Deutscher Wetterdienst

Berichte des Deutschen Wetterdienstes

204

Spectral and Integral Observations of UV-B-Radiation and Ozone Measurements

von
Ulf Köhler, Winfried Vandersee
Peter Winkler, Leonhard Gantner

Offenbach am Main 1998
Selbstverlag des Deutschen Wetterdienstes

Content

Zur Herstellung dieses Buches wurde chlor- und säurefreies Papier verwendet.

ISSN 0072-4130
ISBN 3-88148-341-1

Herausgeber und Verlag:

Deutscher Wetterdienst
Frankfurter Str. 135
63067 Offenbach am Main

Anschrift der Autoren:

Dipl.-Met. Leonhard Gantner
Dipl.-Met. Ulf Köhler
Dipl.-Met. Winfried Vandersee
Dr. Peter Winkler
Deutscher Wetterdienst
GB Forschung und Entwicklung
Meteorol. Observatorium Hohenpeißenberg
Albin-Schwaiger-Weg 10
82383 Hohenpeißenberg

SUMMARY

Initial investigations of the properties und capabilities of the Brewer spectrophotometer as a UV-measuring instrument were done at Hohenpeißenberg before 1990. In this BayFORKLIM-project, however, a more exact and comprehensive analysis was carried out. Possible sources of errors, namely, wavelength instability, temperature and humidity dependence, non-linearity of the detector, straylight effects, cosine error and quality of the calibration lamps have been investigated and most of them could be quantified. Systematic errors can now be corrected in the evaluation procedure. Although the Brewer is only a single monochromator, it proved to be a relatively precise and very reliable instrument for monitoring purposes.

Minor error sources (maximum error < ± 1%) are concerning wavelength setting and temperature dependence of the entire system. Errors up to ± 5% may occur due to non-linearity and straylight (below 300 nm) if no correction is applied. The main causes of measurement errors are uncertainties in the calibration lamps and the non-ideal cosine response of the entire spectrometer. Errors of more than 10% are possible and a correction requires a large amount of effort but is absolutely necessary.

Relocation of the instrument and changes in the local geography can be important for the homogeneity of long time series. The Hohenpeißenberg Brewer #010 was moved in May 1993 in order to be able to see the entire horizon. This relocation has lead to systematic changes in the measured UV-B of about + 10%, for clear sky and high sun, up to + 20% at low sun and enhanced turbidity. Corrections have been applied to the first period of the entire UV time series in order to remove the bias resulting from the relocation.

Good agreement was found in comparisons with other instruments and model data. Differences between the integrated spectra were less than ± 5%, but deviations up to ± 15% may occur for single wavelengths. Reasons for these discrepancies may arise from different slit functions and half widths of the instruments. When compared with model calculations, extraterrestrial sun data and the absorption spectra used by the model, were found to be of crucial importance.

After five years of routine UV-B measurements, climatological investigations can already be made. Changes in UV-B due to the variability of total ozone can be detected. During years with high total ozone, like 1991, low UV-B values were found. A distinct increase of UV-B, coinciding with exceptionally low total ozone values, was observed in the fall 1992 and throughout 1993, 1½ years after the Pinatubo eruption. For example, in April 1993 ozone values were 12% below the five year mean (1990-1994). At the same time, the erythemally weighted UV-B increased by 30% over the five year mean. In this case, the "amplification factor" amounted to about 2. This factor depends on total ozone and solar height. The strongest dependence of UV-B on total ozone was

found at low sun angles.

The spectral analysis showed that changes of total ozone between 280 to 450 D.U. do not affect UV-B very much at wavelengths of about 320 nm. At 295 nm on the other hand UV-B is altered by more than one magnitude.

1 Introduction

During the last years a possible enhancement of UV-radiation due to the observed trends in ozone (depletion in the stratospheric ozone layer, increase in the troposphere, *Claude et al.* 1994a, *Claude et.* al 1994b) had to be expected. The UV-B radiation between 280 and 320 nm is highly dependent on the total amount of ozone in the atmosphere. Also, the largest threatening potential is expected in this UV-range, as many action functions (e.g. erythemal action function, DIN 5031) have their maxima there. Ozone trends, observed at the Met. Obs. Hohenpeissenberg and worldwide, especially in mid latitudes, should definitely cause an opposite trend in UV-B. The UV-C (<280 nm) and UV-A (320-400 nm) are less effected.

In opposite to the long and mostly very reliable total ozone measurements, only a few longer lasting UV-B series exist, which possess the necessary reliability for trend analysis. The homogeneity of the long term series in the USA, measured with Robertson-Berger filter instruments, have been questioned recently (*WMO* 1991, *Bojkov* 1994). Another large disadvantage of these filter instruments is the strong dependence of the measured values on the transmission of their filters. Statements on spectral changes are not possible at all. Investigations by *Blumthaler and Ambach* (1990) resp. *Ambach and Blumthaler* (1992) on the Jungfraujoch confirm, that a UV-increase in the alpine region has taken place since the beginning of the eighties. Measurements in New Zealand (*Basher* 1994, *Basher et al.* 1994) and Canada (*Kerr and McElroy* 1993) are also indicating a UV-increase. All these UV-enhancements are accompanied by a simultaneous depletion of the ozone layer.

In spite of clear trends in the total ozone, (e.g. of about -3% per decade at Hohenpeissenberg since 1968), a corresponding increase in the UV-B-irradiation cannot simply be deduced. UV-radiation is not only affected by ozone and its vertical distribution, but also by turbidity and cloudiness. The global radiation at Hohenpeissenberg has diminished by about 2.8% per decade (*Liepert et al.* 1994), attributed to an increase in turbidity. In connection with the hypothesis that the UV-B will decrease at the same total ozone level due to a shifted ozone profile (*Brühl and Crutzen* 1989), it can be concluded, that the UV-B radiation may decrease at least in highly industrialized and populated areas (*Ambach und Blumthaler* 1994).

In order to figure out the correlation between ozone and UV-B all various influencing factors have to be included in well grounded investigations. After that it should be possible to do long term trend assessments with this correlation. The Met. Obs. Hohenpeissenberg offers the best conditions for these investigations. Very long and homogeneous data of ozone (total ozone and vertical profile, both recalculated a short time ago (*Köhler and Claude* 1996, *Köhler and Claude* 1998, *Köhler* 1997) and of all meteorological parameters (e.g. global radiation, cloudiness, visibility (indication of turbidity) etc.) and regular UV-B observations with the Brewer Spectrophotometer, which is usually used for total ozone measurements, commenced in 1990.

This project within the **Bay**erische **KlimaFor**schungsprogramm BayFORKLIM enabled the investigation of the reliability and quality of the Brewer UV-observations and to state initial correlations between UV, ozone and the rest of the meteorology and to do initial climatological evaluations. Laboratory investigations inclusively calibrations, comparisons with other UV-instruments and with radiation models (STAR, Meteorological Institute of the University Munich, Köpke-group) served for these purposes.

2 Brewer-Spectrophotometer

2.1 General Description

The Brewer Spectrophotometer #010 has been used for total ozone observations at the Met. Obs. Hohenpeissenberg since January 1983. This type of spectrophotometer was developed in the early seventies (*Wardle et al.* 1963, *Brewer* 1973). It was planned as a supplement or replacement for the old, completely manually operated Dobson Spectrophotometer. The Brewer is a PC-controlled, nearly fully automated instrument. It allows a flexible measurement schedule and requires less personal intensive operation. Its rugged construction makes it suitable for deployment even in climatologically extreme areas like the tropics (*Cuevas and Redondas* 1993) or the polar regions (*Nichol and Valenti* 1993).

Several long term investigations have proved its qualification as total ozone measuring instrument (*De Backer und De Muer* 1991, *Feister* 1991, *Feister* 1994a, *Kerr et al.* 1988, *Kerr et al.* 1989, *Köhler et al.* 1985, *Köhler und Attmannspacher* 1986, *Köhler et al.* 1988, *WMO* 1994).

The Brewer is suited for UV-observations as well. At Hohenpeissenberg sporadic UV-observations in the wavelength range 290 - 320 nm were started in 1985 after having received the required software from AES-Toronto and SCI-TEC-Saskatoon, Canada. After having gained sufficient experience (optimal schedule, calibration procedure and their accuracy, instrumental properties) regular observations of complete UV-spectra each half an hour from dawn to dusk were started in January 1990. Thanks to more or less regular calibrations and the participation in several national and international intercomparisons the quality of data is suitable for intensive investigations of correlations between UV, ozone and other meteorological parameters like global radiation, turbidity, cloudiness as well as for preliminary trend analyses.

Apart from the Met. Obs. Hohenpeissenberg (*Vandersee und Köhler* 1994, *Vandersee* 1994) the Brewer is employed as UV-instrument at many stations worldwide. Institutions with longer UV-experience are the Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping (*Josefsson* 1986), the Aristotle University in Thessaloniki (*Bais et al.* 1994, *Bais* 1994a), Japan (*Ito et al.* 1994) and the Meteorological Observatories of the German Meteorological Service in Potsdam and Lindenberg. Since May 1994 the Brewer is used as interim instrument for the German Meteorological Service UV-network. The Environment Protection Agency (EPA, USA) is just about to establish a major network with Brewer instruments (*Barnard* 1994). A double monochromator Brewer specially developed for UV-observations is used in this network. This instrument has also been employed for scientific purposes at the Met. Obs. Potsdam since spring 1995.

2.2 Technique/Construction

The Brewer spectrophotometer was originally designed for fully automated measurements of the total ozone amount. The instrument itself is mounted on a so-called sun-tracker, which tracks the solar azimuth under the control of a PC. The sun elevation is adjusted by means of a vertically movable prism. It is also possible to measure internal calibration lamps as well as the hemispherical UV-B global irradiation (through a quartz glass dome with a teflon diffusor underneath). In all cases the incoming radiation enters the spectrometer through a foreoptic with iris, various filters and an entrance slit.

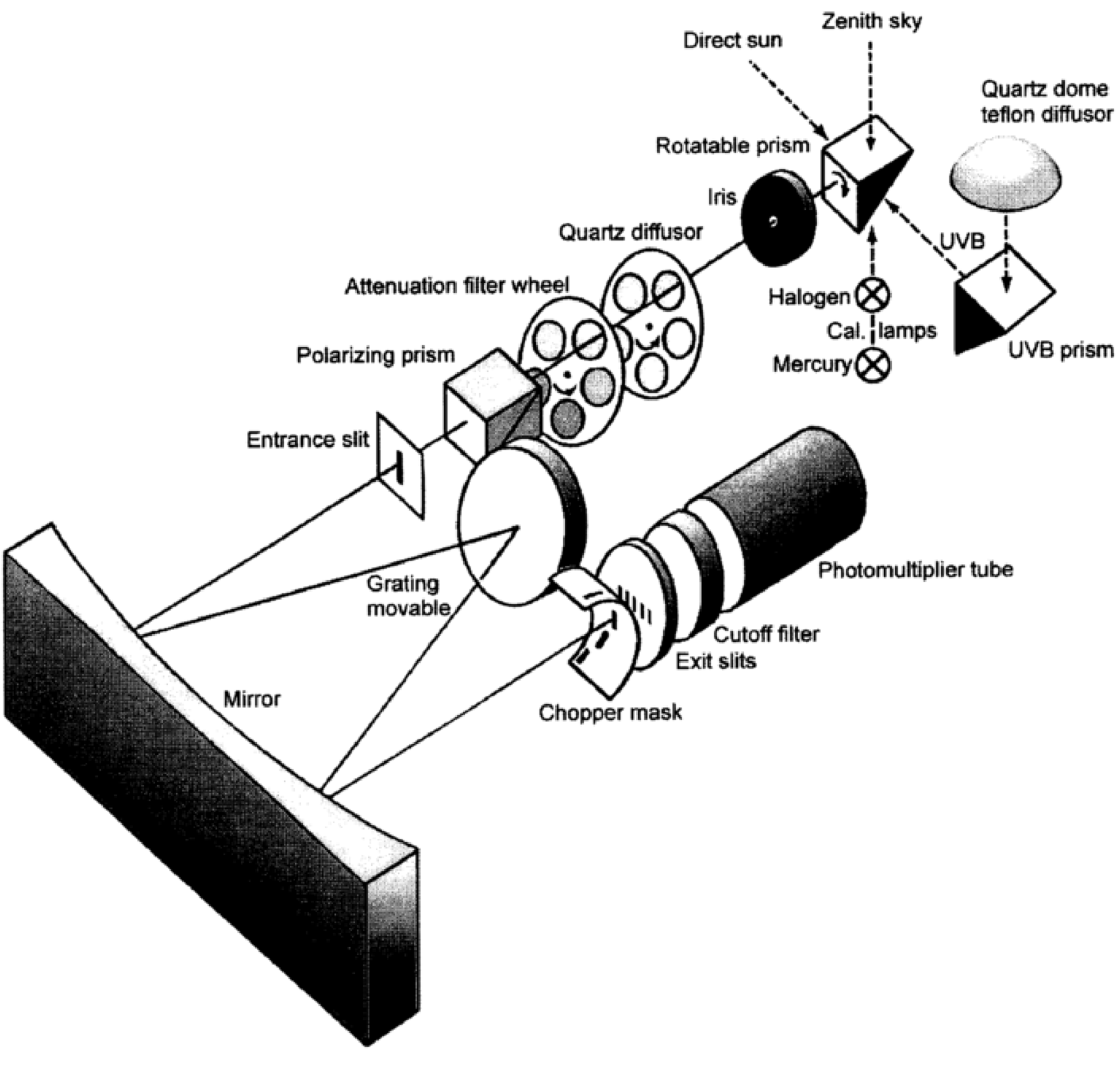


Figure 2.1: Schematic sketch of the spectrometer of the Brewer (from Josefsson *1986)*

This so-called single Eberth-spectrometer (s. figure 2.1, from *Josefsson* 1986) uses a movable holographic diffraction grating with 1800 lines/mm as dispersing element, a mirror and a chopper mask with several slits in the requested wavelengths. The radiation finally reaches the photomultiplier through exit slits and a $NiSO_4$-filter. The transmission of this filter is rapidly decreasing beyond 315 nm. It serves as a straylight filter to reduce the large straylight portion of the longer wavelengths > 320 nm of this single monochromator to a tolerable level.

During total ozone measurements the grating remains in a fixed position, and the chopper mask selects the five wavelengths one after the other for several cycles. The incoming radiation is measured by the photomultiplier in photon-counting mode. This signal is transmitted through the data link to the controlling PC. The ozone value is calculated and archived immediately after the end of the observation.

During the UV-observation the chopper mask is kept in a fixed position, and the grating is turned by means of a step motor to move the spectrum across a fixed slit. Thus a spectrum can be measured between about 285 and 325 nm with flexible step width (usually 0.5 nm). The half-width of the used exit slit is 0.63 nm and its transmission function is nearly equivalent to a Gaussian function. The photon counts are measured by the photomultiplier and transferred to the controlling PC in the same way as in the ozone measurement. The raw counts of each wavelength are separately stored by the software. These raw spectra are usually evaluated later, but an on-line calculation is possible.

The test lamps integrated in the Brewer are of big advantage. They are located beneath the rotatable prism and can be measured fully automatically as well. A mercury lamp (spectral line at 302.5 nm) is used for the correct wavelength setting, a current and voltage stabilized standard lamp (quartz-halogene) allows a check of the spectral sensitivity. The stability of this internal lamp can be controlled using an external standard lamp. This lamp is normally used to check Dobson-instruments. It can be measured through the quartz window using a self-constructed holding device.

All above mentioned technical data have not been determined or measured at the Met. Obs. Hohenpeissenberg, but are drawn from manuals of the manufacturer. Half-width of the slits and their transmission function are additionally measured and confirmed by laboratory measurements at the Met. Obs. Potsdam in August 1997 to a great extent.

2.3 Instrumental Properties

Investigations of instrumental properties and capacities were carried out mainly in this project as well as in the late eighties (*Köhler et al.* 1988). At the moment the Met. Obs. Hohenpeissenberg has a simple optical laboratory at its disposal. The installation of an appropriately equipped facility will be done in connection with the development of the Met. Obs. Hohenpeissenberg to a **G**lobal **A**tmosphere **W**atch (GAW) station. Therefore, some of the instrumental properties were additionally investigated by an optical lab (GIGAHERTZ-OPTIK, MUNICH) to confirm our own results. These results will be discussed in the following sections. The dark count is not treated intensively, as it is separately determined for each measurement and correspondingly applied in the evaluation of the raw data. Therefore, it can be neglected as an error source.

2.3.1 Wavelength Setting

Tests with the internal mercury lamp are performed several times per day. The 302.5 nm spectral line of the internal mercury lamp is measured and the Brewer is set at this wavelength with a precision of 0.005 nm (after specifications of the manufacturer). A necessary correction is fully automated by the controlling PC. The precision of the wavelength setting within the entire spectrum from 290 to 320 nm in the allowed temperature range of -40 to +50 ^{0}C should not exceed 0.01 nm. Comparisons of the position of measured and actual Fraunhofer lines, with spectra of other instruments and with model calculations, indicate, that the precision of the wavelength setting is better than 0.1 nm.

Easy calibrations can be done very frequently and possible misalignements due to grating movements during the UV-observation can be detected and removed quickly. During the past years only very small corrections were necessary, even after frequent UV-observations and additional large instrumental temperature variations. Problems with the sticking mechanism can easily and quickly be removed by cleaning the corresponding parts.

A properly functioning wavelength setting shows that the measurement errors are clearly less than ± 1% and consequently negligible.

