, there are other factors than SZA and TOZ affecting the spectral distribution, such as ground albedo and aerosol load. Therefore, this type of correction will not be perfect. As the algorithm is based on data measured at the site of the SL501 #922 instrument it is assumed that the average influence of these factors will be properly accounted for. The main assumption is that the use of relSCF will remove most of the systematic differences dependent on the SZA and the amount of total ozone.

One major reason for applying this correction is to remove (reduce) systematic influence on the daily and yearly UV. Otherwise this may have an influence on the long-term trends and on the UV variation over the day and the year.

It can clearly be seen in Figure 3.2.1.2 that using a constant factor on the output of this instrument to get a CIE-weighted UV-irradiance will give an unsatisfactory result. For all occasions with a large SZA one would thus expect a systematically too low irradiance.

3.2.2 Non-perfect cosine responsivity

Another imperfection of the UV radiometers is their poor cosine responsivity. The main problem is that the output signal depends of the angle of incidence of the incoming radiation. This directional dependence is often azimuth independent and can thus be summarised as a dependence of the cosine of the angle of incidence of the radiation. This so-called cosine error can be and has been characterised in the laboratory of SMHI. The relative cosine error, Θ, of a radiometer is given as a function of the angle of incidence θ

$$\Theta(\theta) = R(\theta) / R(\theta=0°) / \cos\theta$$

where $R(\theta)$ is the measured signal at angle θ and $R(\theta=0°)$ is the corresponding signal at normal incidence. A perfect entrance optic would produce a value equal to unity for all angles of incidence between 0° and 90°. The results for the RB #38 and the SL501 #922 are shown in Figure 3.2.2.1. A slight azimuth dependence for the SL501-instrument has been neglected.

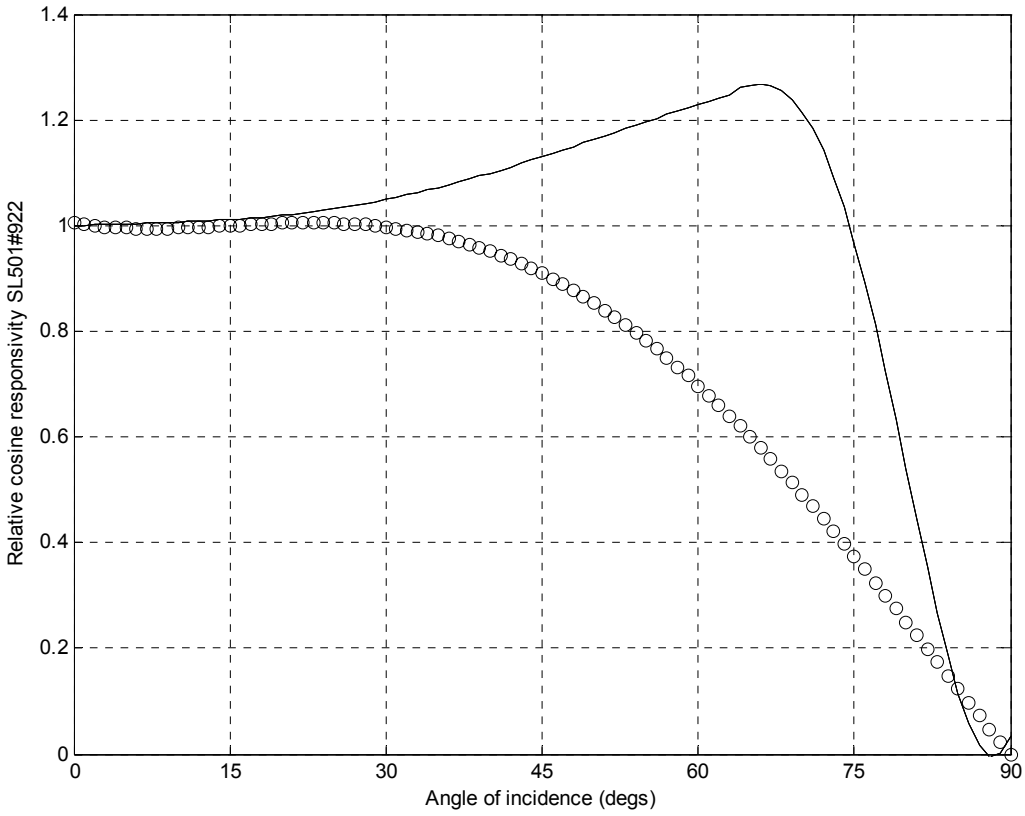

Figure 3.2.2.1 Polynomial approximations of the relative cosine responsivities of RB-meter #38 (o) *and SL501 #922* (full line) *based on measured data.*

Briefly, a complete correction of this error demands knowledge of the sky radiance distribution. This information is normally not available. To overcome this obstacle simplification is necessary. In this case two idealised sky radiance distributions are assumed. Either the sky is free from clouds, having a typical northern european aerosol load and a ground free from snow, or the sky is completely overcast. For these two opposite sky conditions solar zenith angle (SZA) dependent correction functions are established for each instrument.

The sky radiance distribution for a clear sky is assumed to consist of a direct component positioned at the sun and a diffuse component having an isotropic distribution. The relative magnitude of the components is found by the shading method from measurements during clear sky conditions using the instrument itself but also from modelling, Figure 3.2.2.2. No spectral dependence is assumed. The relative overcast sky radiance has been measured using the Brewer spectrophotometer. In this case it was found that both the spectral and azimuth dependencies of the radiance are small. Therefore, these factors have been neglected for the cosine correction in this application.

Unfortunately, there are very few measurements available of the sky radiance for various sky conditions. However, examining some available data, Dorno and Lindholm (1929), Eckel (1934), Josefsson (1986) and recent UV-radiance measurements recorded by the Brewer spectroradiometer at the site in Norrköping and the papers by Grant R. H. et al. (1997a, 1997b) show that there is a distinct deviation from isotropic distribution for *low solar elevations* for clear skies and, as it seems, for overcast skies in general.

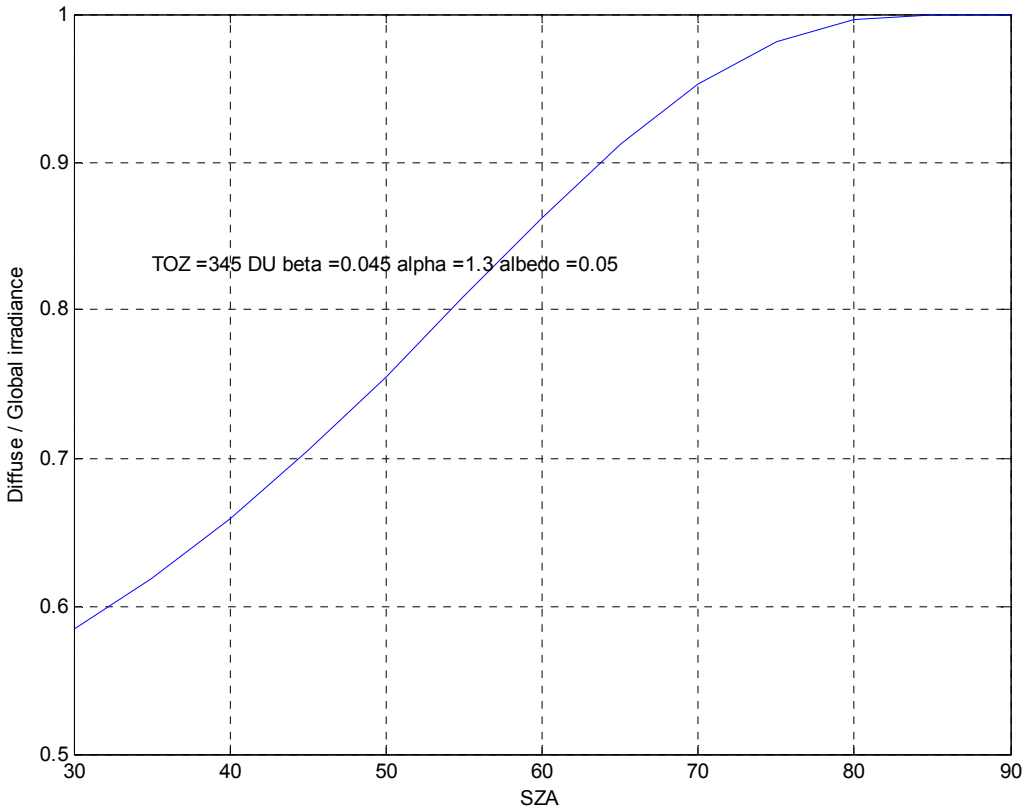

Figure 3.2.2.2 The partitioning of global UV-irradiance into a direct and a diffuse part during clear sky average conditions.

From these parameterised relative radiance distributions of clear and overcast skies, and the partitioning of the global irradiance, it is possible to cosine correct hourly values for these two types of skies. To be able to correct for the skies having a broken cloud cover it is assumed that this can be done by interpolation between the clear and the overcast cases. This is done for each hourly value by linear interpolation using concurrent observations of the sunshine duration.

RB-meter

This correction method was developed and applied for the RB-data, Landelius and Josefsson (2000) and has been used here as well. Because of the bad cosine responsivity the correction will be relatively large. Factors in the range 1.1-1.3 are applied.

SL-501

When the comparisons (calibrations) were made no correction was applied for the deviations in the directional responsivity. Therefore, the influence from this imperfection of the instrument will implicitly be part of the calibration. Also in this case a relative correction is applied to overcome this problem. Assuming that the calibration is done for clear sky conditions, and for an average solar elevation of 40° (SZA=50°), the following correction functions are used for a cloud free sky and an overcast sky respectively.

For a clear sky the following cosine correction factor, CCF, can be applied. It is normalised using the CCF value 0.917 valid for SZA=50°. This is because the absolute calibration for the SL501 #922 refer to a SZA range close to this value.

$$CCF = (-1.095113E\text{-}08*SZA^4 + 2.027615E\text{-}06*SZA^3 - 9.851512E\text{-}05*SZA^2 - 4.029910E\text{-}04*SZA + 9.880532E\text{-}01) / 0.907$$

The fit to the theoretical data is not perfect. But, considering the uncertainties in the assumptions and the normal variability of the sky, the discrepancies are not large. For most solar zenith angles this relative CCF introduces changes in the data of about one percent or less. For an overcast sky a constant CCF can be applied

$$CCF_{overcast} = 0.917217 / 0.907 = 1.011$$

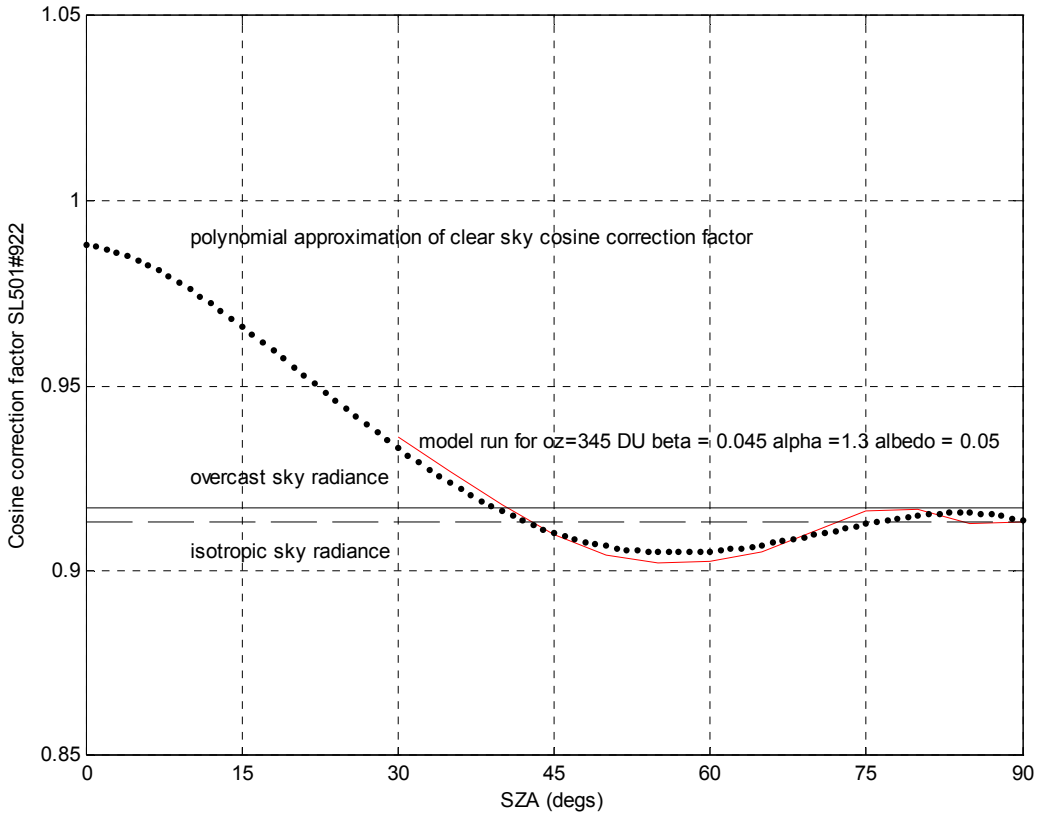

Figure 3.2.2.3 Cosine correction factors for various sky conditions and SZA. Before application these numbers are normalised by the clear sky value valid for SZA=50°, corresponding to average calibration SZA.

3.2.3 Temperature dependence

RB-meter

It is well known that the old RB-meters suffer from a severe temperature dependence, about 1%/ °C, Blumthaler and Ambach (1986), a similar magnitude as for the Solar Light Model500, Johnsen and Moan (1991) and Jokela et al. (1991). The sensitivity increases with temperature. A too high temperature will give a too high measured value.

Unfortunately, there has not been any determination of the temperature coefficient for the RB #38-instrument. Therefore, it was decided to use 1% per 1°C, which seems to be a reasonable number for RB-meters, Berger (1976), Blumthaler and Ambach (1986), Kennedy and Sharp (1992), DeLuisi et al. (1992). The temperature correction of *RB*-data is applied on hourly values using temperature and global irradiation data collected a few meters away from the instrument. A small study of the relation between air-temperature, global radiation and the output of this specific meter *RB#38* and the temperature stabilised *SL501 #922* instrument gave corrections similar to and of the same magnitude that the ones found by others.

SL501-meter
The SL501 #922 detector is equipped with a Peltier element in order to keep the detector at a stable temperature of 25°C. This should minimise the large temperature dependence that exists for the older non-temperature stabilised Robertson-Berger type instrument.

Most of the time it is plausible that the temperature stabilisation is successful and thus removes the temperature influence. However, during days with high irradiance and high temperature there may be slight problems keeping the temperature sensitive parts of the detector sufficiently stabilised. The black top filter strongly absorbs heat from the solar radiation and it will thus be at a high temperature, i.e. more than 50°C.

Unfortunately, the temperature recorded inside the instrument is not measured at the most sensitive part. Because of the strong temperature dependence, only a few degrees deviation from the intended temperature will cause a notable error.

3.2.4 Long-term changes in responsivity

RB-meter
The long-term changes in the responsivity of the RB-meter could not be directly traced. During the years it was used there has only been one calibration using a travelling standard from the Solar Light Co. Unfortunately, it was performed under low-irradiance conditions and the result did not add much information. Other methods had to be used. Assuming that all changes have been slow, daily RB-data were compared to a synthetic clear sky UV value based on an empirical model using global radiation and total ozone as input. Only days with a relative sunshine duration larger than 0.75 and a daily global radiation value larger than 1000 Whm^{-2} were used.

SL501-meter
The long-term changes of this instrument are assumed to be fully described by the comparisons (calibrations). A more detailed discussion of this is presented in section 3.2.9.

3.2.5 Time errors

Both the RB-meter and the SL501-meter have their own autonomous data acquisition systems. Unfortunately, this will introduce a temporal error source. In this case small temporal errors, of the order minutes exist and will be discussed. Obviously an error in the time will give data referring to an erroneous time. For data integrated to daily or longer periods the effect of this error disappears. But, comparing data samples for

shorter time periods will be attributed with a scatter due to non-synchronisation. This is caused by the rapid variation in UV-irradiance.

The timing of the observations depends on the individual system. A printout of the RB-meter is made every 30-minutes. The clock of this system was not easy to correct. Power failures are not frequent but they do happen and then the time of the printout had to be adjusted. Another time related problem with this system was that it was operated in true solar time during an initial period. Later it was shifted to local standard time for better agreement with other observations.

The SL501 data was collected in local standard time up to 3rd of October 1993 when it was shifted to UTC. Over the years the clock of the unit has been corrected about once a month. Typical corrections are within a minute. However, there have been periods when the clock has drifted several minutes. Although it might seem to be small amounts of time, the UV-irradiance can change rapidly. Therefore, comparison between RB and SL501 data will produce a larger scatter due to bad timing than it would have been if the timing had been perfect. This was clearly seen when processing the overlap period.