2.3.2 Temperature and Humidity

No laboratory investigations of temperature dependence were done at the Met. Obs. Hohenpeissenberg. After *Josefsson* (1986) and personal communication with the Canadian Brewer-experts (AES and SCI-TEC) it should be possible to apply the temperature compensation, which is normally used for the total ozone measurements, to UV-observations too. These temperature coefficients of all five wavelengths have been specifically determined for each instrument over a wide temperature range (approx. 0 to 35 ^{0}C) using a large number of standard lamp tests. The reason for this temperature dependence is mainly attributed to the $NiSO_4$-filter. Other electronical and optical parts do not have any effect worth to be mentioned.

The following formula for calculating the effect of temperature is drawn from the calculation algorithm of the total ozone measurement and is applied to the measured photon counts.

$$Temp.\ Corr.\ in\ \% = 100 \times \left(\exp\left(\frac{(\Delta T \times TC) \times 2{,}302585}{10\,000} \right) - 1 \right)$$

From the above formula the following corrections are calculated for the temperature coefficients of the selected five wavelengths and for a difference of $\Delta T = +10$ K between instrumental reference temperature during calibration and instrumental temperature during measurement:

λ [nm]	306,325	310,071	313,52	316,82	320,027
Correct. [%]	0,81	0,76	0,7	0,65	0,41

Table 2.1: Temperature depending correction at given wavelengths and a temperature difference of +10 K.

Correspondingly, inter- or extrapolated values have to be applied to the single wavelengths of the spectral UV-observation. So far, the evaluations do not include this temperatur correction, but will be considered in future calculations. Originally, the magnitude of this temperature dependence would be verified by means of a statistical investigation of measured data on fair days with constant ozone and a large diurnal variation of the Brewer temperature (max. about 20 K). Due to the comparatively small effect, this does not seem to be very promising. Other effects such as slightly changed meteorological conditions, would exceed the influence of this temperature signal.

Another negative property of the straylight filter is its tendency to attract water, which causes a change of the spectral transmission in the presence of humidity inside the instrument. This effect was discovered by means of the standard lamp tests, but it was not quantified in relation to the UV-B-measurements. A simple solution to this problem is the installation of vessels with silicagel as a desiccant, at several places inside the Brewer case. The desiccant has to be checked and changed frequently. Investigations by *Bais* (1994b) proved, that this precaution measure is sufficient to eliminate the humidity effects on total ozone and UV-B-measurements to a great extent.

A more expensive treatment of temperature- and humidity-effects on operational measurements does not seem to be useful. These error sources are comparably small. An airconditioner is too expensive and unwieldy for a normal field instrument like the Brewer and would unnecessarily raise its cost. It is, however, an essential condition for most precise observations and therefore extremely useful for a reference instrument, as it has been installed by *Seckmeyer* (1989) at the Fraunhofer Institut für Atmosphärenforschung (IFU) in Garmisch-Partenkirchen.

2.3.3 NON-LINEARITY

Non-linearity is caused by the deadtime of the photomultiplier. If too many photons enter simultaneously, the photomultiplier is unable to count all of the photons. This error increases with increasing signal exponentially. The so-called deadtime correction of the total ozone measurement, which also increases exponentially with raising signal, is applied to correct for the non-linearity effect. The comparison of the magnitude of this correction with laboratory investigations (simple ones at the Met. Obs. Hohenpeissenberg and more sophisticated ones at GIGAHERTZ-OPTIK) showed the agreement of these values. GIGAHERTZ-OPTIK found a non-linearity effect of about -4% at a signal of 100 000 photoncounts (PC) while our own, less exact values indicated approx. -2%.

The following iteration formula has to be run through eight times:

$$PC(i+1) = PC(0) \times \exp(PC(i) \times deadtime)$$

The calculated deadtime correction (the experimentally found deadtime of the Brewer is 3.8×10^{-8} s) for 100 000 is equivalent to a -1.8% loss due to non-linearity. The correspondence between deadtime correction and the values measured in the laboratory is relatively good. The maximum correction at photoncounts up to 180 000 is slightly above 3%. A spectral dependence, ineffected by the difference of irradiance (typical values are about 3 200 photons at 300 nm and about 100 000 photons at 317.5 nm at the same time) could not be detected and should not exist.

2.3.4 Straylight

The above described Brewer spectrophotometer is a single monochromator whose suppression of straylight is poor compared with double monochromators (like e.g. the Bentham DM 150). The very small signal especially at short wavelengths below 300 nm is disturbed by the radiation of longer wavelengths. The Brewer uses a straylight filter ($NiSO_4$) with a rapidly decreasing transmission above 315 nm, located in front of the photomultiplier entrance. The spectral measurement values between 290 and 295 until 300 nm (depending on sun elevation) are obviously enhanced.

Simple assumptions are made to correct this effect: It is assumed that no natural, solar UV-radiation below 293 nm is able to reach the surface under the present total ozone conditions. The measured signal between 290 and 292 nm is completely attributed to straylight and its average is subtracted from all other spectral values.

Figure 2.2 clearly shows the improvement. The uncorrected Brewer UV-B below 295 nm is obviously higher than the values measured with the double monochromator (Bentham of M. Blumthaler) and calculated values of the STAR-model, respectively (upper part of the depiction). After correction, a good agreement exists until 293 nm. The double monochromator also exhibits typical symptoms for straylight contamination. The last values are enhanced compared to the model, which is assumed to simulate more likely the natural course of the UV-B spectrum.

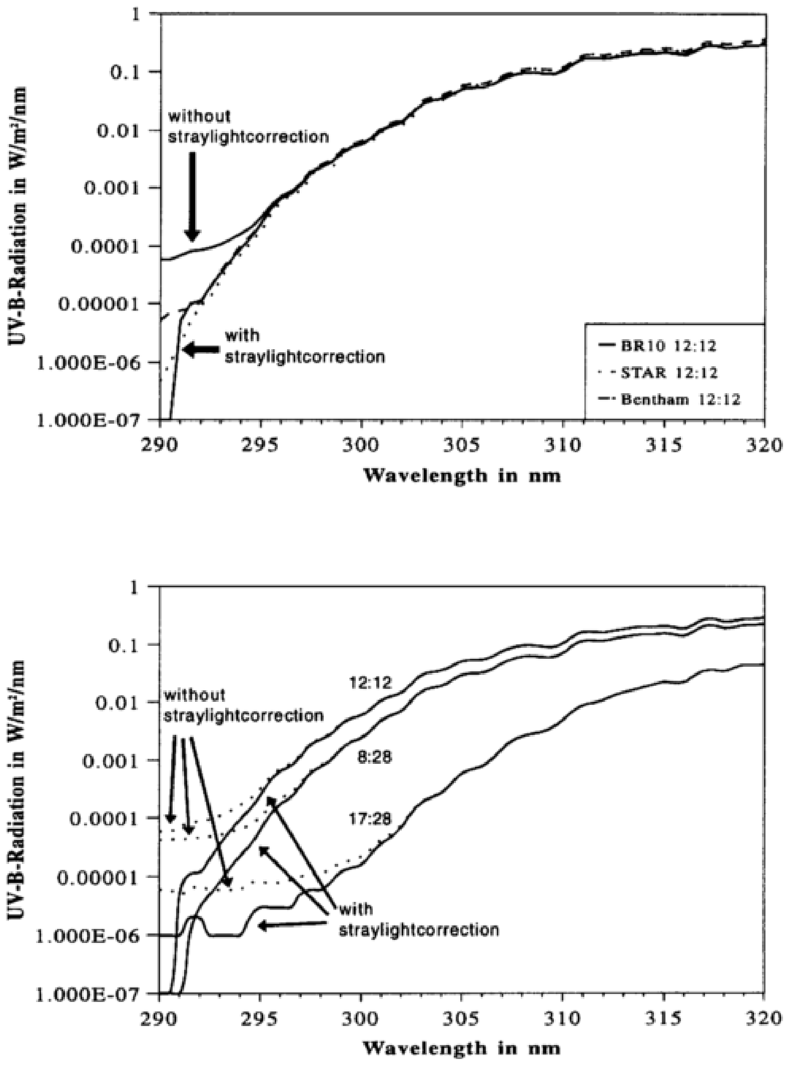


Figure 2.2: Straylight influence.

The shift of the straylight effect to longer wavelengths at lower sun levels can be seen in the lower part of Fig. 2.2. The measurement at 17:28 UTC was performed at a sun elevation of about 15^0. Here, wavelengths up to approx. 302 nm are already effected. The correction improves the measurements down to 300 nm.

The share of straylight in the measurement signal at two different sun elevations is shown in Figure 2.3. At high sun the straylight exceeds the 1%-limit below 300 nm. This limit is reached already at approx. 305 nm at low sun. The straylight between 295 and 296 nm is almost of the same order of magnitude as the real signal. The straylight share at the wavelength 290 nm relating to the entire integral value 290 - 320 nm amounts to about 2 to 3 × 10^{-5} (after measurements at the Met. Obs Hohenpeissenberg). Investigations at GIGAHERTZ-OPTIK yielded comparable results. Straylight measurements by means of two different longpass edgefilters revealed straylight shares of 2.5 and 7.1 × 10^{-5} at 290 nm.

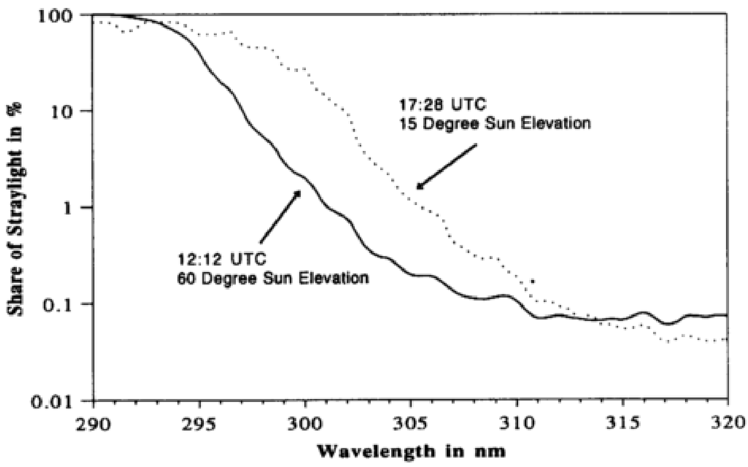


Figure 2.3: Share of the straylight depending on wavelengths at different sun heights.

This straylight effect can be neglected in investigations of integral UV-B. A correspondingly good correction is of extreme importance for a consideration of only short wavelengths. Many important action functions (e.g. erythema, DIN 5050) have their maximum at about 300 nm. Here, the best possible suppression of straylight plays an important role, whether by instrumental improvements (double monochromators) or by appropriate empirical corrections, as it is applied here. This simple subtraction method, however, will work correctly only as long as the ozone layer protects fairly well against UV-B. In the event of the feared continuous depletion of the ozone layer, the spectral portion of the UV-B reaching the ground will be enhanced and a shift of the shortwave edge further toward 290 nm will occur. A separate examination is required to find if the assumptions of this correction procedure remains valid.

2.3.5 Cosine Response

A further, major error source, besides the uncertainty of the calibration lamps, is the deviation of the diffusor from the ideal cosine response to incoming radiation. This deviation can easily be determined in the laboratory for a point source, but the transfer to a spatial source is more difficult.

This holds in particular for the UV-radiation, which extremely differs from a point source because the diffuse part of radiation reaches 70 % and more depending on turbidity, cloudiness and sun height.

The Brewer uses a quartz dome on the upper side of its housing with a flat teflon diffusor underneath. This configuration, however, does not have an optimal cosine response for the incoming radiation. Radiation from large zenith angles does not follow the cosine law.

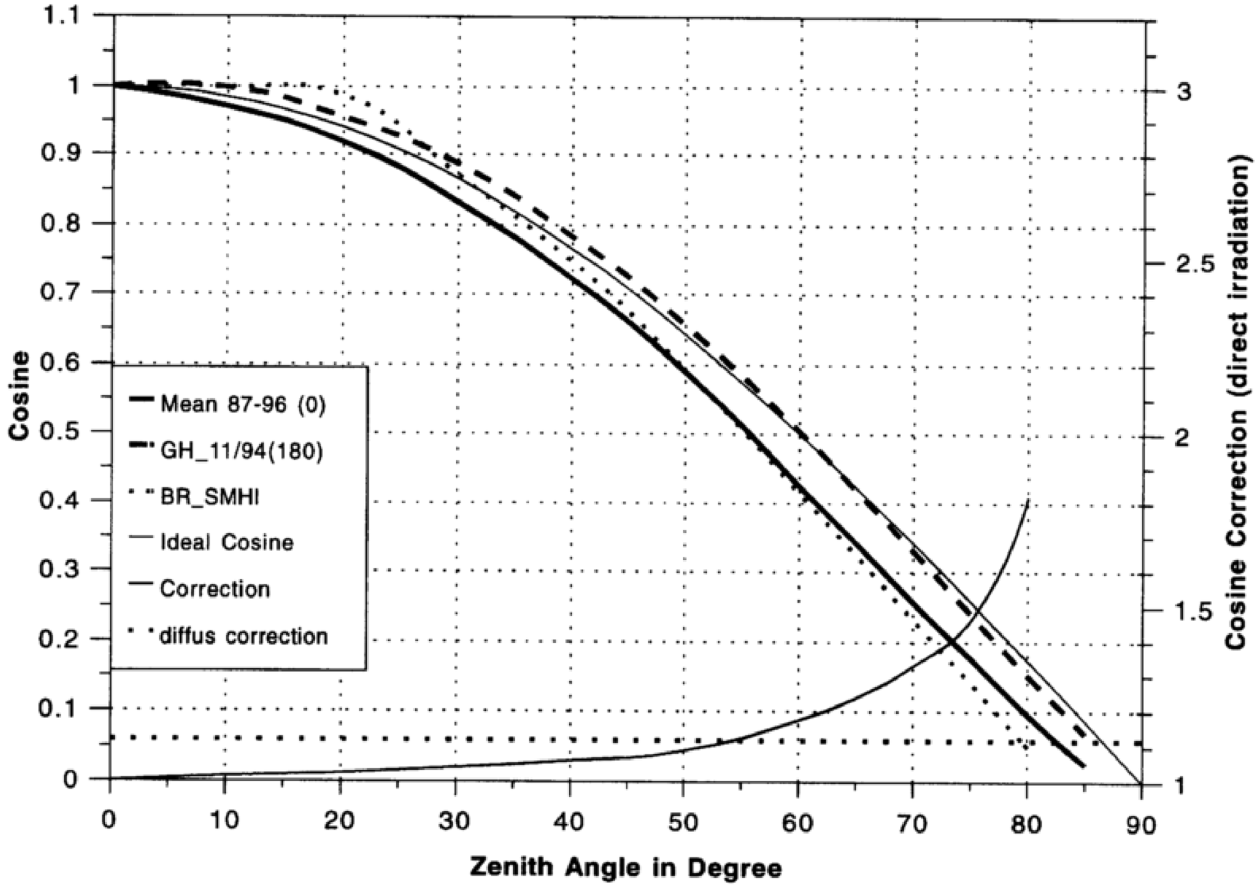


Figure 2.4a: *Deviations of the cosine responses of Brewer #010 and the SMHI-Brewer from ideal cosine as well as the resulting simple cosine correction for point sources and diffuse radiation befor prism alignment.*

The response function of the instrument for angles between 0° and 80° was determined several times between 1987 and 1994 using calibration lamps. The latter had to be mounted in a vertical position for technical reasons. The Brewer itself was tilted and rotated by the selected angles. During the first tests the Brewer stood on its wide side for safety reasons (better stability). It was, however, not possible to simulate the normal sun movement in this position. The sun simulated by the light source moved to the right and left side, respectively, instead of sinking in front of the instrument. Since homogeneity of the diffusor had been assumed, these results should be comparable with a more realistic construction. This was confirmed in an experiment with a mobile lamp carried at the Met. Obs. Potsdam some time later. The deviations from the ideal cosine response, determined during the various tests corresponded within the bounds of the measurement accuracy. The bold solid line in figure 2.4a represents the average of all tests. A spectral dependence could not be determined. The deviation from the ideal cosine law is nearly constant over the entire wavelength range. Small differences to the results in former publications are due to more laboratory cosine measurements additionally used for calculating the mean values. Remarkable, however, is the difference between Brewer #010 and the Swedish Brewer (dotted, of the same age) of the SMHI (from *Josefsson* 1988) up to a zenith angle of about 40°.

The cosine test and other tests were repeated at GIGAHERTZ-OPTIK in order to exclude erroneous measurements at the Met. Obs. Hohenpeissenberg. Our first results were confirmed. By accident, the test lamp was once lowered at the back of the Brewer, opposite of the normal sun position. In this case the cosine response looked similarly strange like that of the Swedish Brewer (dashed line, GH_11/94 (180)). Another test at Met. Obs. Hohenpeissenberg at only three angles confirmed the facts. In the meantime it was discovered (*Josefsson* 1995) at SMHI too, that the first, published cosine tests (*Josefsson* 1986) were probably done with the "wrong" lowering of the light source to the instrumental rear.