3.2.6 Low resolution in data sampling

The RB-meter measured UV-radiation by integrating the current from a phototube, Berger (1976). This is done by charging a capacitor to a pre-set value. Every time the capacitor reaches this value a count was registered and the capacitor was reset. Therefore, discrete counts correspond to a certain amount of UV (roughly 0.2 $mWhm^{-2}$ CIE-weighted UV). Around noon in the summer several counts can be recorded each minute. But, during the winter the corresponding noon irradiance often gives less than ten counts per hour, Table 3.2.6. Also in the early morning and late evening the number of counts recorded during an hour was less than ten.

Table 3.2.6. Examples of the relative influence (%) of 1 missing or one extra count on typical hourly noon values of the RB-meter at Norrköping. Please, note that during the period November to January the daily values are less than 100 counts per day. The typical December daily sums of counts are in the range 5 to 60.

Month	Typical noon value counts/hour	Relative influence by 1 count	Relative influence by 0.001 MED
Jan	10	10 %	3.3 %
Feb	40	2.5	0.8
Mar	120	0.8	0.3
Apr	270	0.4	0.1
May	350	0.3	0.1
Jun	600	0.2	0.06
Jul	700	0.1	0.05
Aug	300	0.3	0.1
Sep	250	0.4	0.1
Oct	70	1.4	0.5
Nov	15	6.6	2.2
Dec	10	10	3.3

Also the SL501 data is not highly resolved. The primary data collection is integrated half-hour values given as MEDs with a resolution of 0.001 MED. This corresponds to about 0.06 $mWhm^{-2}$ CIE-weighted UV, which is only about a factor three better than the old RB-meter.

In all situations with low UV-irradiance the use of a low resolution (discrete counts) will limit the accuracy of individual hourly values and sometimes even the daily values. As an example, for the RB-meter, in the morning when the integration of UV starts the capacitor may only be half charged when a printout of counts is made. If this is the case, no UV is connected with the time period prior to the printout. The UV-amount will be recorded, but at a later time. Therefore, daily values will suffer less from this problem.

From Table 3.2.6 it is clear that comparisons of data for individual hours collected during low irradiance conditions will inherit large differences due to low resolution in original data.

3.2.7 Missing data

An interesting source of uncertainty in climatological studies, though not always discussed, is the influence of missing data. Most monitoring suffer from gaps in the data flow. In this study most gaps have been filled by synthetic data. Smaller gaps by inter-/extra-polation and longer ones by simple empirical modelling. The empirical model is given in the Appendix 1. For some applications these synthetic data should not be used. For the RB-part of the series typically one or two days are missing per year up to 1991. Therefore, the uncertainty introduced by missing data is almost negligible compared with other sources. The only exception is in the summer of 1992 where more than a month was missing due to cable problems. In the later parts of the RB-series the cable problem increased and long periods are missing. However, at this time the SL501 was in operation.

For the SL501 part of the series the influence due to gaps is larger, mainly caused by participation in comparisons and once by a failure in the power supply. To get an idea of the uncertainty caused by using modelled data, E_i, the empirical model applied has been compared with the measured data, M_i. The result is summarised in Table 3.2.7. Here the relative RMSD has been used, i.e. the RMSD (root-mean-squared deviation) divided by the average value, **M**, expressed in percent has been used.

$$\text{Relative RMSD} = 100 * ((\Sigma (E_i - M_i)^2)/N)^{1/2} / \mathbf{M}$$

Table 3.2.7 Comparison between empirical model and measured data given as RMSD (%).

Time period	RB #38	SL501 #922
Hours from overlap	15.2	9.7
ditto for SZA<65°	12.2	7.7
Daily values	8.4	7.2
Monthly values	4.0	

The results for the monthly, daily and also for the hourly SL501 data are based on the final homogenised data set. The study of the hourly RB-data is before the final

homogenisation. The hourly data are from the overlap period mentioned in section 3.3.1. The hourly data included in the study consists of more than 11000 values for hours with SZA< 65°.

To have consistency between monthly values and daily values one can make a rough estimate that the systematic uncertainty of the model for daily values is about 3% (at 95% coverage, k=2) and the random uncertainty is 5% (at 67% or k=1) which sums up to 8%. To have full 95% coverage (k=2) of the uncertainty for a daily value the latter number has to be doubled and the one gets 13% (3 + 10). This is further discussed in section 4.

3.2.8 Maintenance, humidity, snow, others

At the measuring site Norrköping the winter is characterised by several occurrences of snowfall. Probably more frequent and severe is the occurrence of rime (frost) on the domes of the radiometers. During working days the rime and snow is removed. Over weekends this is not always the case. One problem with rime is the tendency of re-occurrence some minutes after removal. In most cases the recorded values will be too low.

Other depositions such as raindrops and dust probably have had minor influence on the data. The average relative frequency of time with precipitation is roughly 15%, higher during winter and consequently lower in summer. Half of the time is night and precipitation is usually associated with thick clouds giving low irradiance values. Therefore, the number of hours affected by deposition from precipitation will probably be less than 8%, and most of these values are low radiation values. Thus the influence on radiation values integrated over longer periods, dominated by the high irradiance, will probably be relatively small.

The actual effect from deposition has not been studied or estimated. The action taken is inspection and cleaning of the domes every workday and also often during weekends. Thus, dust and other deposits are removed.

In a recent paper Huber et al. (2003) have investigated and discussed the effect of humidity on measurements of the SL501 type of instrument. According to their findings a variation of the internal humidity can cause large changes (of the order of 10%) in the instrument output. In this study it has not been possible to verify or detect the possible influence of humidity, as there is no information available regarding the internal humidity status.

3.2.9 Absolute irradiance level

<u>RB-meter</u>
A first rough conversion to an absolute level of irradiance for the RB-meter was done by transfer of the calibration from the SL501 #922 at SZA less than 50 degrees using a constant factor. This simple factor application does not take into account the RB-meter spectral difference as compared to the CIE-erythemal action spectrum. This effect and others are dealt with using the overlap period, see below.

SL501-meter

The basis for converting data to an absolute scale related CIE-weighted irradiance is the comparisons versus well-calibrated and properly maintained spectroradiometers. The SL501 #922 has participated in the following comparisons: NOGIC-93 (Wester, Leszczynski and Dahlback (1994)), WMO/STUK-1995 (Leszczynski et al. (1997b, 1998b)), NOGIC-96 (Leszczynski Visuri and Ylianttila (1997b)), LAP/COST/WMO 1999 (WMO/GAW) and NOGIC-2000 (not yet published), see Figure 3.2.9**,** where the absolute calibration factors of SL501 #922 are plotted versus time. The individual calibrations are connected with various sources of uncertainties, Leszczynski (2002). Also plotted are the calibration results of two other SL501-instruments #635 and #1466 (data from Lasse Ylianttila, STUK, personal communication). Looking at the pattern it seems that the WMO/STUK-1995 calibration may give a too high calibration factor. By, ad hoc, lowering this calibration by 6%-units and applying a linear regression, the long-term relative change in the instrument constant, $C_{\#922}$, for the years from November 1992 and to mid-2000 is assumed to be as given by the following equation

$$C_{\#922} = -\ 0.0090827 * yyyy + 19.1407$$

where *yyyy* is the time in years. For the following years

$$C_{\#922} = 0.97$$

is applied.

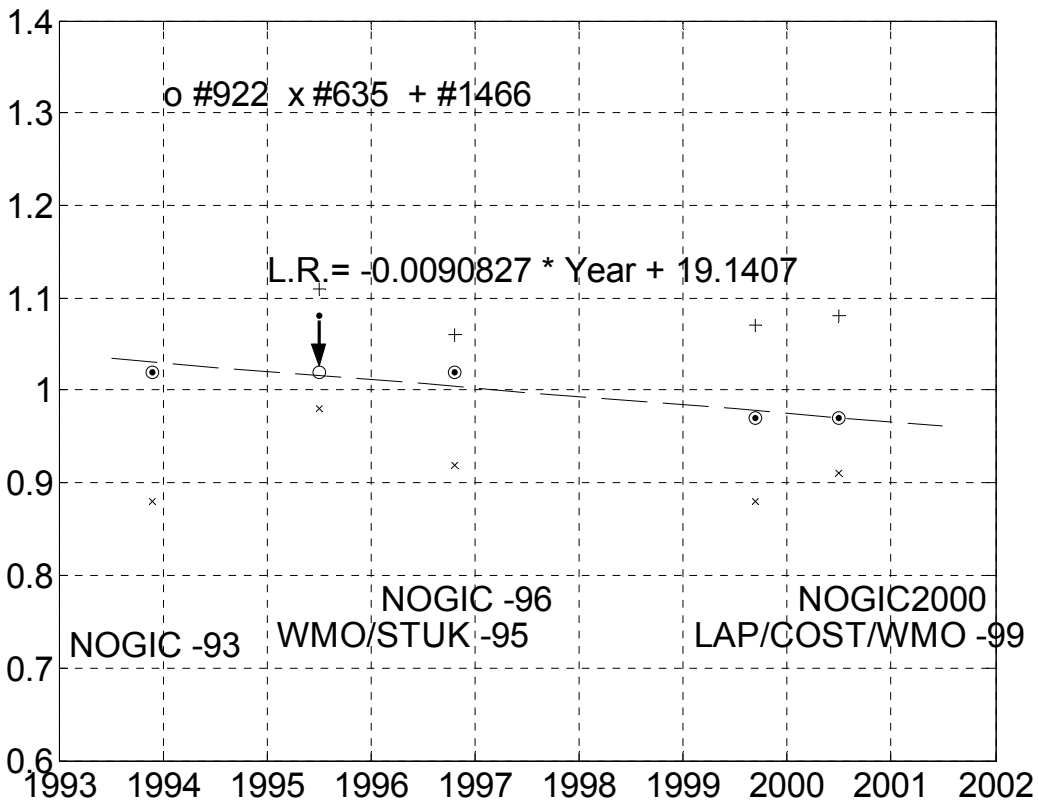

Figure 3.2.9 The results of the comparisons of SL501 #922 (•) and after a shift of the WMO/STUK-95 value (o)*. Also plotted are the results of the SL501-instruments #635 and #1466.*

The real variation most probably differs from this simplified description. It may occur step-wise and more or less rapidly depending on environmental conditions. Looking at the calibrations in Figure 3.2.9 one could easily make the assumption that the instrument was stable from 1993 up to 1996, and that some time thereafter there has been a jump or slow decrease in the instrument calibration factor to a lower level.

However, from the limited set of calibration data and from available ancillary data no such variation has been resolved. For example a preliminary comparison versus CIE-weighted erythemal irradiance as measured by a co-located Brewer spectroradiometer could not give any clear answer regarding the long-term change of the SL501 responsivity different from the one assumed here. Therefore, the calibration factors as presented above have been applied.

As can be seen from the linear equation the relative change per year is assumed to be about 0.9% in the early years. For the following years included in this study the long-term change of the instrument responsivity is assumed to have levelled out. For this period 0.97 is assumed to be a proper constant.

3.3 Homogenisation

The corrections applied on RB- and SL501 data for temperature dependence, improper cosine responsivity, spectral deviation from the CIE erythemal action spectrum and long term changes in the overall responsivity of the instrument are based on statistical average factors. Therefore, individual hourly data will inherit a large uncertainty even though corrected. Also some daily data can contain severe errors.

Factors causing this uncertainty are unknown spectral distribution of the radiation, unknown spectral sky radiance distribution, true temperature in the instrument and so on. However, it is assumed that data on the average will be more accurate after the corrections have been applied than before. So far the data from the two instruments have been treated separately.

Now is the moment for integrate the data sets and minimise the differences.

3.3.1 Use of overlap period

Data measured with the RB #38 and corrected as described above may be compared with the corrected SL501 #922 data for overlap period between November 1992 and December 1997. Both data sets are given as CIE-weighted erythemal radiation and refer to an absolute scale of irradiance. But, there are still some remaining artefacts, mainly in the RB-data set, causing inconsistency. The most obvious one is the use of a constant factor to convert from counts to radiant energy (e.g. Whm^{-2}) for the RB-meter. The spectral dependence has so far been neglected as mentioned above. The temperature dependence correction is probably far from perfect. Therefore, some systematic errors will remain. To reduce the effect of these and to adjust the RB-data set to be as similar to the SL501 data set as possible the overlap period has been used to construct an empirical conversion model in Matlab®.

This model minimises the radiation weighted ratio between the two data sets for a selected part of the overlap period. All night values and most of the low-irradiance values have been removed as well as some obvious out-liers. The model has the following terms

SZA^4*TOZ^2 SZA^4*TOZ SZA^4 SZA^3*TOZ^2 SZA^3*TOZ SZA^3 SZA^2*TOZ^2 SZA^2*TOZ SZA^2 SZA∗TOZ^2 SZA∗TOZ SZA TOZ^2 TOZ

Srel Gh^2 Gh jnr^4*SZA jnr^3* SZA jnr^2*SZA jnr∗SZA

where SZA is the solar zenith angle, TOZ is the total ozone, jnr is the daynumber, Gh is the global radiation and Srel is the relative sunshine duration. All data are hourly values.

It is assumed that the application of this model will remove most of the systematic differences between the two radiometers and thus make the two data sets comparable, i.e. homogenous. The improvement in the agreement of the sample test data set can be seen in Figure 3.3.1. The unfortunate time error is probably the main factor for the remaining scatter.

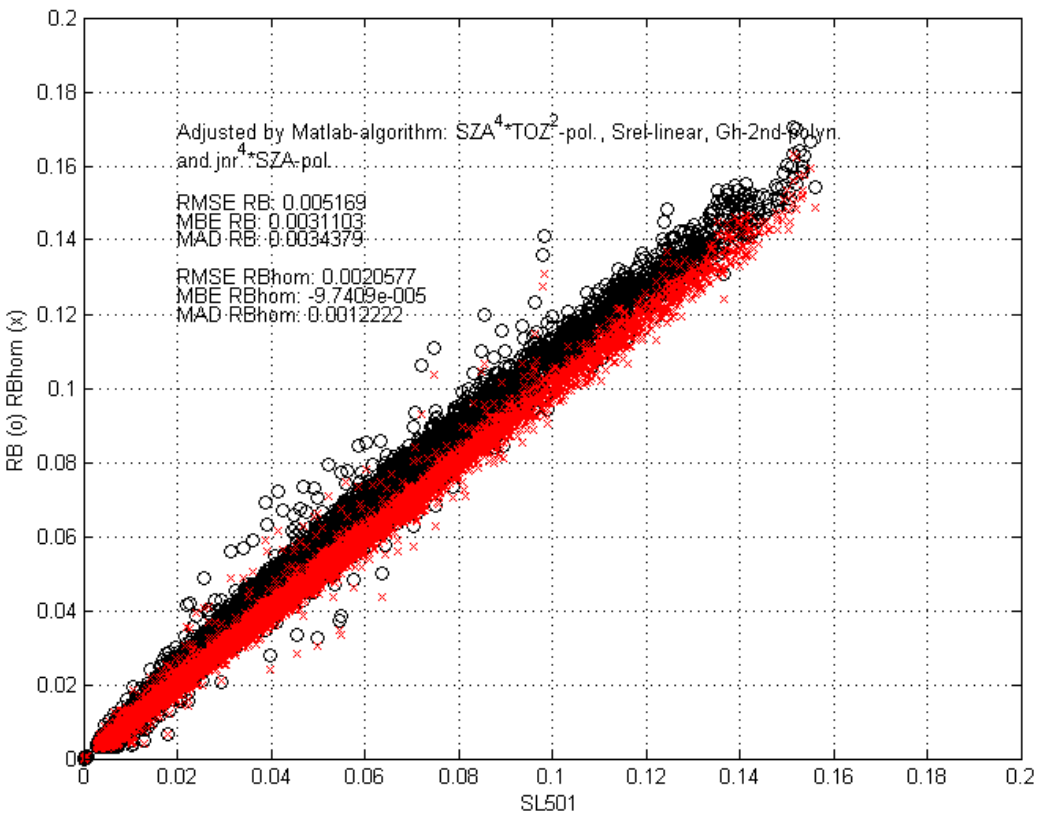

Figure 3.3.1 The selected sample for the overlap period plotted as uncorrected RB (o) *and adjusted* Rbhom (x) *versus* SL501*. The RMSE, MBE and MAD is given for the two sets.*

The RMSE (root-mean-squared-error), MBE (mean-bias-error) and MAD (mean-absolute-deviation) used in Figure 3.3.1 are defined as

$$RMSE = (\Sigma (RB_i - SL_i)^2)/N)^{½}$$

$$MBE = (\Sigma (RB_i - SL_i)) / N$$
$$MAD = (\Sigma \ ABS(RB_i - SL_i)) / N$$

where RB_i and SL_i are the N pairwise observations made by the RB and SL501 instruments. The suffix hom denotes the data where the RB-data has been adjusted (homogenised) by the algorithm.