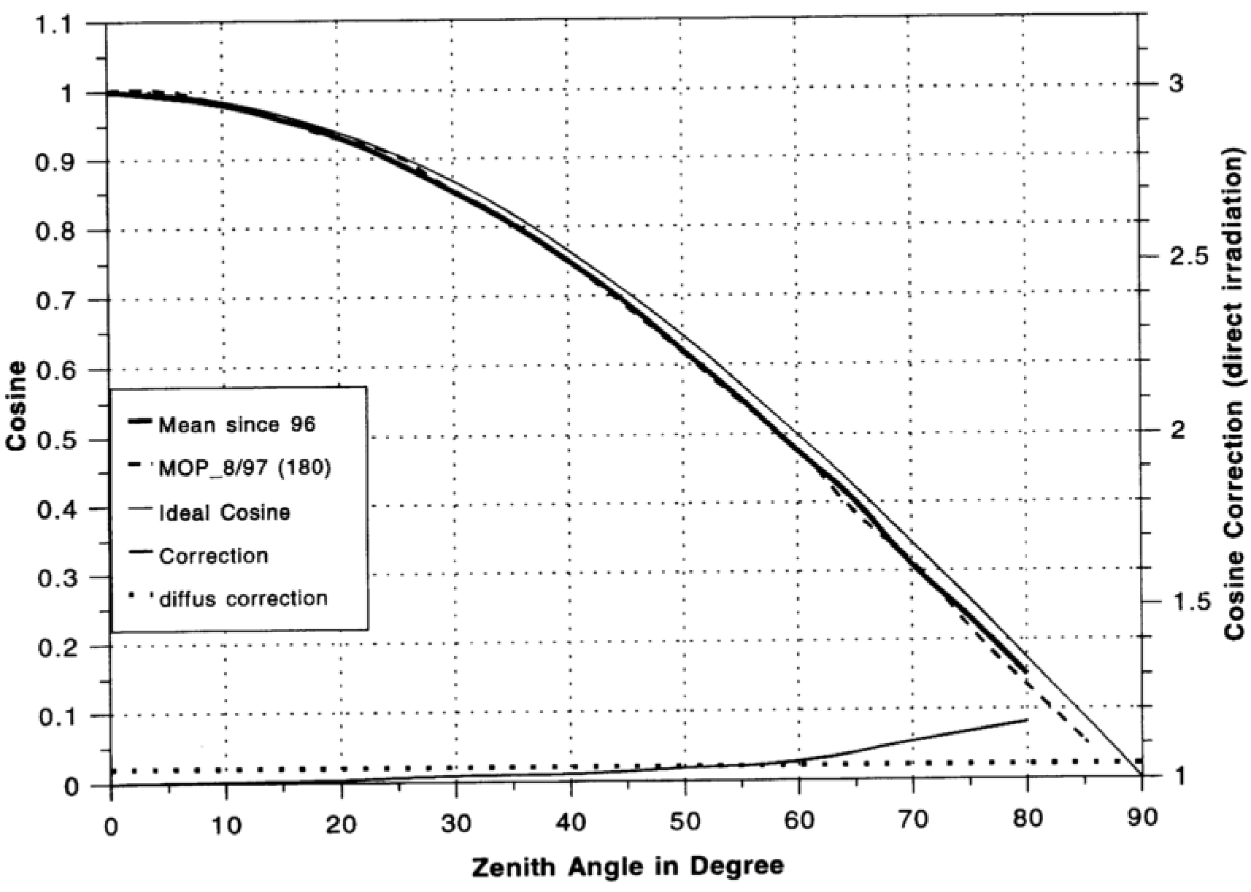


Figure 2.4b: *Deviation of the cosine response of Brewer #010 (most recent measurements in 1997) from ideal cosine as well as the cosine corrections for point sources and diffuse radiation after prism alignment.*

The reason for this anisotropic behaviour was probably a misalignment of the rotatable prism. This prism was adjusted in August 1996 during a regular maintainance service in order to optimize the amount of measured photon counts from a calibration lamp mounted upon the quartz dome. Most recent laboratory investigations (August 1997 at the Meteorological Observatory Potsdam, repetition at MOHp in November 1997) of the optical properties of the BR10 after the prism-alignment resulted in a totally different cosine response (figure 2.4b), which is now very close to the ideal cosine. Even the rear side values are identical with the cosine response of all other directions.

An improvement of this simple cosine correction valid for point sources (= direct radiation) is the method developed by *Nagel and Leiterer* (1995) at the Met. Obs. Lindenberg: The direct radiation (from the point source sun) is treated with the angle depending cosine correction, whereas the diffuse fraction of the radiation is corrected by a constant mean factor, which was determined for the MOHp-Brewer #010 according to the Lindenberg method. This factor is 1.118 for the period 1/1990 to 8/1996 and 1.041 thereafter. The decrease of the original former value (from 1.194 to 1.118) is caused by the use of additional laboratory investigations and by the consideration of the old rear cosine response. The relationship between diffuse and direct radiation is assumed to be of equal size, which is the lowest limit for the ratio diffuse/direct (*Dehne*, 1989, *Feister et al.*, 1997) at high sun during summer season. This ratio increases with lower sun and larger turbidity.

For further improvement it is necessary to know the exact relative contributions of direct and diffuse light as a function of sun elevation in order to optimize the above mentioned improved cosine correction. For that purpose representative relations have to be defined for various atmospheric conditions (sun position, turbidity etc.) in co-operation with the University of Munich (radiation group) using radiation model calculations (STAR). Nevertheless, a remarkable increase in data quality is in any case already obtained with the simple fifty percent assumption.

The consideration of a "diffuse" cosine correction term in addition to a cosine correction of only the direct radiation results in differences of not more than +5% and -3% for solar zenith angles between 20° and 60°. This is the normally interesting range. The relative difference exceeds -15% only at angles above 70°. Although a recalculation of all UV data has been made for the current regular MOHp-UV-database, it was decided to present the new data only in Fig. 4.9 and to keep the rest of the manuscript unchanged. In Fig. 4.9 it was necessary, since a UV-climatology is presented in comparison with modeled data in the annual course, which comprises solar zenith angles of 70° and even more during winter season. In the rest of the manuscript a complete redrawing of all figures would have caused only marginal changes, since the most important results were obtained at high sun elevation, where the improvement due to the introduction of the additional diffuse correction is small.

2.4 Error Assessment

The following table gives a survey about possible instrumental and calibration lamp related errors and their magnitude before and after application of possible corrections. An exact spectral distribution was left out to have more clearness. The given values are normally related to the integral value of the UV-B radiation between 290 and 320 nm.

Error source	high Sun clear	high Sun cloudy	low Sun clear	low Sun cloudy	λ-dep.
Wavelength setting	<< ± 1%				-
Temperature, Humidity	± 0.5%	± 0.4%	± 0.3%	± 0.2%	yes
after correction	± 0.25%	± 0.2%	± 0.15%	± 0.1%	
Non-linearity	– 4%	– 2%	– 1%	< – 1%	no
after correction	– 1%	< – 1%	< – 1%		
Straylight	integrated < + 0.1% > + 1% according to solar position below 305 - 300 nm > + 10% below 302 - 297 nm				yes
after correction	after corr. remaining uncertainty below 300 nm < + 5%, below 295 nm > + 10%				
Cosine response	–5 - –10%	–10 - –15%	–10 --50%	–10 --50%	no
after simple correction	< – 5%	< – 10%	> + 10%	> + 10%	
Instrument error (integral)	–10 - –15%	–15 - –20%	ca. –25%	ca. –35%	yes
after correction	< – 5%	< – 10%	ca. +15%	ca. +25%	
Calibration lamps	dep. on lamp type, age and transfer order ±5 bis 10%				yes

Table 2.2: Error assessment for various sun heights and atmospheric conditions

The measurement error caused by the calibration lamps amounts to a considerable part of the total error. At present, it is of the same order as the instrumentally caused error. Better and more accurate calibration lamps will be available in the medium-term future, thus this portion will be reduced remarkably.

The largest relative measurement errors occur after these results during low sun, cloudy skies and therefore at low radiation as well as at short wavelenghts (straylight effect!). These low UV-doses, however, are not as important in view of possible harmful effects of enhanced UV-radiation. The large errors at short wavelenghts can be remarkably reduced by means of the simple straylight correction. Therefore, reliable data can also be obtained in this range, in which a lot of biological action functions have their maxima. Large public interest, however, is certainly laid in the maximally expected UV-values and their possible trend. But these high UV-B values only occur at high sun and clear, respectively slightly cloudy sky (≤ 3/8 cloud cover) as well as at longer wavelengths. The Brewer provides its most reliable measurement values under these conditions. The uppermost realistic limit of the combined instrument and lamp errors for the integral UV-B under operational conditions is assessed to be around ± 10%. This accuracy is certainly sufficient with regard to the expected UV-trends within the next decades due to ozone variations.

A further not yet mentioned error source is the relatively long lasting measurement duration of about seven minutes for one complete scan. The problem of the variation of the sun position during this time is largely removed by averaging of both parts (upward scan from 290 - 320 nm, downward scan from 320 - 290 nm), since the sun movement can be assumed as linear in this short time. Major problems are expected with rapidly changing cloud conditions. The measured spectra can be considerably falsified and distorted by cloud effects. All measured spectra are correlated with a given reference spectrum and marked with a flag as doubtful in cases of cloud influence. These measurements are still available in the data base, but not used in the evaluations.

3. UV-Data

3.1 Data Aquisition/Measurement Schedule

Spectral UV-B observations with the Brewer Spectrophotometer were performed only sporadically before 1989. A regular measurement schedule was started in January 1990. The largest problem to include UV-observations into the normal schedule was caused by the long measurement duration. The procedure of a spectral UV-measurement, described in section 2.2, between 290 and 320 nm and backward in 0.5 nm steps inclusively all preparations (e.g. filter adjustments) and final steps like data storage takes approx. seven minutes. A higher observation frequency than two per hour was not possible due to the condition, that the regular total ozone observations and the necessary lamp tests must not be impeded. The half-hourly scans of complete spectra are done independently from weather conditions from dawn to dusk. Normal total ozone observations are made after each UV-measurement. Mercury lamp tests to calibrate the wavelengths are additionally performed every two hours.

The measured raw data (photon counts) per wavelength are averaged and stored on a disc in the control PC. Additional information like date, time, location, sun position, instrumental temperature, spectral range, step widths and measured dark count rate are written into the data head of each observation. A complete storage of both values per wavelength, e.g. to recognize cloud disturbed measurements, was given up in order to save storage capacity. A huge bulk of data are produced even in this compressed form. Disturbed spectra are identified out by other methods too (s. section 2.4).

All spectra of a day are stored in one file. They are archived and copied for further processing in a data base after their quality check at the end of each month. Final data processing is presently done after each month, but a nearly on-line calculation is on principle possible.

3.2 Data Management

The Brewer does not measure the UV-B radiation in absolute values, but in corresponding photon counts. Thus the instrument needs a calibration to convert these raw data into radiation data. Regular calibrations are necessary to obtain reliable UV-data, which can be used for investigations of the impact of ozone changes on UV-B irradiation. A couple of calibrations with different types of lamps were done between 1987 and 1994: on one hand mercury lamps with discretes lines were used, on the other hand quartz-halogene lamps with a continuous spectrum and various wattage (100 until 1000 W).

3.2.1 Calibration Procedure

All calibration lamps were measured following the same procedure as in the regular UV-observation, that means a scan is made of a complete spectrum in 0.5 nm steps via the same slit. Simple procedures were applied to evaluate the calibrations and to get relations between measured photon counts and irradiance of the lamps:

For mercury lamps, 5 nm-intervals were defined around the three available mercury lines between 290 and 320 nm, which are 297, 302.5 and 313 nm. The spectral irradiance per nm of the calibration certifications and the measured photon counts in these intervals were integrated. The quotient of both sums gives the calibration value (irradiance per photon) at the corresponding centre wavelength of the spectral line. This integration avoids a time consuming folding of the discrete lines of the lamps with the transmission functions of the Brewer slits, in order to get the really measured radiation at the given wavelengths. The averages of the 5 nm intervals agree very well with the calibration values of the exact method.

The calibration with the continuously emitting quartz-halogene lamps is slightly different but as simple as well. The measured photon counts (PC) at the calibration points of the lamp are integrated with a weighting factor according the following equation:

$$PC = 0{,}5 \times (PC_{\lambda - 0{,}5nm} + PC_{\lambda + 0{,}5nm}) + PC_{\lambda}$$

The quotient of lamp irradiance at the wavelengths of the calibration points and the thus determined photon counts gives the spectral calibration values (irradiance per photon).

The complicated procedure of convolution/deconvolution of the lamp irradiance with the transmission function of the Brewer slit, being necessary for an exact determination of the calibration values, was not applied. The irradiance of the lamps is normally given in W/m^2, the photon counts as determined by both procedures are also related to a 1nm-interval. It should be taken into account, that the spectral photon counts of the raw data are related only to 0.5 nm. To get irradiance per 1 nm both surrounding wavelengths have to be included using the above mentioned weighting factor. Only this procedure provides the correct spectral lamp irradiances applying the calibration function to the photon counts obtained during the calibration. The same holds also for the measurement of the solar UV-radiation. The applicability and a sufficient exactness of this simplified method is confirmed by the measurement results and especially by intercomparisons with other instruments and radiation models.

3.2.2 CALIBRATION FUNCTION

In Figure 3.1 the calibration functions are presented which were determined in the period 1987 - 1994. Triangles denote calibrations with mercury lamps, circles and open squares those with quartzhalogene lamps. Black slanted squares denote calibrations with a lamp which was calibrated in autumn 1994 by the firm GIGAHERTZ-OPTIK. A first calibration with this lamp and a highly stable power supply was performed in late 1994.

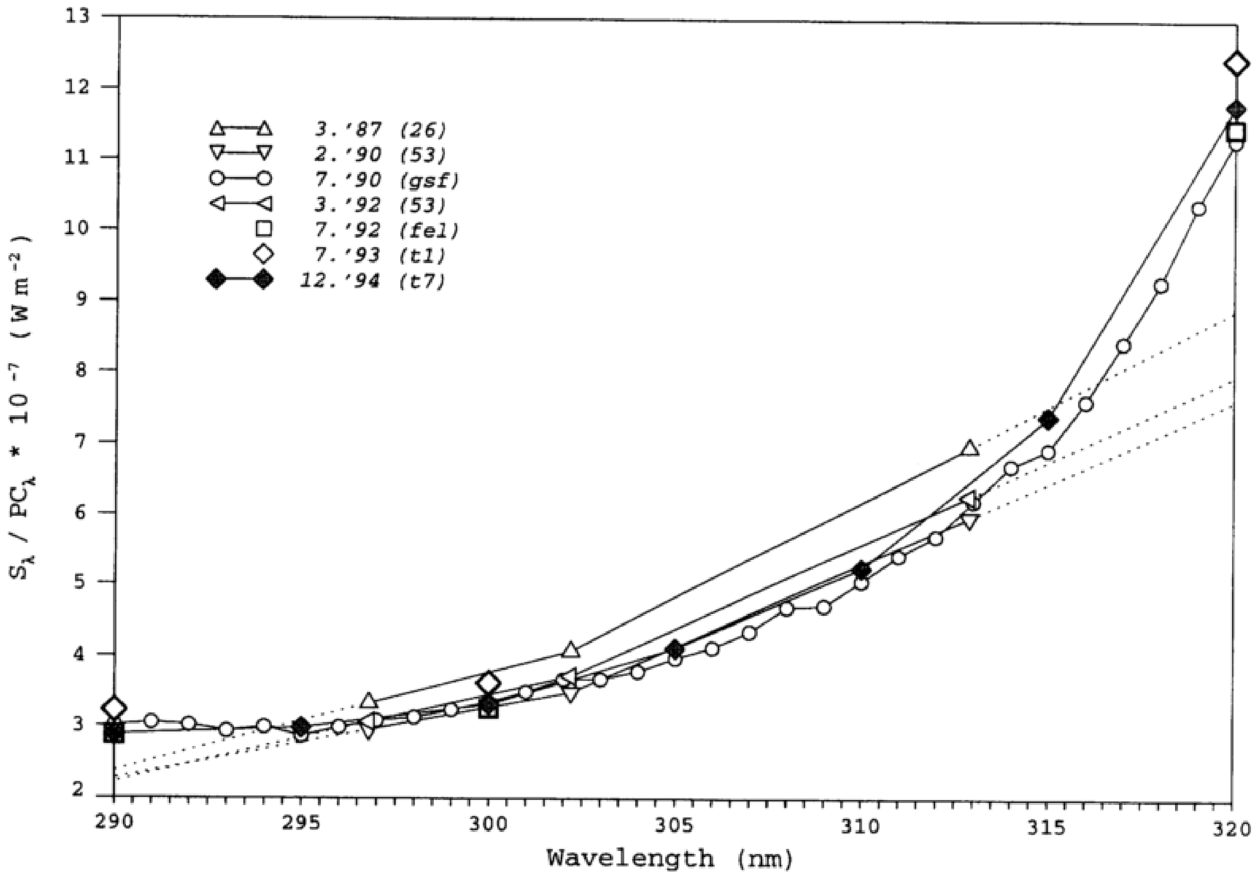


Figure 3.1: Calibration functions of Brewer #010 for the period 1987 to 1994, as determined with several lamps.

The lamps *fel* and *t1* were provided by the Met. Obs. Hamburg and Potsdam, however, they allow for a calibration only at three distinct wavelength. The lamp termed *gsf* was owned by Gesellschaft für Strahlenforschung (GSF) and could be used during a comparison. In former publications the lamp *can* was included, which could be used during a maintenance service by the Brewer manufacturer. This lamp was not used for an absolute calibration of the Brewer due to doubtful results, but only for the determination of the generalized calibration function (s. below). The mercury lamps (*26* and *53*) were provided by Met. Obs. Hamburg from time to time in order to calibrate the MOH3 filter instrument. They were also used for Brewer calibrations, however, since no mercury lines between 313 and 320 nm are available mercury lamps cannot be used to document the strong reduction of the Brewer sensitivity in this range caused by the $NiSO_4$ filter which is necessary for the straylight reduction. The first calibrations (*Köhler et al.* 1988) being based on linear inter - and extrapolations were thus not very satisfactory (see dotted lines in Figure 3.1).

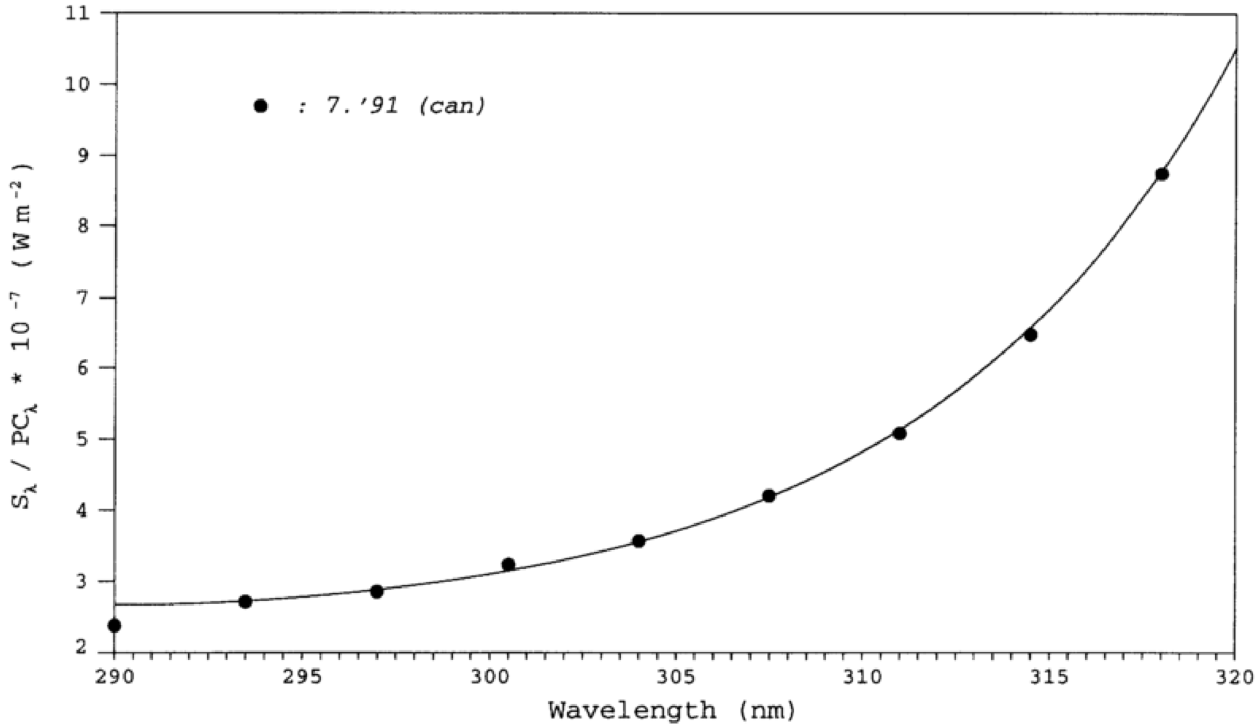


Figure 3.2: Generalized calibration function (line) of Brewer #010 fitted to measured data of the canadian lamps (measuring points).

In order to utilize different calibrations with continuous functions as well as mercury lamp calibrations a generalized calibration function was empirically determined on the basis of the canadian lamp (Figure 3.2), which can be analytically described by

$$y = a \times x^{b} \times e^{(c \times x)} + d$$

with $x = \lambda - 286.5$ and λ = wavelength in nm a, b, c and d are empirical constants which were determined to 0.676653, -0.562101, 0.13403 and 2.142, respectively. The mean deviation between the points and the curve is 0.12 %. The value at 290 nm is considered as an outlier (straylight problem).

A calibration is performed by multiplying the universal calibration function by the average ratio between a calibration value and the universal value at the relevant wavelength according to

$$quot = \frac{1}{n} \sum_{i=1}^{n} \frac{cf_{i,\lambda}}{uf_{\lambda}}$$

with	n	=	number of calibration points
	cf	=	calibration value at wavelength λ
	uf	=	universal calibration factor at wavelength λ

In this way the universal function is adapted to an actual calibration and multiplication by the raw data (i. e. measured and straylight, dark count and deadtime corrected photon counts) results in the values of the UV-B spectrum.

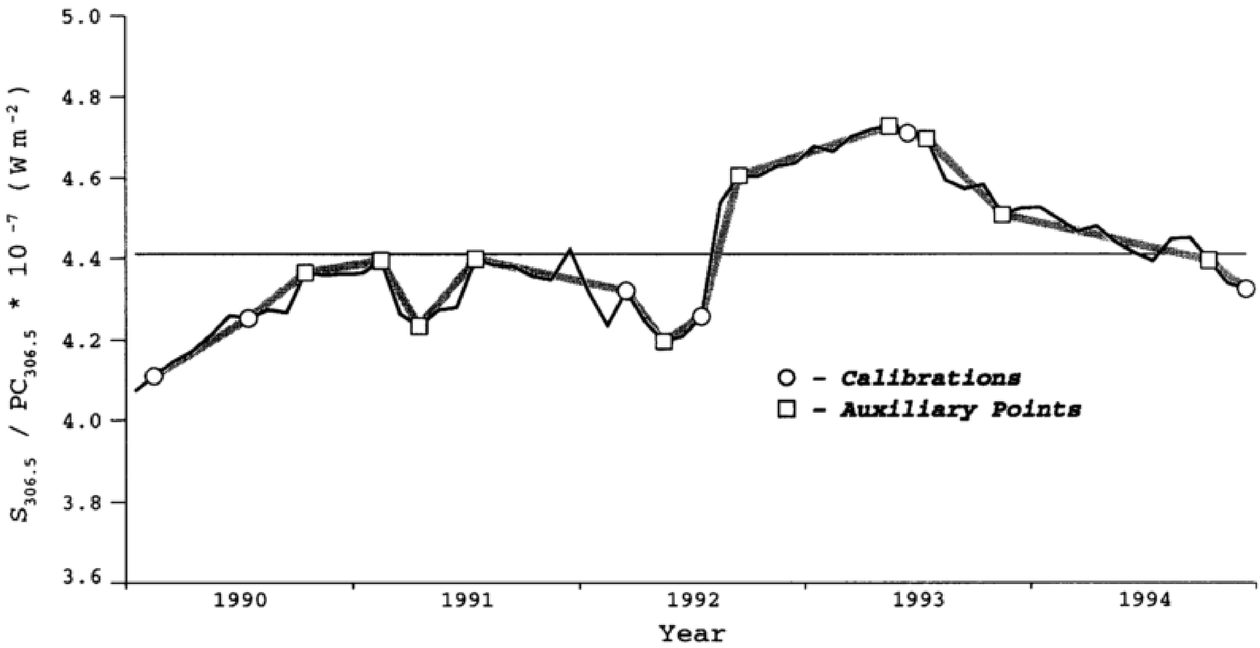


Figure 3.3: *Long term changes of the Brewer-transmission at 306.5 nm derived from calibration exercises (circles) internal standard lamp tests (black curve) and approximated linearly (grey curve with auxiliary points (squares)).*

It is obvious that a calibration is valid only for a short time period. Between two calibrations the sensitivity of the Brewer can change. To follow this development internal standard lamp tests are available which are measured three times per day at a wavelength of 306.3 nm. These measurements were used to calculate monthly averages. The variability due to variations of the power supply or other parameters (like temperature) was thus reduced and the irradiance of the standard lamps were assessed in this way. Under the assumption that only long term ageing processes are responsible for changes of the irradiances of the standard lamp the sensitivity of the Brewer can be assessed between calibration exercises for the wavelength 306.5 nm (Fig 3.3). The thin black line shows the result. In between the calibration points (circles) the development may be approximated as a quasi linear drift if certain sub-periods are fixed. These sub periods are marked by squares (auxiliary points) and were defined subjectively. Under the further assumption that the Brewer sensitivity can be approximated by a linear change between calibration points or auxiliary points the thick grey curve was derived for the period 1990 - 1994. Since the deviations between black and grey curve do not exceed 2%, we consider the grey curve as a good approximation for the drift of the Brewer sensitivity. This obviously pronounced changes of the Brewer sensitivity are not attributed to a long term drift, since it is considered to be stable, but to exchanges or repairs of optical and electronic parts since changes in sensitivity are correlated with such events.

Keeping in mind that the overall precision is up to 10% the procedure described here seems to be an appropriate tool for purposes of long term monitoring of the UV-B. Regular calibrations are mandatory and important in any case. The absolute level of the calibration with the *can*-lamp was not reliable being confirmed by the regular standard lamp tests, thus it was left here.

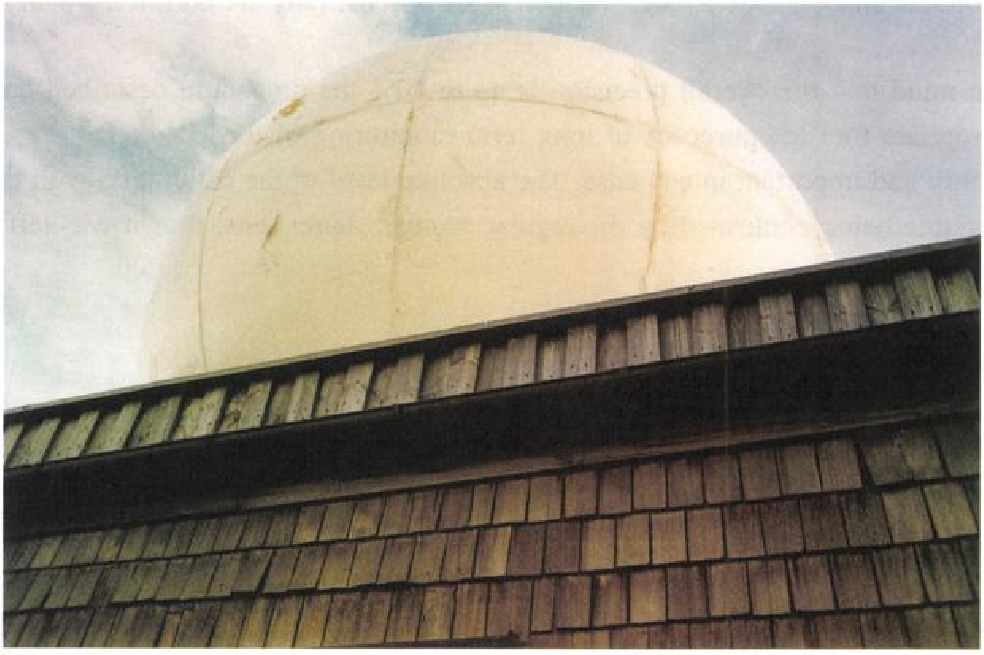
3.2.3 HOMOGENIZATION

Inhomogeneities in longer series can be caused by extremely different reasons: the following problems could be conceivable with UV-time series:

- Instrumental drift (slow and/or rapid)
- Variations in the radiative output of a calibration lamp or change to a new one
- Environmental changes

The first problem was solved satisfactorily by the examination of the calibration state between the calibration exercises by means of the internal standard lamp and a corresponding interpolation (s. section 3.2.2). It is, however, difficult to detect jumps in the lamp stability or after an exchange of the calibration lamps and a quantification of the effects is even more difficult. The only proof for the presumption, that no serious differences exist between the various lamps, is the fact that the various calibrations except the first one do not differ by more than 10 %.

The most important problem in the UV data of the Met. Obs. Hohenpeissenberg should be the removal of the Brewer from the original location on the balcony of the tower onto the platform for weather observations on the main building in May 1993. The large shading of the northern horizon by the wall of the 7th floor and the radom on the roof was the motivation for this removal. Thus, approx. 20 % of the sky were covered, which cannot be neglected, although being in the north, due to the large contribution of the diffuse to the global UV-B radiation. The current location has a nearly free horizon. Comparative measurements with Brewer were alternately performed half a day on the tower and on the platform just before the relocation on two rather clear days during summer. Unfortunately, the results were not clear. The average differences were about 10%, their variation from day to day, however, was large. This was caused by very different contributions of the diffuse to the global radiation. Differences between fore- and afternoon observations amounted to 10 - 20 % at the same sun elevation. This can be explained by a diurnal course of the lifting of the mixing layer and the turbidity, respectively. The enhancement of the diffuse portion of the UV-B radiation should even be larger. This additional uncertainty almost disabled a quantitative assessment of the shading effect at the tower site, using the comparison of tower- and platform-observations before and after sun maximum.



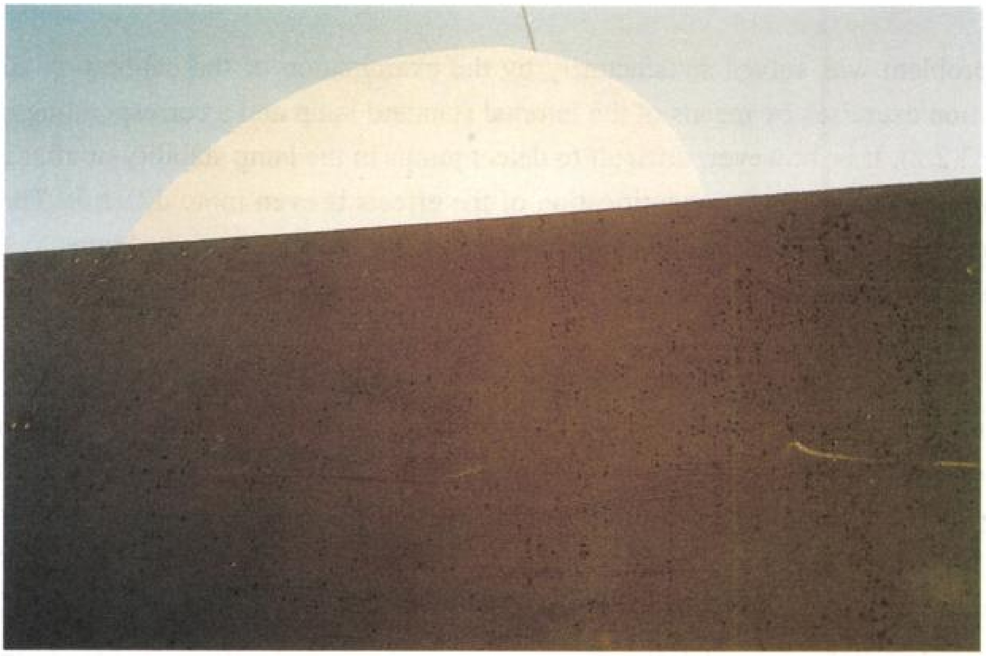


Figure 3.4: *Upper photo: view of the Brewer #010 to the north at site "balcony".*
Lower photo: simulation of this northern view at the site "platform" by a dummy

Therefore a different method was applied, to quantify and to eliminate the adverse effect of the tower on the observations before May 1993: A wooden tower dummy was build, which simulated the shading of the horizon, which the Brewer was exposed to on the balcony. Figure 3.4 (copy of two photos) shows the northerly quadrant of the sky seen by the Brewer on the balcony (top) and the platform with tower dummy (bottom). The reduced wooden dummy is obviously a good simulation of the conditions on the tower. The highest point of the radom corresponds to a horizon shading of about 65^0.

UV-measurements were taken on the platform with and without dummy within short intervals. Thus, it was guaranteed that the atmospheric conditions like ozone amount and mainly turbidity (and consequently the ratio diffuse/direct) remained almost constant. The result of one day in September 1994 is shown in Figure 3.5. The loss of radiation due to shading on the tower compared with the platform amounts to approx. 10 % at sun elevations between 42^0 and 32^0. This loss reaches more than 15 % at lower sun. These values are valid for a relatively fair day and should even be somewhat higher on days with enhanced turbidity and cloudiness.

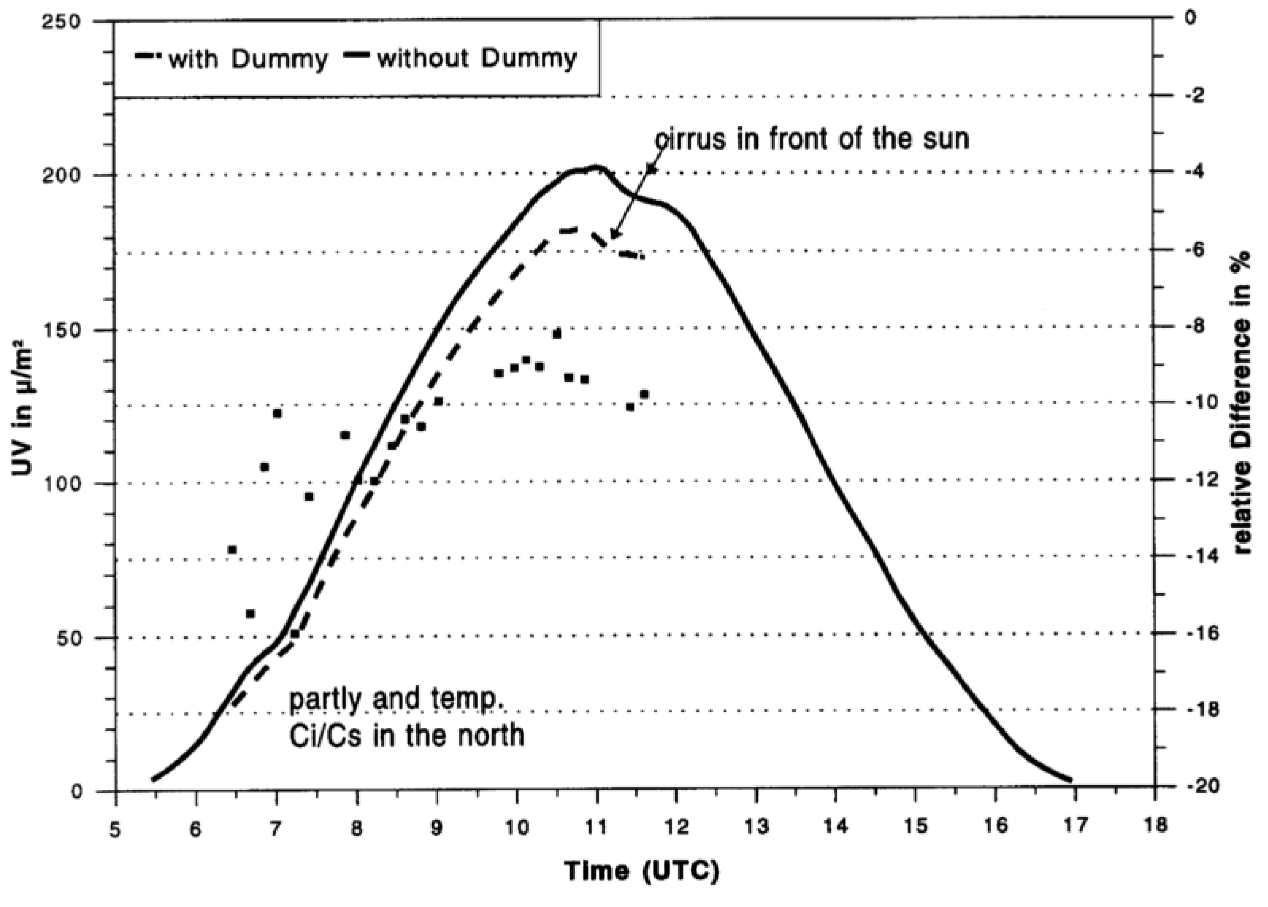


Figure 3.5: Comparison of observations at the locations "tower" (simulated by a dummy, dashed) and "weather observation platform" (without dummy, solid) in the diurnal course, squares represent the relative difference.