4 Uncertainty estimate

Starting from the estimates summarised by Lesczcynski (2002). The uncertainty budget of the spectroradiometric calibration of erythemally weighted radiometers in solar radiation against CIE-weighted data is given as 7.8% expanded uncertainty at 95% (k=2). This can be regarded as the absolute uncertainty for a calibration of the temperature stabilised UV-broadband instruments, e.g. the data points of SL501 #922 in Figure 3.2.9.

The absolute uncertainty of individual hourly data during monitoring conditions will be of this magnitude or worse. The absolute uncertainty of RB#38 hourly data will be even larger due to non-temperature stabilisation and to the lack of spectral characterisation. For longer integration periods the random error components will cancel out. In addition other factors will add up that are not involved during periods of calibration, see Table 4.1.

Two important factors are of interest when looking at long-term data sets. Firstly, the effect of missing data and the maintenance will add uncertainty. Random components will level out when long-term integrated data are considered. Secondly, we may be interested in trends and not the absolute level of irradiance. In this case also some components of the systematic uncertainties can be disregarded as long as they don't change over time.

Reducing the long-term random uncertainties according to the integration time and removing the systematic uncertainties will give an estimate of the precision of the data. In Table 4.1 such estimates of the precision can be extracted for monthly and yearly values of the final data set.

The uncertainty estimates are based on the methods recommended by ISO TC30 SC9 (1987). A more detailed description of how these methods can be applied to solar radiation data is presented in Persson (2000). Briefly, the uncertainty, U, has two components a systematic one, B, and a random one, S. For each source of uncertainty both components should be estimated. The random one is estimated with a statistical coverage of 95%.

$$U = B + t_{95} * S$$

For large samples the Student's t_{95} may be approximated to 2. Otherwise a larger range is needed to get a 95% coverage. In Table 4.1 the coverage estimates are 95%. The components, i, of the systematic uncertainty are added as

$$B = (\Sigma B_i^2)^{½}$$

and the same procedure is done for the random components.

Uncertainty analysis of UV-broadband Coverage 95% t_{95} k=2				**Daily values** Monitoring between calibrations				**Monthly values**				**Yearly values**	
Unit: %	**Calibration conditions**							**Winter**		**Summer**			
	clear sky sza<30			Nice days		low irradiance days							
Error sources	**U**	**B**	**t_{95}S**	**B**	**t_{95}S**	**B**	**t_{95}S**	**B**	**t_{95}S**	**B**	**t_{95}S**	**B**	**t_{95}S**
Absolute irradiance calibration	**7.8**	3.9	3.9	3.9	3.9	3.9	3.9	3.90	0.71	3.90	0.71	3.90	0.21
Non-CIE spectral responsivity not corrected for				1	3	3	5	2.60	0.84	1.40	0.62	2.00	0.21
Additional spectral uncertainty for RB-meter				0.5	0.5	1	1	0.90	0.16	0.60	0.11	0.75	0.04
Non-perfect cosine responsivity correction				1.5	2.5	1.5	2.5	1.50	0.46	1.50	0.46	1.50	0.13
Non-perfect temperature dependence correction SL501				0.2	0.1	0	0	0.04	0.00	0.16	0.01	0.10	0.00
Non-perfect temperature dependence correction RB				3	6	2	4	2.20	0.80	2.80	1.02	2.50	0.26
Long-term changes in responsivity				2	1	2	1	2.00	0.18	2.00	0.18	2.00	0.05
Time errors (disappears for daily values)				0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Low resolution in data sampling					0.05		0.1	0.00	0.02	0.00	0.01	0.00	0.00
Missing data								0.06	0.09	0.06	0.09	0.06	0.03
Maintenance, humidity, snow, others								1.50	2.00	1.00	1.50	1.00	0.43
Total systematic and total random unc.(95%)			SL501	**4.74**	**5.61**	**5.52**	**6.89**	**5.52**	**2.34**	**4.94**	**1.84**	**5.15**	**0.54**
			RB	**5.63**	**8.23**	**5.95**	**8.03**	**6.01**	**2.48**	**5.71**	**2.11**	**5.77**	**0.61**
Total uncertainty (%) B+t_{95}S	**7.8**			SL501	**10.4**	SL501	**12.4**	SL501	**7.9**	SL501	**6.8**	SL501	**5.7**
				RB	**13.9**	RB	**14.0**	RB	**8.5**	RB	**7.8**	RB	**6.4**

Table 4.1 Estimate of the systematic and random uncertainty components (%) *for calibration conditions, Leszczynski (2002), for high and low irradiance daily values, for typical winter and summer monthly values and for yearly values of the UV-data series compiled for Norrköping 1983-2003. Shaded areas are specific for the RB-meter.*

5 Results and discussion

The primary result is hourly values of CIE-weighted UV-radiation from March 1983 up to December 2003. These values are first integrated to daily values for each instrument and also for the simple empirical model. To get one series of daily values the following priority is used. SL501 daily data have the highest priority followed by the RB data. If none of these are available the empirical daily values is inserted.

The unit that has been used in the data set and also in Tables and Figures is Whm^{-2}. All daily, monthly and yearly values are sums. The data refer to NOGIC-2000 and LAP/COST/WMO-1999 scales of irradiance.

From the daily data set monthly values are aggregated. Due to a systematic error of the empirical model for low solar elevations January and February of 1983 is not replaced in this manner. For these two months the monthly values have been calculated using a simple linear model. This model is based on all the other January and February monthly UV-data and the measured global radiation for each month respectively.

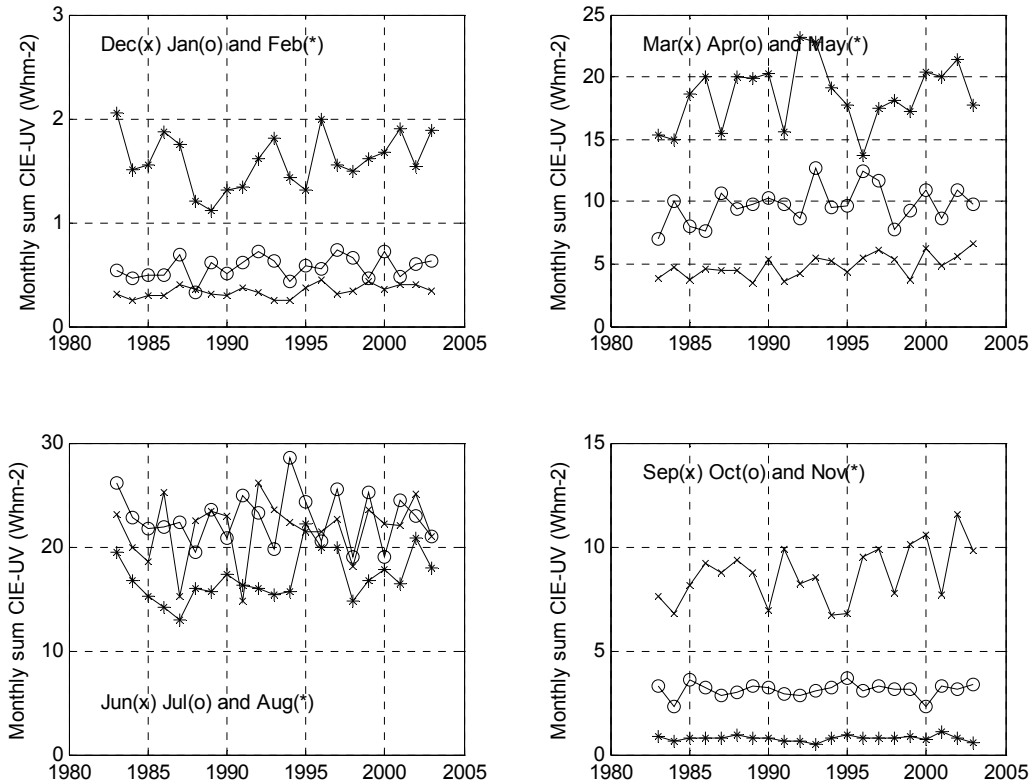

Figure 5.1 Monthly values 1983-2003 of CIE-weighted UV radiation for Norrköping Sweden. Note the difference in scale on the axis of irradiation.

In Figure 5.1 all monthly values are plotted with the months grouped by season per subplot. The next plot, Figure 5.2, shows the seasonal values in each subplot. Here a linear model is fitted to the data and the trend expressed as change in percent per year is given. For the period 1983-2003 all trends show an increase of the UV-irradiance. To find out the significance of the trends they were tested applying the

null-hypothesis at 0.05 using Student's t=2.093 for 19 degrees of freedom, i.e. 21 years minus two.