A spectral analysis of these observations gave the astonishing result, that no wavelength dependence of this shading loss could be detected over a wide range of sun elevations. It could be expected after both scattering processes (Rayleigh scattering with a wavelength dependence of λ^{-4} and Mie-scattering with an average of $\lambda^{-1.3}$), that shorter UV-B wavelengths should have a larger diffuse portion than longer wavelengths. An explanation of this phenomenon is given by the ozone absorption, which strongly increases with shorter wavelengths. This effect nearly compensates the enhanced scattering at short wavelengths, so that almost no wavelength dependence in the diffuse UV-B radiation is detectable at sun heights > 10^0.

The results of these corresponding simulation measurements are surely better than the above described method with operating the Brewer alternately on the tower and on the platform during fore- and afternoon, respectively. It is planned to use the STAR-model, to quantify the portion of the diffuse radiation, coming from the shaded area, for different conditions (sun height, ozone values and turbidity), in order to improve the correction of the data before the Brewer removal.

3.3 Evaluation of data

3.3.1 Data preparation

The data processing is schematically shown in Figure 3.6. The DOS-PC controls the Brewer-spectrometer and stores the measured data. The usefulness of these raw data was tested in a first step to create a corrected raw data set. After generalization of the quality criteria and automating the raw data tests, the actual data could easily be tested and processed. The following criteria were applied in order to provide validated data:

- each spectrum must exhibit more than 1000 photo-counts
- each spectrum was linearly as well as logarithmically correlated with a standard spectrum.

For the calculation of the UV-spectra a unix work station was available where as much as 65000 UV spectra (as of October 1997) were managed by means of a data base management system, allowing for a relatively simple evaluation and scientific interpretation in connection with relevant data like radiation parameters or total ozone.

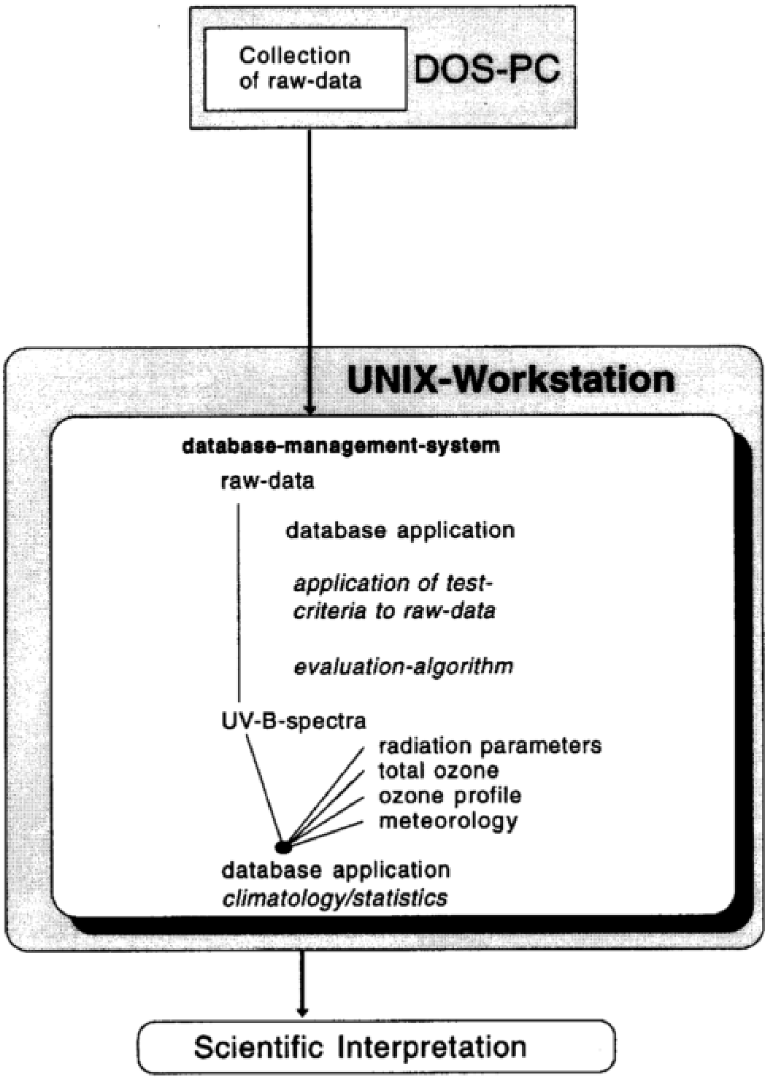


Figure 3.6: *Flow chart describing the UV-data handling*

3.3.2 EVALUATION ALGORITHM

To calculate individual UV-B spectra at first corrections for dead time and temperature effects are applied to the raw data. In the next step the stray-light fraction is calculated and subtracted together with the dark counting rate. The conversion of photoncounts into UV-B values is performed using the calibration functions at calibration points or auxiliary points and linear interpolations in between. This modified and adapted calibration function is applied to the corrected raw data. As cosine correction the improved version is presently applied to these data with respect to the sun elevation and assuming a 50:50 relationship between diffuse and direct irradiation. That means: 50% of the radiation are multiplied with the sun height depending correction factor (measured in the laboratory for a point light source), 50% are multiplied according the results described in 2.3.5. STAR-results will again be used in the future to improve this correction.

4 Results

4.1 Instrumental comparisons

In addition to quality assurance tests the measuring and data quality can be assessed by means of instrumental comparisons. In the past years some national and international UV-B comparison experiments were arranged (*Gardiner and Kirsch*, 1993, *Gardiner and Kirsch*, 1994, *Seckmeyer et al.* 1994), during all but one the Brewer #010 of Met. Obs. Hohenpeissenberg was involved.

4.1.1 Comparison with Filter Instrument

A broad band UV filter instrument (MOH 3), developed by *Dehne* (1986) at Met. Obs. Hamburg was operated side by side with the Brewer #010. The MOH 3-filter instrument was operated since 1985. This instrument uses a special UV-filter the transmission function of which was adapted as good as possible to the (old) erythemal action function (DIN 5031) in the wavelength range between 300 and 330 nm; the UV contribution below 300 nm is insignificant, although it is biologically active. The MOH 3 instrument was calibrated against a mercury standard lamp, from which only the emission of the spectral line at 302.5 nm is used. An absolute calibration for the complete spectral range is obtained assuming that the relative spectral sensitivity and that the filter transmission function simulates the relative erythemal action function to a good approximation. In reality some deviations from the ideal proportionality are unavoidable, which, however, can be corrected for with respect to the so called average main wavelength of the erythemal radiation at 308 nm by a certain factor. Since the average main wavelength slightly depends on sun elevation and total ozone the calibration of the filter instrument MOH 3 is not completely correct.

As an example, Figure 4.1 shows a comparison of daily cycles of UV-B (erythema) of Brewer #010 and the MOH 3 filter instrument for the 15^{th} and 16^{th} of April 1991. The Brewer spectra were multiplied with an an action function corresponding to the MOH3 transmission function and integrated. The discrete half hourly data points were fitted by a cubic spline function. In contrast, the filter instrument continuously measures the erythemal radiation as integral values from which hourly sums were calculated and also fitted by a cubic spline function. For the 15^{th} of April the agreement is comparatively good considering that the MOH 3 instrument is sensitive beyond the UV-B-erythemal range and that its sun elevation dependent calibration factor as described above may cause systematic deviations between both instruments.

The agreement between both instruments is comparable for April 16 disregarding the period 11 am to 2 pm where cirrus clouds may be made responsible for deviations. Rapidly changing cirrus cover influences the Brewer #010 half hourly measuring times much more than the hourly sums of MOH 3, so that the deviations reaches values up to 30%. The general increase in UV of 24% from the first to the second day is due to a reduction of total ozone from 392 D. U. at April 15 to 348 D. U. at April 16. The integral amplification factor is 2.2.

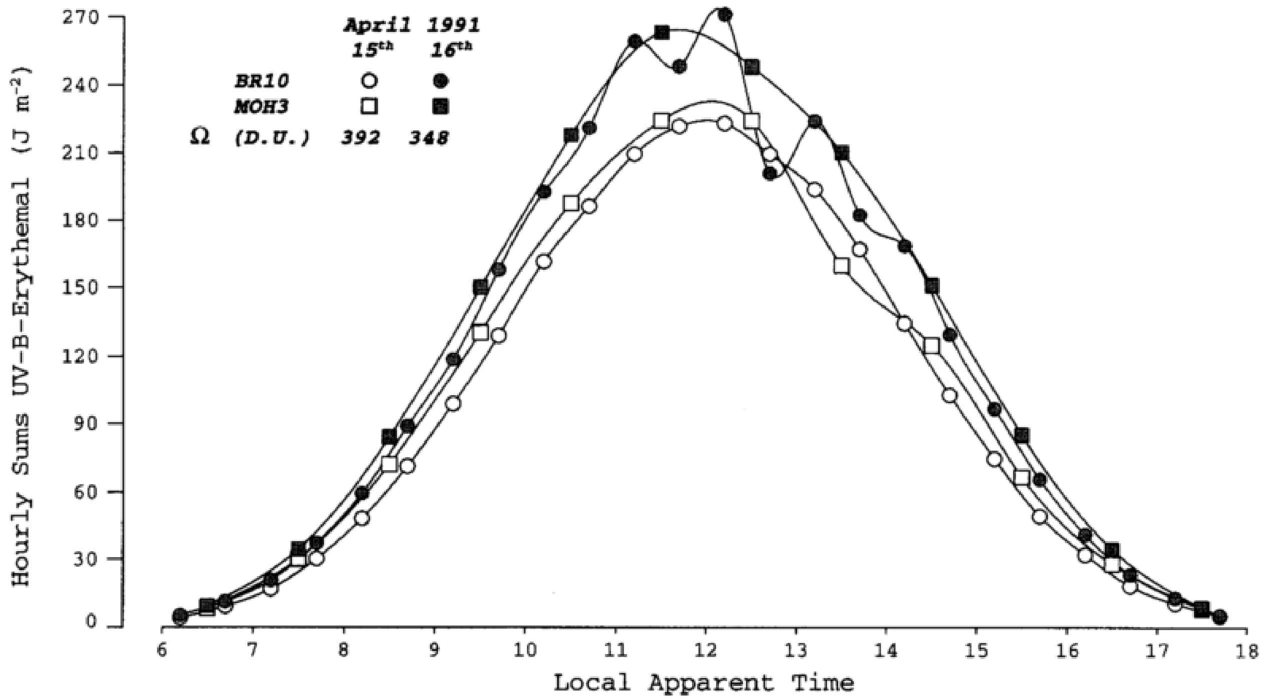


Figure 4.1: *Daily courses of the integrated erythemal UV-B on April 15 and 16, 1991, measured with Brewer #010 and MOH3 filter instrument.*

It should also be considered that the atmospheric conditions changed between the two days. While the global short wave radiation essentially remained constant the turbidity increased. The horizontal visibility, being some indicator for the turbidity, decreased from 40 km to 22 km, caused by a change in wind direction.

Overall, it can be stated that both instruments are suitable for recognizing UV-B changes from one to the next day. One important advantage of the spectral over the integral measurement is that any action function can be applied to the spectral measurement. The advantage of a filter instrument lies in its capability for continuous measurements.

4.1.2 Comparison with another spectrophotometer

In July 1990 and 1993 the Brewer #010 participated in two international spectrometer comparisons (*Seckmeyer et al.* 1994; *Gardiner and Kirsch*, 1993). Some examples of comparisons of the Brewer #010 with the Bentham double monochromator DM 150 of the University Innsbruck are shown in the following section.

Figure 4.2 presents two spectra measured at 13.07.1990 at Neuherberg north of Munich at highest sun elevation. At wavelength below 295 nm the increasing influence of straylight is clearly seen in the not straylight corrected spectrum of Brewer #010. Inspite of the $NiSO_4$ filter the signal is higher by more than one order of magnitude at 290 nm. After application of the numerical correction procedure as described in chapter 2.3.4 the signal of Brewer #010 agrees much better with that of Bentham DM150 (curve with slant crosses). This measurement demonstrates the usefulness of the correction procedure down to a wavelength of 294 nm while below the detection limit of the Brewer #010 is reached. In this lower range of the spectrum the expected radiation flux reaches values between $5 \cdot 10^{-7}$ and 10^{-6} Wm^2 nm^{-1} at maximum. With a calibration factor of about $2.5 \cdot 10^{-7}$ Wm^2/photoncount the counting rates are between 1 and 2 per 0.5 nm. Disregarding the fact that only complete photons are counted, the errors of counting rates of 1 or 2 are between 100 and 70% according to the Poisson-statistics.

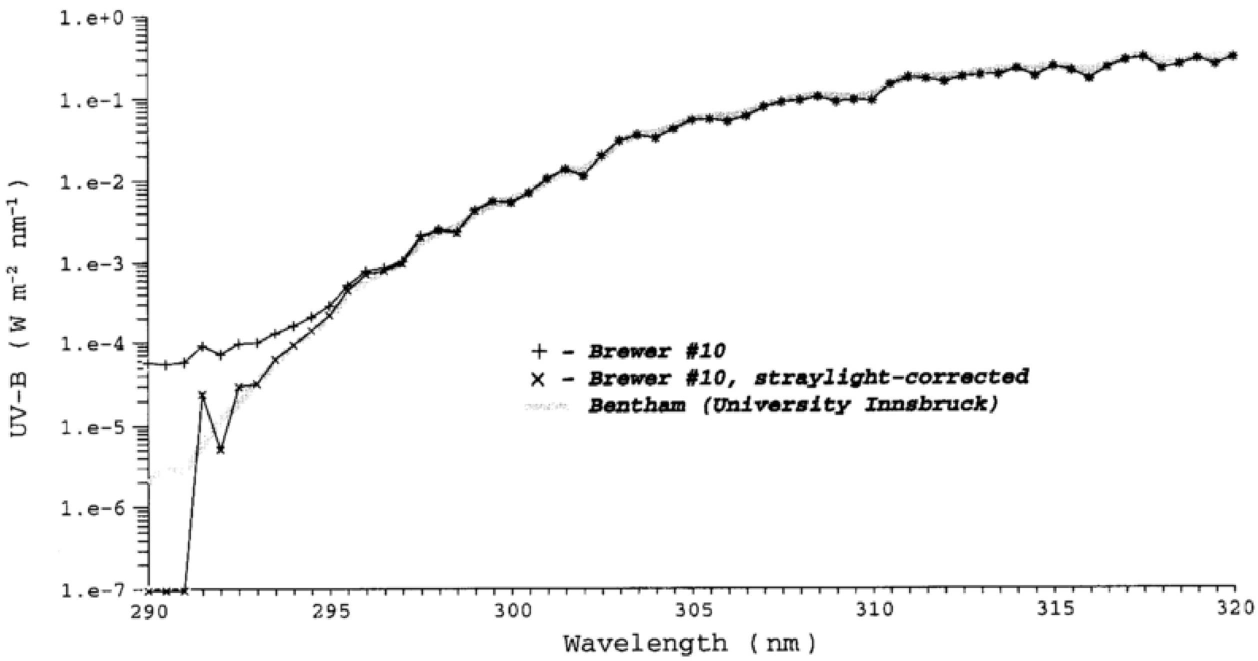


Figure 4.2: *Comparison of UV spectra measured with Brewer #010 and Bentham (owner University Innsbruck) on 13.07.1990 at 12:12 UTC during the international comparison of UV spectrometers at GSF, Neuherberg.*

At higher wavelengths the agreement between the two instruments is much better. Figure 4.3 presents the same data in a linear plot. It can be seen that typical structures are present in the spectra which are more pronounced in the Brewer #010 data and more smoothed in the Bentham data due to its less good resolution (1 nm). The wavelengths are measured correctly by both instruments as maxima and minima are congruent in the whole range.

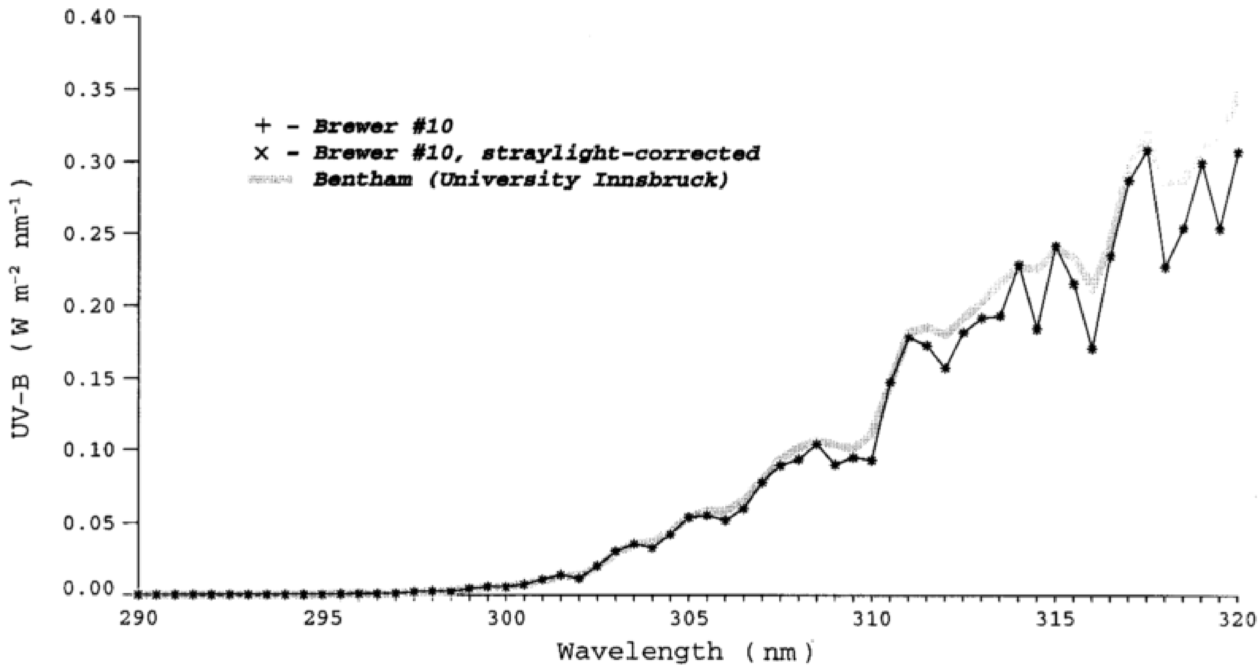


Figure 4.3: *Same as Figure 4.2, but with linear UV-B scale (y-axis).*

The mean relative deviation from the mean of both measurements is -3.6 % for the Brewer #010. Due to the less good spectral resolution of the Bentham it is clear that the relative deviation is larger at a single wavelength. For a quantitative comparison, a numerical filter was applied in order to adapt the spectral resolution. While the spectra were scanned in steps of 0.5 nm and the half widths are 0.63 and 0.5 nm, respectively, the exact slit function of the Bentham was not known. We therefore filtered the Brewer data for reasons of simplicity according to the following weighting formula:

$$fw_0 = \frac{\sum_{i=-1}^{1} w_i \times f_i}{\sum_{i=-1}^{1} w_i} \quad ; \quad w_{-1} = w_1 = 0{,}2937 \;, \quad w_0 = 1{,}0$$

Values above or below are added according to their fractional difference of the half widths and half by half. The result is shown in Figure 4.4 using the average of both spectra as a reference. While the grey curve represents the relative difference between average and unfiltered Brewer data the black curve shows the relative difference after filtering. In the range above about 303 nm the difference is relatively constant around -6% on average. In the range 293 - 303 nm the relative deviations are decreasing from about 15 to -5%.

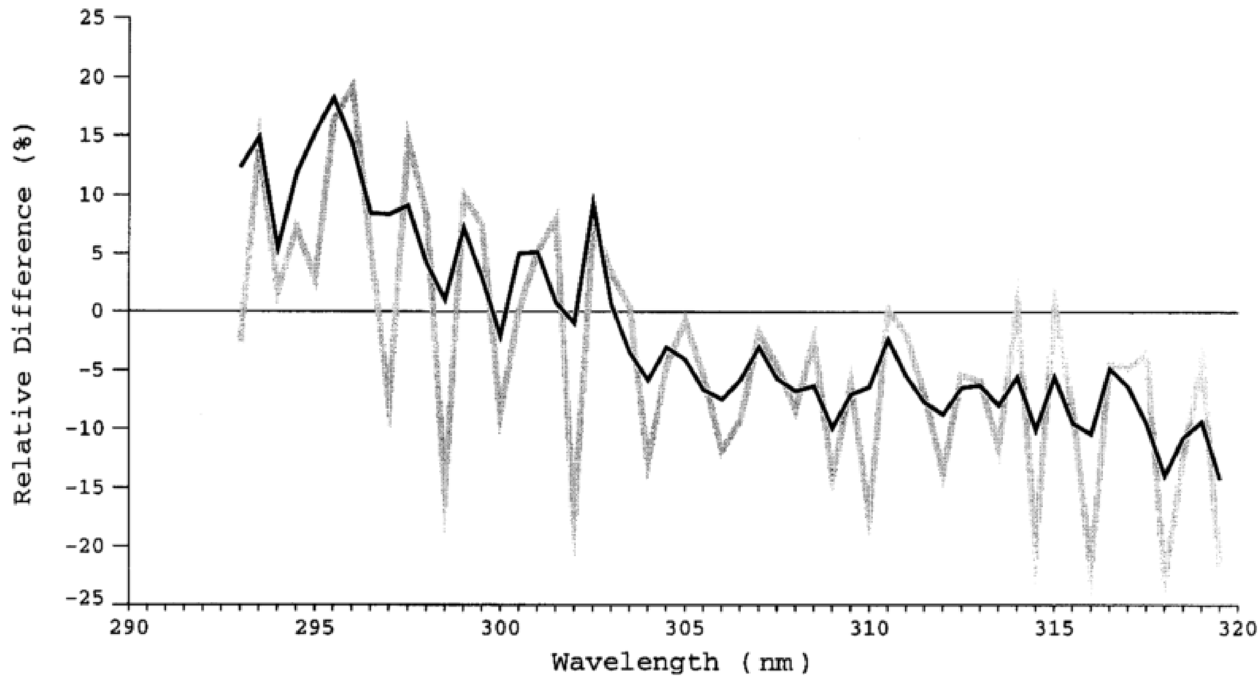


Figure 4.4: *Relative difference between the spectra of Brewer #010 and Bentham from the average of both instruments. The grey line is the difference of the original data, the black line describe the difference after adapting the half widths.*

Several reasons may be responsible for this behavior:

- uncomplete straylight correction of Brewer #010, which could produce too high values at short wavelength,

- uncorrect cosine compensation: at high sun elevations the simple cosine error correction (chapter 2.3.5), which was still used for these comparisons accounts for too small diffuse fractions, probably producing the negative deviation of the Brewer at wavelength > 303 nm

- all parameters with relevance to the calibration can be of importance for deviations of the Bentham.

It thus cannot be decided whether systematic deviations can be attributed only to one of the instruments.

The fine structure of the deviations are of the same order of magnitude as for other instrumental comparisons. More details of this international comparison can be found in *Seckmeyer et al.* (1994). They compare the measured spectra to calculated model data as a reference. The model which was used has still several deficiencies and thus their conclusions with respect to the instrumental data must be considered with caution.

4.2 Comparisons with model calculations

It was of interest, to compare Brewer #010 measurements with results of advanced UV-B models. The STAR-model (*Ruggaber et al.*, 1994 and *Ruggaber* 1994) considers all important processes in the atmosphere relevant to radiative transfer in the 280 to 700 nm range. The radiative transfer equation is solved in the model for horizontally homogeneous layers considering molecular scattering as well as absorption and extinction by gases and aerosol particles. For simulations actual values of total ozone, pressure, temperature, humidity, aerosol optical depth, surface albedo and SO_2 are used to realistically calculate the UV-B, using up to 35 layers to simulate the vertical distribution of relevant parameters. The spectral resolution is limited by the ozone absorption coefficients (0.5 nm) and the extraterrestric sun (0.2 and 0.1 nm). For reasons of comparison the two suns STAR and LOWTRAN7 were used.

In Figure 4.5 the UV-B sections of both suns are depicted with their available resolutions, the grey curve denoting the STAR sun and the black line denoting the LOWTRAN7 sun. The LOWTRAN7 sun has a higher radiative output and less pronounced peaks at single wavelength compared to the STAR sun. In some spectral ranges slight spectral differences can be recognized which may be caused by differences in spectral resolution of the extraterrestrial suns. In Figure 4.5 the surface UV-B distribution was also calculated for 24.07.1993 11:03 a.m. UTC corresponding to 28.3° zenith distance where 88% of the maximum is expected according to cosine law (measuring site Garmisch, curves in the lower half of Figure 4.5). Due to ozone absorption ground level UV-B is reduced by 30% at the high wavelengths near 320 nm and by about 6 orders of magnitude at the short wave range of UV-B.

The Brewer #010 data mostly lie between the two sun simulations. For reasons of completeness it should be mentioned, that all spectral calculations were multiplied with the Brewer slitfunction in order to make measurement and simulation comparable. As the comparison with the Bentham DM150 had already shown, the wavelength accuracy of the Brewer #010 is very good, except for those wavelengths where the STAR sun deviates from the LOWTRAN7 sun.

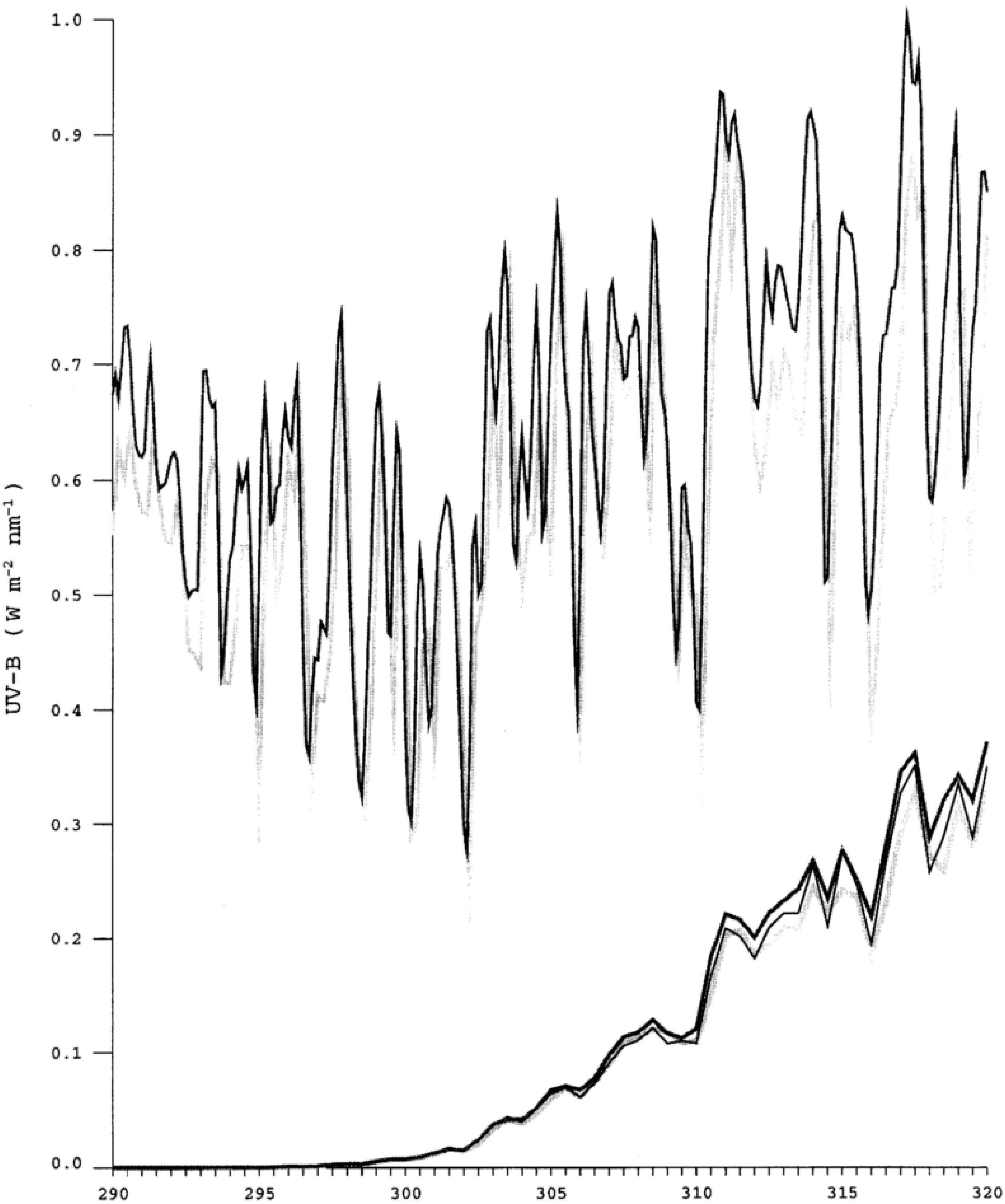


Figure 4.5: *Upper curves: Extraterrestrial UV-B output of the model suns STAR (grey) and LOWTRAN7 (black); lower curves: comparison of UV-B after transmission through the model atmosphere (simulation for two suns) and measured data of Brewer #010 for the site Garmisch at 24.07.1993, 11:02 UTC*

For a quantitative comparison a relative difference between Brewer and the respective sun was calculated, the reference being the relevant mean value. The results are presented in Figure 4.6.

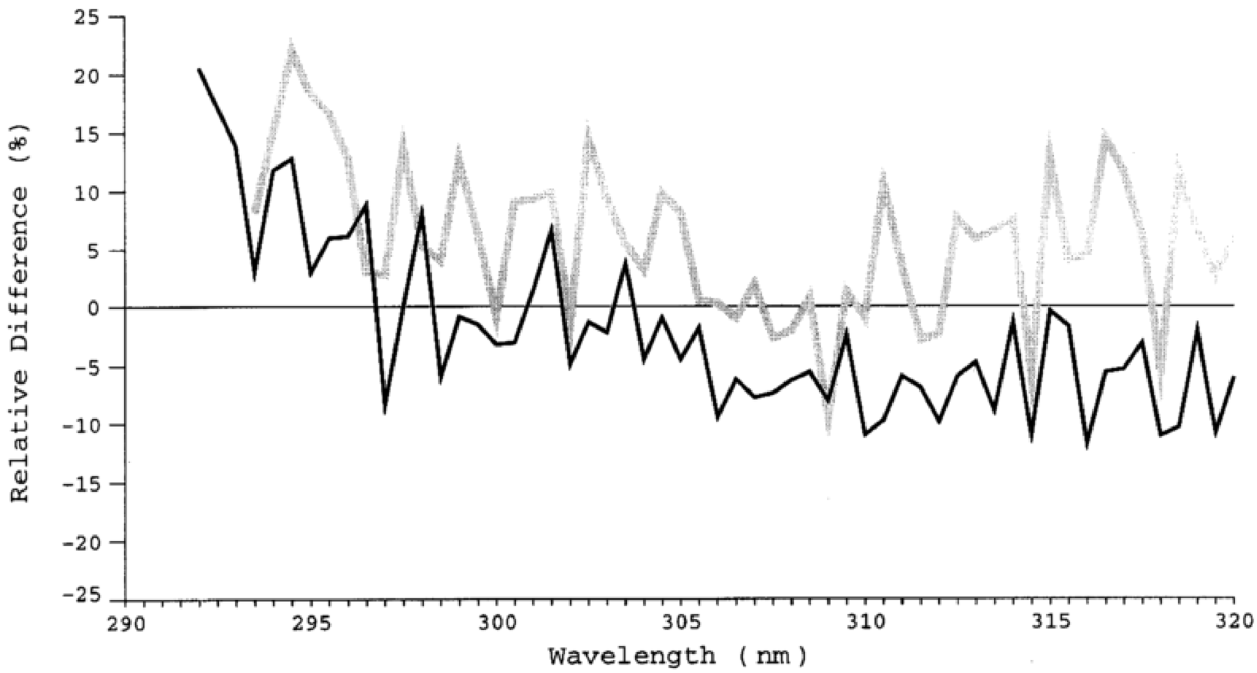


Figure 4.6: *Relative difference between Brewer #010 and UV-B simulated with the STAR model in relation to the average of both. The grey curve was calculated with the STAR sun, the black curve for the LOWTRAN7 sun at Garmisch 24.07.1993, 11:03 UTC.*

The grey curve refers to the STAR sun and the black curve to the LOWTRAN7 sun. Nearly in the complete wavelength range the Brewer shows higher measuring values with a large modulation of the amplitudes for different wavelengths. The amplitudes in the LOWTRAN7 simulation are smaller as compared to the STAR simulation. The LOWTRAN7 sun seems to better describe the extraterrestrial conditions as the wavelength agreement with the Brewer data is better and because of a greater similarity in the deviation pattern of the Brewer-Bentham comparison.

For the field comparison in Potsdam (June 1993) similar model calculations were performed and one example is given in Figure 4.7. Here, the measurement data of the Brewer are significantly lower as compared to the calculation. Most probably the turbidity in the model calculation was set too low since measured data of the much cleaner site Lindenberg, 50 km distant from the UV measuring site Potsdam, were used. Another simulation for the following day shows even larger discrepancies, especially in the morning, confirming the interpretation that the turbidity input was not representative. An error in the calibration of the Brewer can be excluded since the Brewer was calibrated in Potsdam and the time gap to the Garmisch comparison was to small as to be responsible for the large differences found between the two experiments.