The result is summarised in Table 5.1. Here trends in percent per year and 95% confidence intervals are presented for the four seasons and for the yearly values. The corresponding test has also been applied on the trends for global radiation and for total ozone. The null-hypothesis is rejected for the UV and for the global radiation, but not for the total ozone. Thus the observed trends for yearly UV and for the global radiation is significant at the 95% level.

The trend results for the yearly quantities give support to each other. A reduction in the ozone layer should give an increase in the UV. But, as can be seen most of the increase in UV can probably be explained by processes also effecting the global radiation. The most evident candidate is the cloudiness. This hypothesis is supported by a high correlation between sunshine duration and UV. For the monthly values of Norrköping 1983 to 2003 the correlation range from 0.641 (December) to 0.975 (July). The variation in sunshine duration is strongly connected to variation in cloudiness.

Table 5.1 Trends (%/year) and confidence intervals for the period 1983-2003 for Norrköping and test results for significance at 95% level. Values are given for each season and for the yearly value of the CIE-weighted UV. Also presented are the yearly trends for global radiation, G_h*, , sunshine duration,* Sdur, *and total ozone,* TOZ.

Period Quantity	Trend (%/year)	Conf. Int. (%)	Sig. @ 95%
Winter CIE-UV	0.61	±0.92	No
Spring CIE-UV	0.78	±0.70	Yes
Summer CIE-UV	0.31	±0.66	No
Autumn CIE-UV	0.82	±0.72	Yes
Year CIE-UV	0.52	±0.44	Yes
Year TOZ	-0.14	±0.23	No
Year G_h	0.36	±0.33	Yes
Year Sdur	0.67	±0.64	Yes

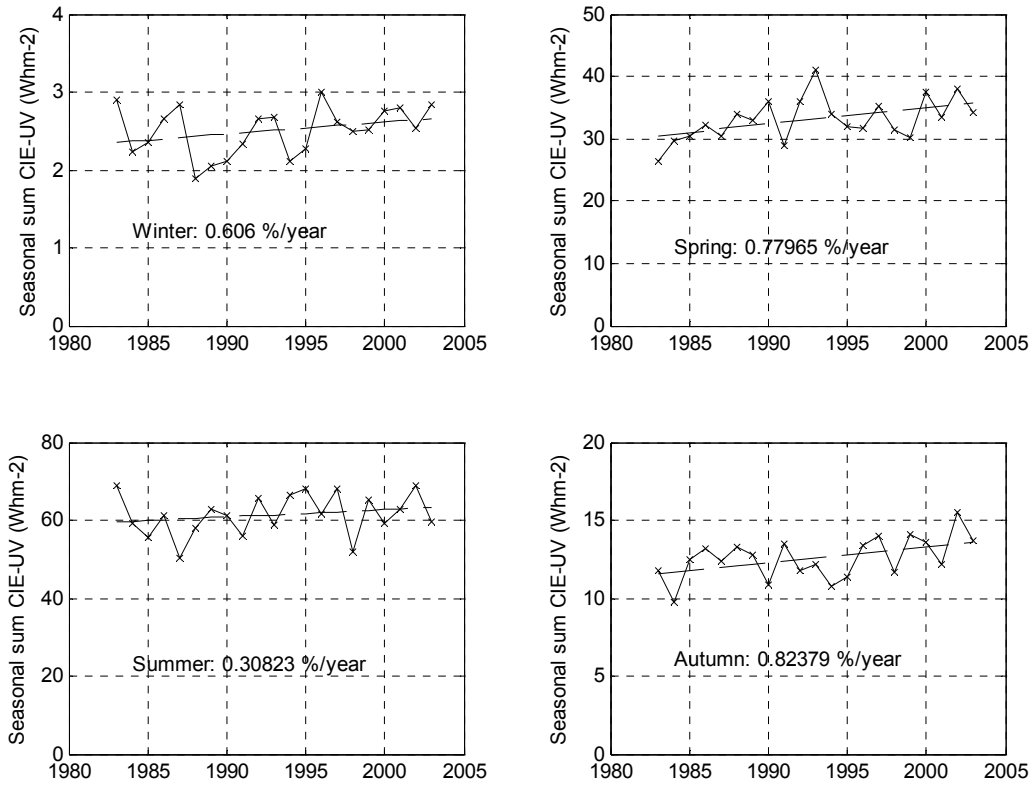

Figure 5.2 Seasonal values 1983-2003 of CIE-weighted UV radiation for Norrköping Sweden. Note that Winter is the sum of the January, February and December of the same year. Also in the graphs are the linear trends for the period expressed as %-change per year.

The yearly UV-values are plotted in Figure 5.3 along with the corresponding values for total ozone, global radiation and sunshine duration. Also the trend is presented as change in percent per year. As can be seen the CIE-weighted UV has increased by 0.52% per year over the period. At the same time the total ozone has decreased by 0.14% per year, the global radiation has increased by 0.36% per year and the sunshine duration has increased by 0.67% per year.

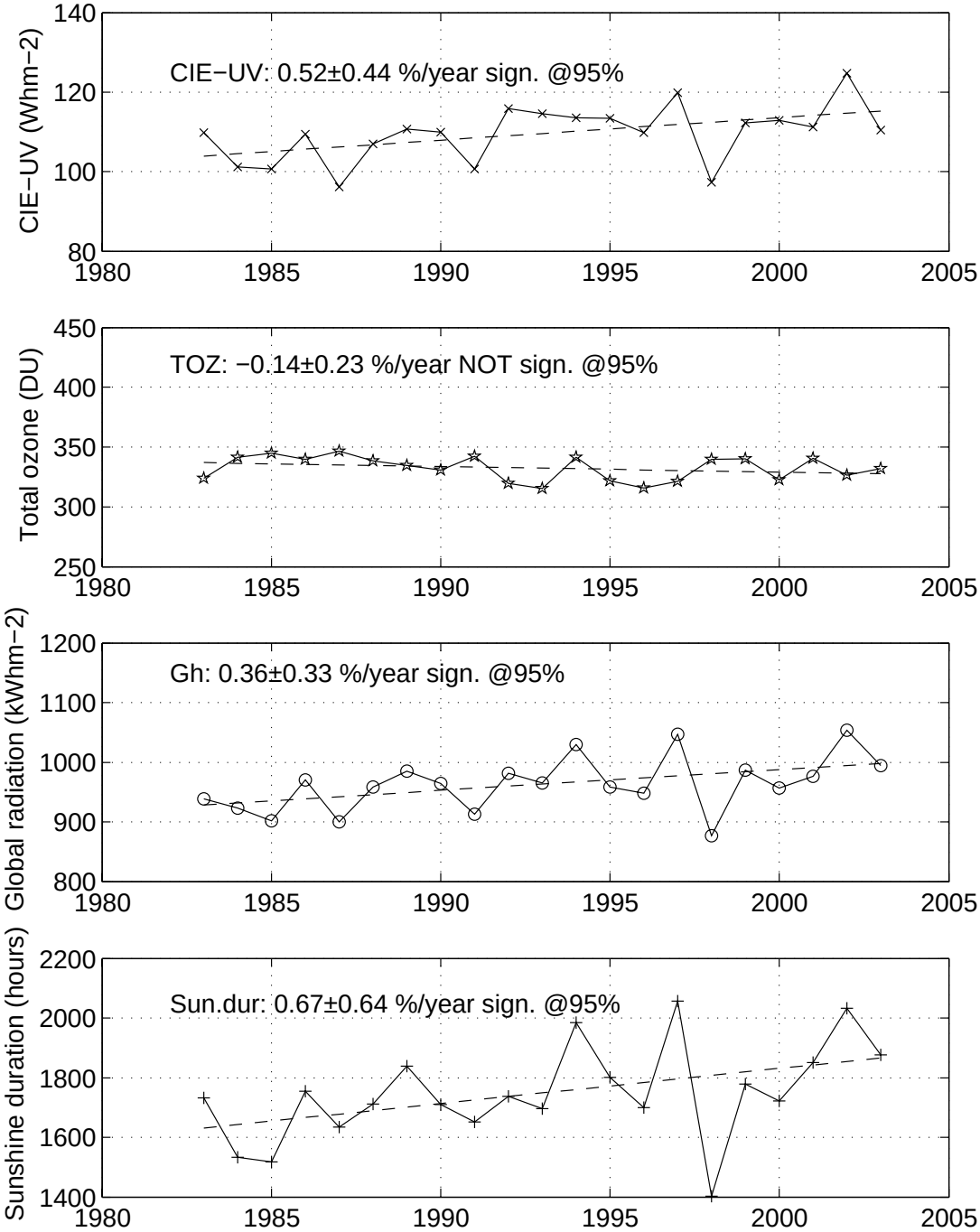

Figure 5.3 Yearly values 1983-2003 of CIE-weighted UV radiation (top panel), total ozone (second panel), global radiation (third panel) and sunshine duration (lower panel) for Norrköping Sweden. Also included are the linear trends for the period expressed as %-change per year. The trends are tested for their significance at the 95%-level.