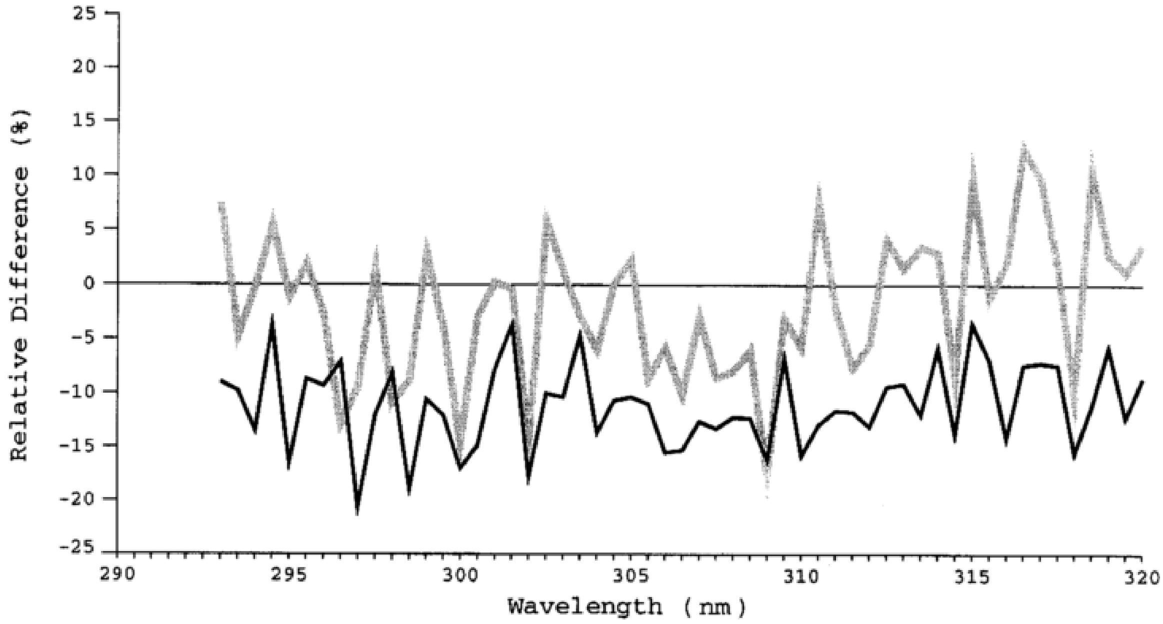


Figure 4.7: *Relative difference between Brewer #010 and UV-B model STAR in relation on the average of both. The grey curve was calculated using the STAR sun, the black curve using the LOWTRAN7 sun for the site Potsdam (09.06.1993, 11:03 UTC).*

This is confirmed by a control run at Hohenpeissenberg, when the Brewer was back after the Potsdam comparison (Figure 4.8). Although the differences at the low end of the UV-B range are slightly above those for the Garmisch simulation, being attributed to not completely corrected straylight, the stability of the calibration is very good.

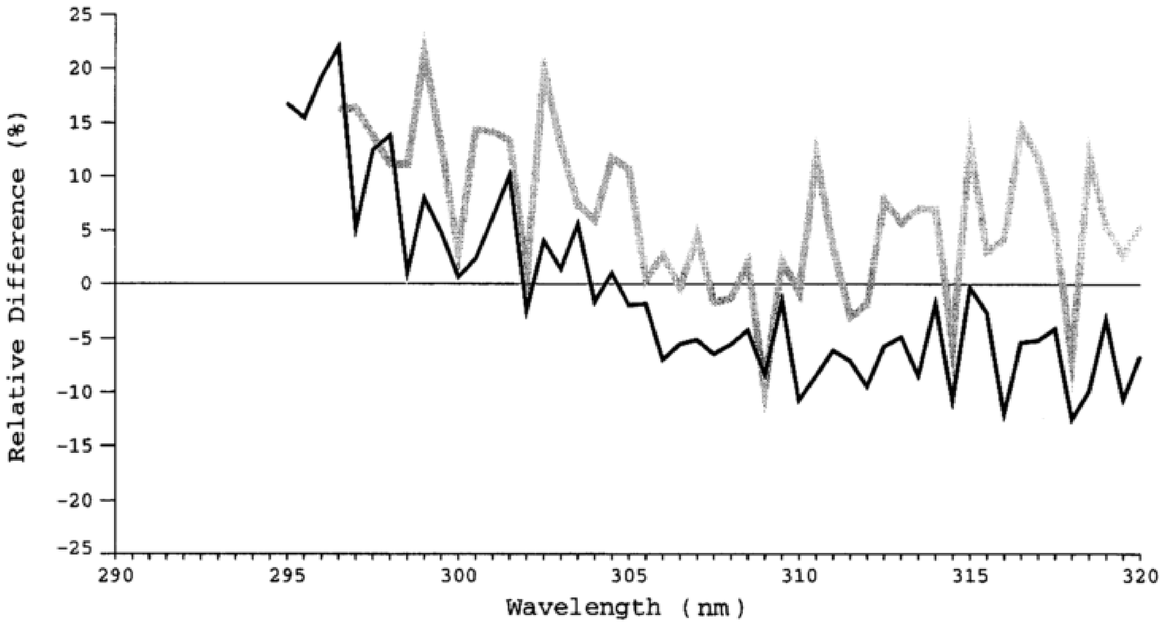


Figure 4.8: *Relative difference between Brewer #010 and UV-B model STAR in relation to the average of both. The grey curve shows deviations to the STAR-sun, the black curve the deviations to the LOWTRAN7 sun for the site Hohenpeissenberg (30.06.1993, 11:03 UTC).*

In summary it can be stated that the Brewer allows spectral UV-B measurements on an operational basis within acceptable error limits and is thus a suitable instrument for monitoring. The good comparability with the double monochromator Bentham shows the Brewer to produce also acceptable data at low wavelength < 295 nm after applying a correction procedure for straylight. The spectral resolution of the Brewer is very good and is of advantage for comparisons with model calculations. Improvements with respect to a better stray light correction and more sophisticated cosine correction (a first step is already done) can still be achieved. At the same time, model calculations are also to be assessed critically. The choice of the extraterrestrial sun leads to different outputs and inconsistent agreement with measured data. The quality of the model output depends also critically from a proper choice of input parameters like absorption coefficients or actual atmospheric parameters.

4.3 UV-CLIMATOLOGY

The precision of the spectral UV-B data of the Brewer is better than 10%. Taking account of this information, the variability of the UV-B radiation can be interpreted with respect to a climatology. A first evaluation is presented for the integrated spectrum. The error of the integral is below 5% since inaccuracies at single wavelength compensate during integration.

In Figure 4.9 yearly cycles of the integrated values in the spectral range 290 - 320 nm are presented for the years 1990 - 1997. The open circles are the measured values for each day at highest sun elevation. The UV-B radiation depends mainly on sun elevation and it is about 8 times higher in summer as compared to the winter months. The UV-B is strongly weakened by clouds. In summer a completely overcast sky can reduce UV-B to values typical for the winter months.

The most interesting aspects derive from clear or nearly clear days. For setting a reference, the grey area was calculated with the STAR-model (*Tamm and Thomalla*, 1995) representing the UV-B integral (290 - 320 nm) calculated for the average range of the observed ozone concentrations $\pm \sigma$ at Hohenpeissenberg. At clear or nearly clear days the measurements are near or in the reference range. As a tendency, measured data are typically above the reference in winter months, which can be attributed to a not optimized cosine correction and to cases with snow cover (high albedo) which were not considered in the reference calculations. Since the total ozone undergoes a pronounced yearly cycle with high and lowest variability in spring and fall, respectively, the reference range is correspondingly asymmetric and broader in spring than in fall. Single years can deviate very much from average total ozone as is shown in Figure 4.10. While the grey area represents average data ($\pm \sigma$) the black line shows the actually measured total ozone for the eight years 1990 to 1997. In 1991 total ozone was mostly in the grey, normal range, even partly in the upper σ range (January to May except March). Summer values for UV and total ozone were rather normal in 1991, single days with low ozone produce high UV-values.

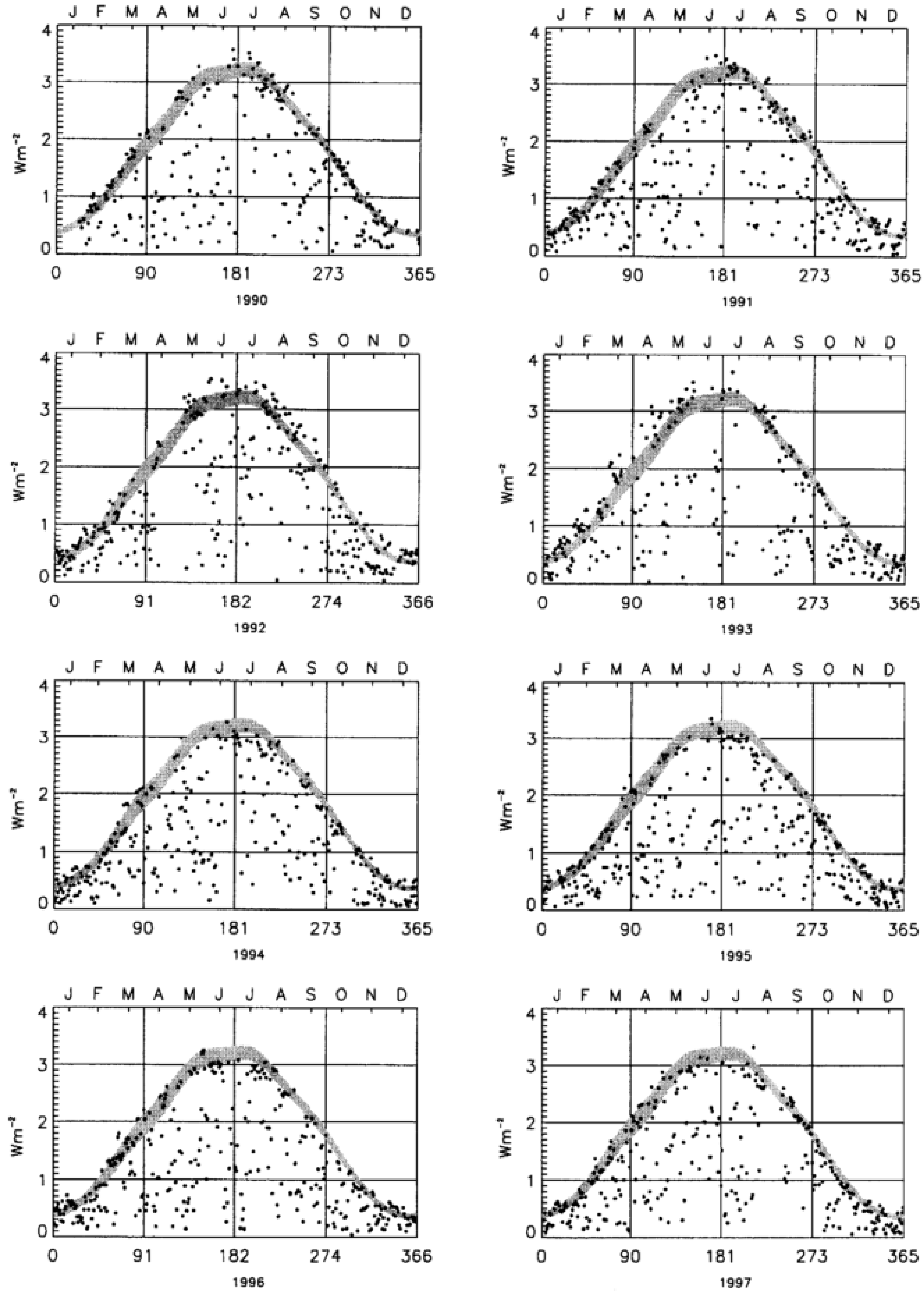


Figure 4.9: *Integral UV-B (290 - 320) measured at Hohenpeissenberg (open circles) at the highest sun elevation for each day of the years 1990 to 1997. The shaded range represents model calculations for average total ozone (± σ) for cloudless sky (Tamm and Tomalla, 1995) and can be used as a reference.*

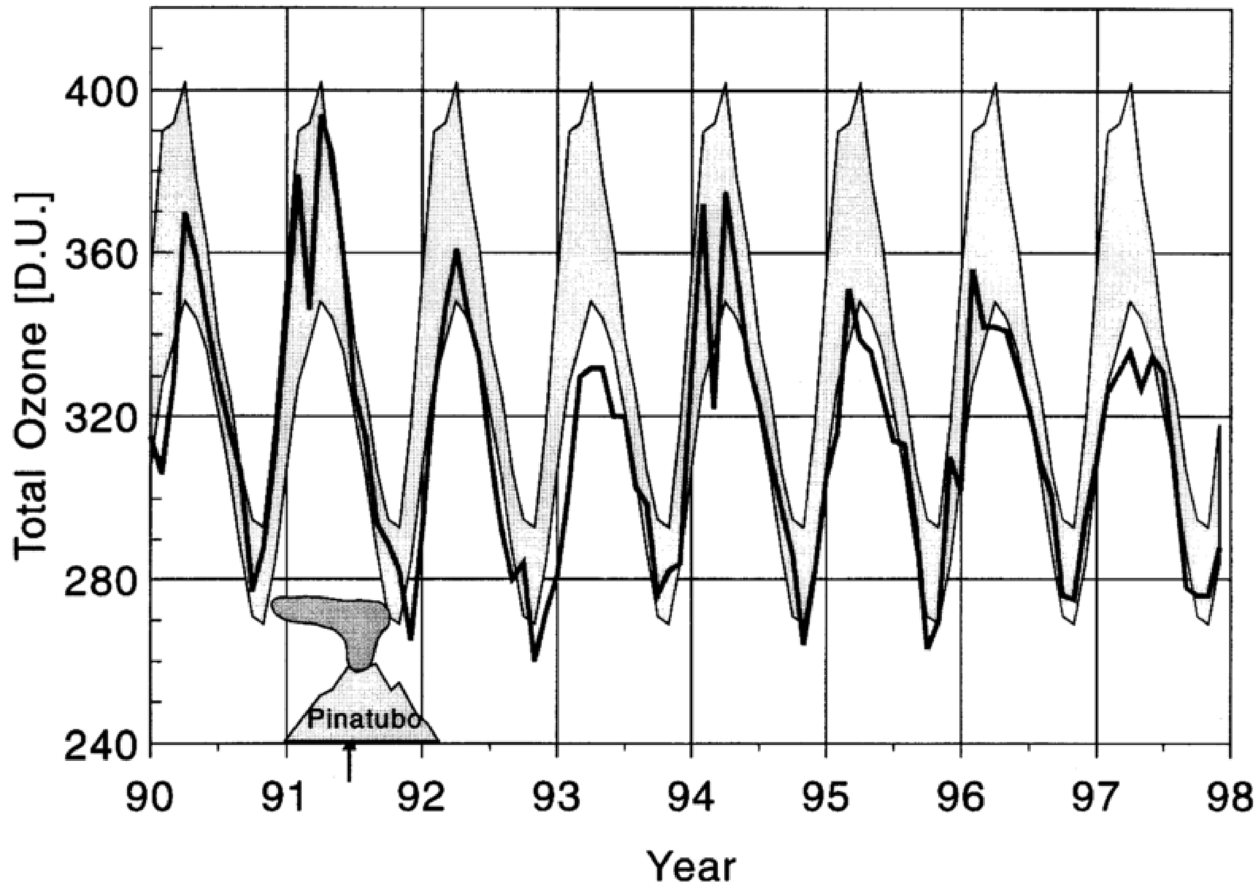


Figure 4.10: Actual development of monthly means of total ozone for the period 1990 - 1997. The shaded range gives the average long term ± 1σ standard deviation of total ozone.

In the following two years the total ozone was disturbed by the aerosol cloud of the Mt. Pinatubo eruption. This aerosol depleted ozone in the range between the tropopause and 20 km, giving a reduction of 10 to 15%. In 1994 the total ozone recovered to normal or nearly normal values. 1995, 1996 and 1997 exhibited again very low total ozone through the entire period. Having this development in mind, the UV-B measurements of the years 1990 - 1997 can be interpreted. The UV-B values of spring 1991 are throughout the lowest since in the complete period the highest total ozone was registrated in that year. In the other years and especially in 1992 and 1993 the UV-B was enhanced due to a pronounced ozone destruction. Compared to the center of the grey reference area UV is up to 30% above normal in spring 1993. Also spring 1997 (March to May) shows in general higher values than the average due to ozone values below normal.

In Figure 4.11 the average daily course of UV-B was calculated as averages for the five year period (1990 - 1994) and for April 1993 for sunny days. The spectra were weighted with the erythemal action function according to DIN 5050 (in the range 290 - 320 nm). It should be emphasized that the erythemal action function reaches into the UV-A range and, in principle, it would be possible to calculate the complete erythemal radiation by assessing the UV-A contribution from the short wave global radiation measurement. Here we confined to the spectral range of the Brewer disregarding the UV-A fraction in erythemal radiation. In Figure 4.11 we included the 1hr sun burn doses line for a fair skinned european for reasons of comparison. The time scale is not the true sun time but CET (summer time) being the reason that the noon maximum appears around 1 pm (13:00 CET). In 1993, the UV-B was elevated by 30% on sunny days as compared to the 5 year average due to a mean reduction in total ozone of 12% (317 D.U. in 1993 and 360 D.U. for the period 1990 - 1994, derived from total ozone on clear days only). The amplification factor was around 2 which is above that of DIN 5050. Since we disregarded the UV-A contribution the measured amplification factor is too high. However, the disregarded UV-A contribution is independent on total ozone and the true amplification factor can be assessed to be of the order 1.2 - 1.5.