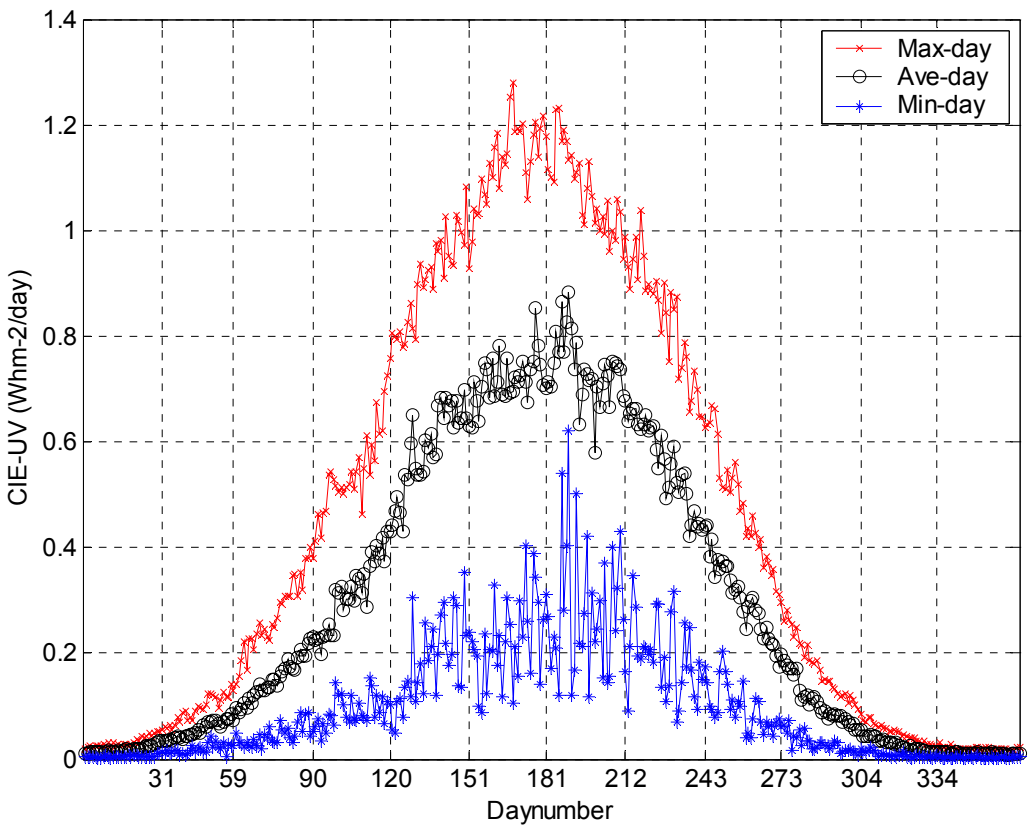

Figure 5.4 For each day of the year the maximum, average and minimum daily values for 1983-2003 of CIE-weighted UV radiation for Norrköping Sweden are plotted.

The data can be presented in many ways. In this paper the focus has been on the long-term aspect. However, the final graph Figure 5.4 shows the yearly variation of CIE-weighted UV for Norrköping. Here the maximum, average and minimum daily value for each day of the year selected from the period 1983-2003 is plotted.

Some interesting features can be seen. The large difference between the summer and the winter. The steep increase during the spring and the corresponding decrease in fall is typical for high latitude sites. Also worth noting are the dates of the maximum of the three data sets. The highest daily value is usually located close to the summer solstice. The dates of the highest average values are slightly shifted to the early part of July. The maximum of the minimum daily values is also located in July. The explanation for this is most likely that the total ozone in average becomes thinner from spring to autumn.

So far no results have been presented for the hourly values. But, in Appendix 2 plots of the yearly and daily variation of hourly UV-index for Norrköping 1983-2003 is given. For each hour and month of the year the *Median, Average, Maximum* and the *Minimum* hourly UV-index have been computed. The plotted values are located at the mid-point of the hours (e.g. 10.5 UTC). Numbers (1-12) indicates the months. For example 6 is representing the month of June. By international convention the UV-index is computed by multiplying the CIE-weighted UV-irradiance expressed in Wm^{-2} by the constant 40 $W^{-1}m^{2}$. Note that individual hourly values may have large errors. This would mainly affect the maximum and minimum values plotted. Another drawback with the hourly values is the time error, see section 3.2.5.

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APPENDIX 1

<u>Empirical model for missing data</u>

An empirical model used for replacing missing hourly data. Needed input is hourly values of global radiation, G_h (Whm^{-2}), relative sunshine duration, SS_{rel} (0-1), relative optical airmass through the ozone layer, my (about 1-12) and total ozone, TOZ (Dobson Units). The output will be CIE weighted UV-irradiation (Whm^{-2}).

IF $G_h > 0$ AND $SS_{rel} > =0$ AND SZA < 92.5 THEN

lnmytoz = ^{e}LOG(MY * TOZ))

Amod = -.0290781 * SS_{rel} * SS_{rel} + .122814925 * SS_{rel} + .282964728
Bmod = .5595159 * SS_{rel} * SS_{rel} - 2.0473375 * SS_{rel} - 4.6381064
Cmod = -2.172774 * SS_{rel} * SS_{rel} + 7.551011 * SS_{rel} + 9.221975

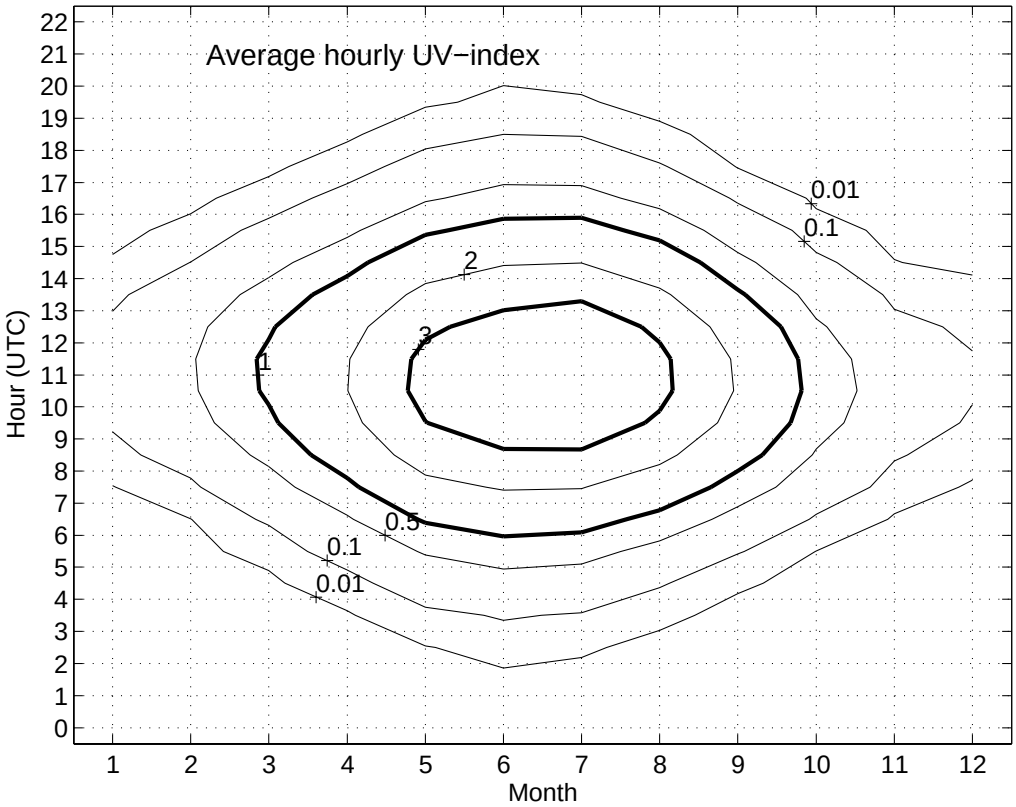
UVmod = G_h * EXP(Amod * lnmytoz * lnmytoz + Bmod * lnmytoz + Cmod)

ELSE

UVmod = 0

END IF

APPENDIX 2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Hour (UTC)
Month
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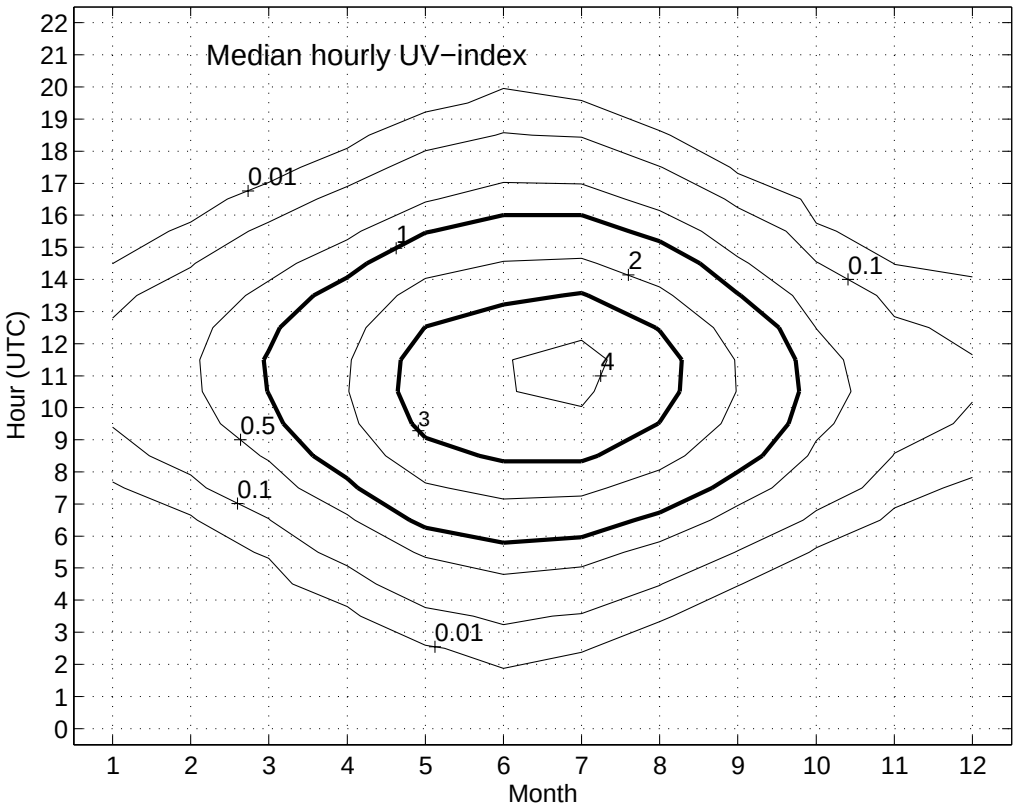
0.1
2
3
1
0.5
0.1
0.01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Month
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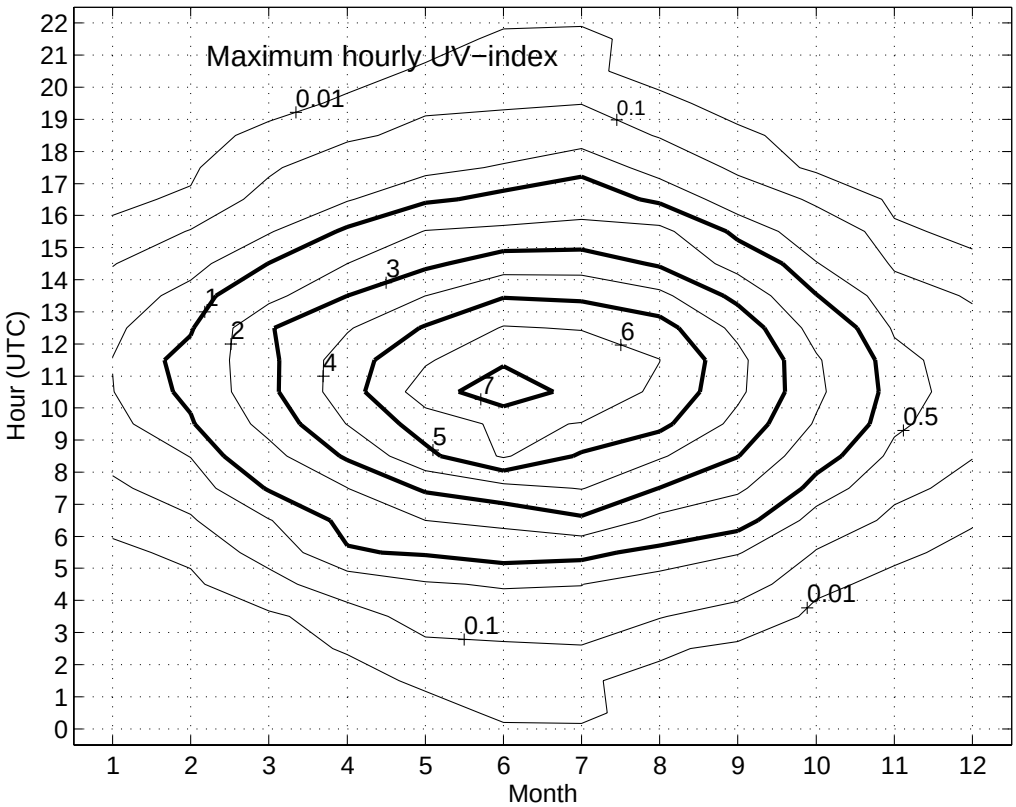
1
2
0.1
4
3
0.5
0.1
0.01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1
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5
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7
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Hour (UTC)
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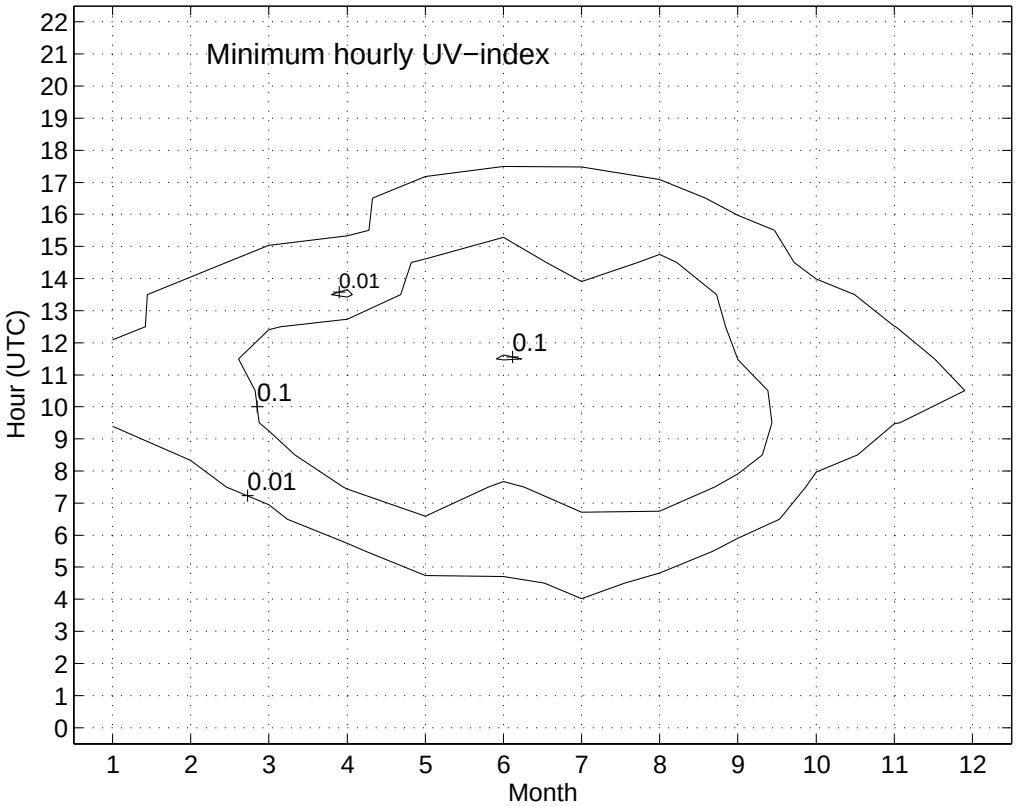
Minimum hourly UV−index
0.01
0.1
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Hour (UTC)
Month

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