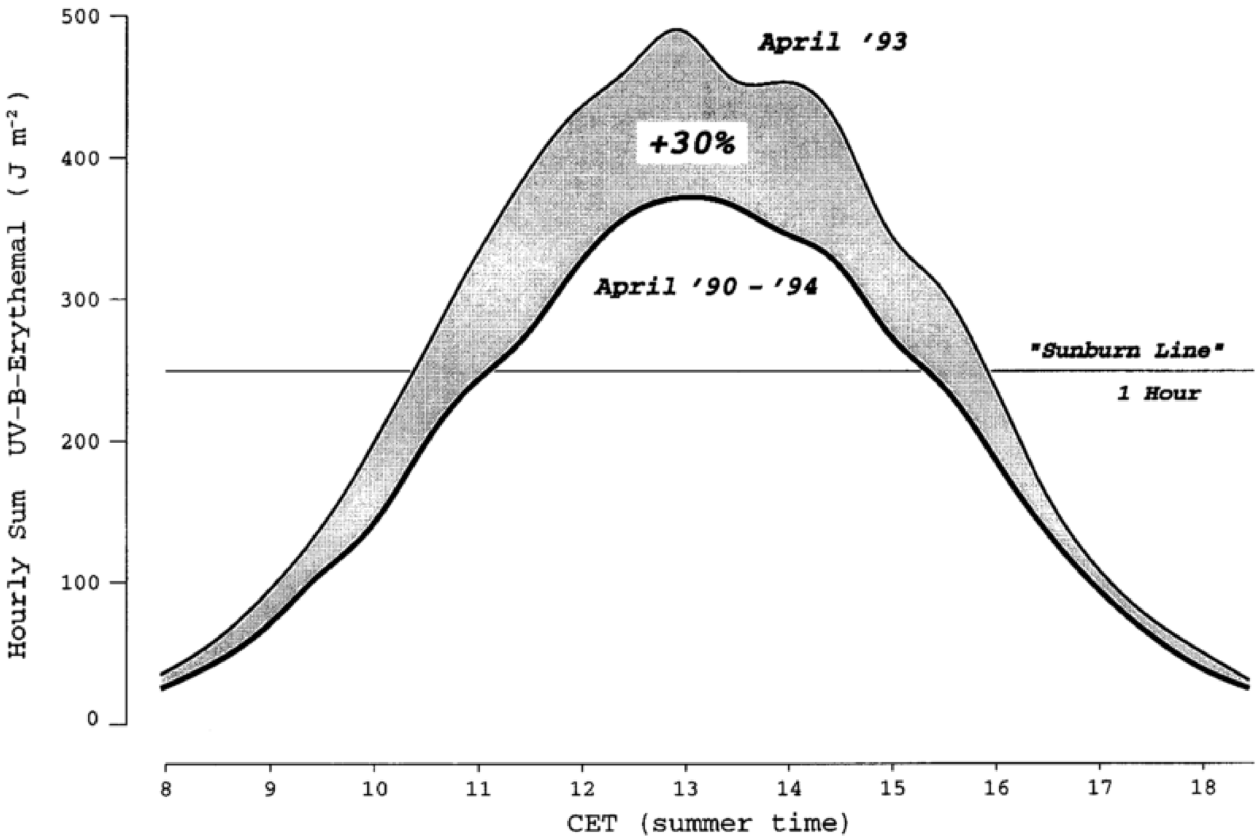


Figure 4.11 *Average daily course for erythemal UV-B at sunny days of April: average of the years 1990 - 1994 in comparison of the average of 1993 with elevated values due to ozone destruction by the Pinatubo eruption.*

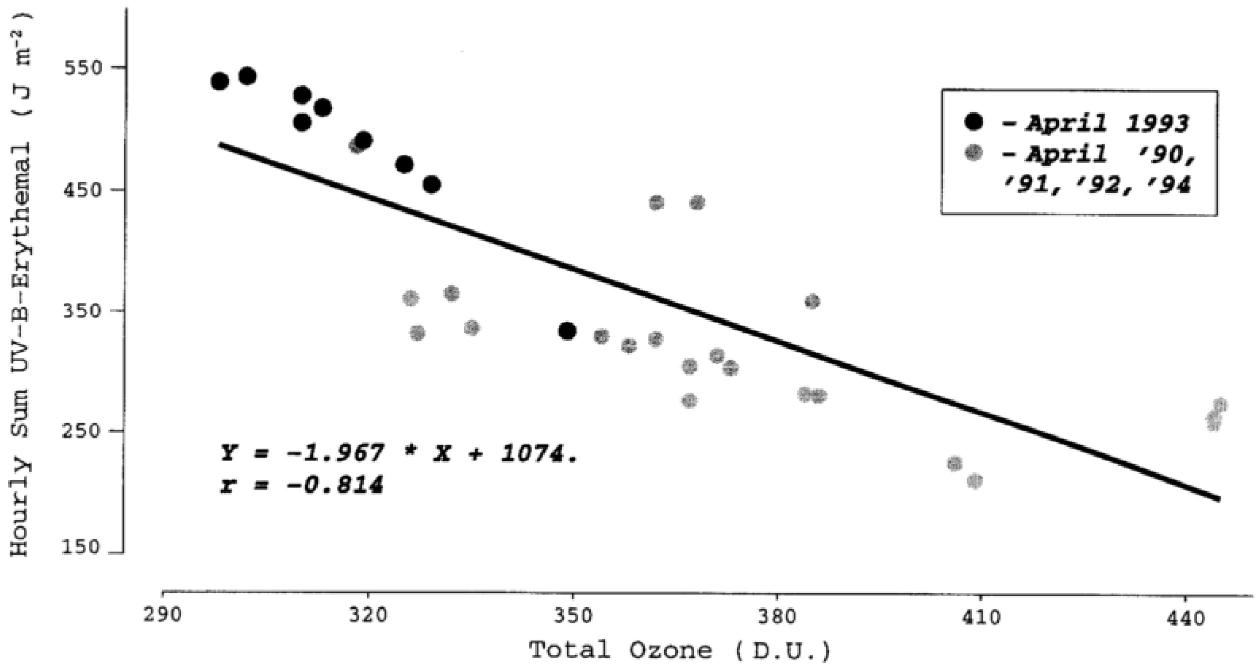


Figure 4.12 *Scatterplot of hourly sums of erythemal UV-B versus total ozone for month of April of the years 1990 - 1994, measured at highest sun elevation.*

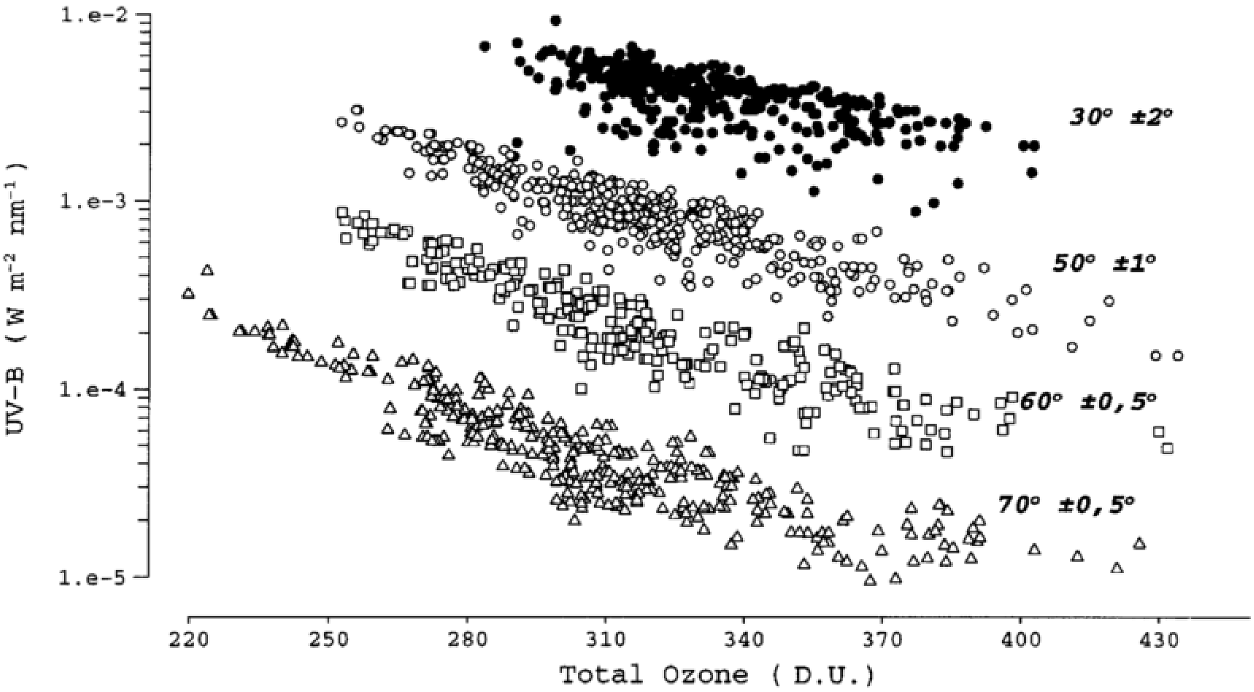


Figure 4.13 *Measured UV-B (300 nm) at selected zenith distances of the sun as a function of total ozone.*

In Figure 4.12 hourly sums of erythemally - weighted UV-B radiation (290 - 320 nm) are plotted versus total ozone for April and sunny days. The dots of April 1993 are given in black. The regression line has a slope of -1.967 and a correlation coefficient of -0.814 being significant on the 3-σ level. More than 65% of the UV-B variance can be attributed to the variability of total ozone. This means that in the UV-B range a 1% ozone reduction increases the UV-B by 2%. Of course, the amplification factor depends on the manner, in which the spectrum is weighted. In addition the sun elevation also influences the amplification factor because of the optical path length through the ozone layer (*Zerefos et al.* 1985, *Feister* 1994 b, *Ito et al.* 1994).

The influence of sun elevation and total ozone on UV-B at 300 nm is shown in Figure 4.13.The scatter of the data at a given sun elevation is caused by variations of cloud cover, turbidity and vertical ozone distribution. The upper relatively sharp edge of a data cloud belongs to situations with clear sky and low turbidity, i. e. the maximum of UV-B irradiation at a given amount of total ozone. In the semi-logarithmic plot this upper edge of the data cloud appears to be linear, i. e. it is a confirmation of Lambert - Beers extinction law. The slope of this linear upper edge increases with increasing zenith distance. At high zenith distances and large total ozone values the linearity seems to change, however, this effect is most probably caused by large measurement errors at this low intensity. It should be mentioned that in this figure only those data have been used where both, UV-B and total ozone, were measured within 15 min (by the Brewer).

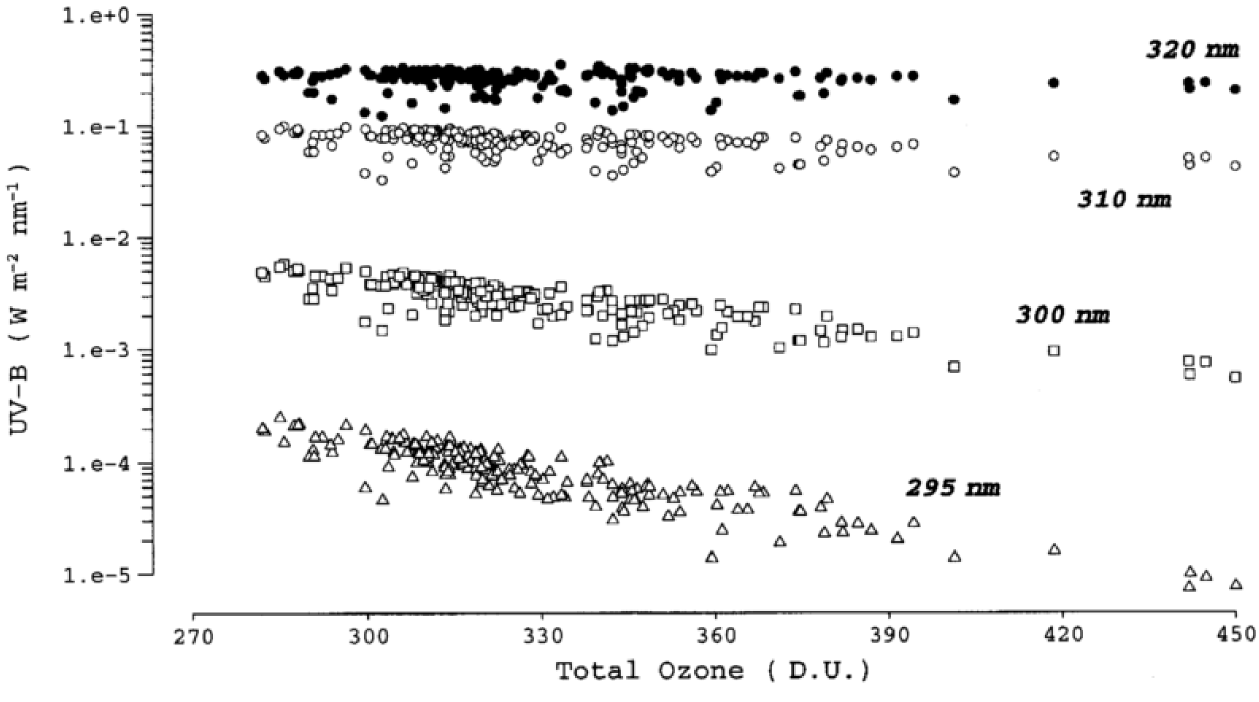


Figure 4.14 *Measured UV-B at selected wavelengths for a given sun elevation of 35° ± 2° as a function of total ozone.*

In Figure 4.14 UV-B is plotted as a function of total ozone at a given solar zenith distance ($35^0 \pm 2^0$) for a number of distinct wavelengths. The zenith distance of 35^0 is reached at Hohenpeissenberg from end of April to end of August. Although a large range of total ozone is observed in this period, it does not comprise minimum and maximum ozone of the annual course. Nevertheless, the variability of total ozone is large enough in order to demonstrate the wavelength dependence of the ozone extinction on UV-B. At 320 nm only a marginal dependence of UV is seen while at the short wave end of the UV-B-range the variation exceeds one order of magnitude.

The 8 years measuring period was long enough to document the dominating influence of the ozone layer to the UV-B radiation at the surface. The Pinatubo eruption in this period caused larger than usual ozone variations, which allowed to measure under normal and extreme conditions. Although such events are natural ones, causing a large variability of the UV-B radiation, it became clear, which extreme UV-B irradiation is to be expected under the continuing anthropogenic destruction of the ozone layer. Though there are additional meteorological parameters which are also influencing UV-B and which can have opposite or compensating effects the possible extremes of UV-B can be assessed. Under the continuing conditions of ozone destruction the short wave fraction will increase strongly. Whether this is of relevance or not depends on the action functions and where they have their maximum. For example, in the UV induced damage of DNA (e.g. *Tevini and Häder*, 1985) the dosis will increase much more than in erythemal UV radiation which changes much less due to its extension into the UV-A range. An increase of UV-B at lower sun elevations is also to be expected under these conditions.

5 OUTLOOK

It has been shown that the Brewer UV-observations are reliable enough for monitoring purposes and climatological analysis and corresponding statements. It is planned to continue this work and to investigate the effects of long-term changes of ozone, global radiation, turbidity and cloudiness, in order to obtain the long term trend of the UV-B.

The necessary records of the various parameters are existing at Hohenpeissenberg:

1. UV-B since 1990 as well as total ozone, ozone vertical profile, additional meteorology incl. radiation, in order to define and to verify the physical relations between these parameters.

2. Total ozone, vertical ozone profile and additional meteorology since at least 1968, so that a possible UV-B trend since 1968 can be simulated, using the correlations as derived above and by means of the STAR-radiation model of the University Munich.

As already explained in this report, the data quality of the UV-B measurements of the Brewer need still some improvements. These will be included for providing a most reliable data base for the investigations of the physical correlations. The observation frequency (a seven minute lasting observation each half an hour) was enhanced with additional, so-called short UV-observations being included in the tight Brewer-schedule.

This observation type only uses the five wavelengths (306.325, 310.071, 313.52, 316.82 and 320.027 nm) through the chopper mask in a similar manner like the total ozone measurement. Thus, the time consuming movements of the grating during a complete scan are avoided. This observation type needs only approx. 1.5 minutes. Investigations should confirm, that it is possible to expand the entire spectrum between 290 and 320 nm only with these five data points. Thus, the frequency of the UV-B observations could be trebled (six instead of two spectra per hour). Furthermore, the disadvantages (e.g. distortion of the spectrum due to passing clouds) are clearly reduced with this short observations.

The quality of the ozone data has also been remarkably improved and their scientific value and reliability has been clearly enhanced due to the recently finished homogenization of the Dobson record (total ozone) and the Brewer/Mast record (vertical ozone profile). The last two figures 5.1 and 5.2 reflect the changes in ozone during the last three decades, using these new, recalculated data sets. It is very likely that the extent of these trends have caused changes in the UV-B too. It is necessary to work out possible compensating effects of the trend of the global radiation (*Liepert et al.* 1994) or how the distortion of the vertical ozone profile may have modified the

UV-B (*Brühl and Crutzen* 1989).

It is in any case alarming, that the strongest total ozone reduction up to 6% per decade occurs in the late winter/spring season (Figure 5.1c), when total ozone is normally very high (Figure 5.2). These trends are also evident at other European and North American stations (*Entzian et al.* 1990). All daily means of the Dobson 104 since 1968 are drawn in Figure 5.2. The annual course of total ozone (maximum in spring, minimum in fall) and its variability (maximum in spring too, minimum in summer) can bee clearly observed. Additionally to the above-average depletion of the ozonelayer during late winter/spring, extremely low values, so-called mini-holes, have more frequently appeared during the past years. During such events ozone values have been observed, which normally occur as lowest values in fall at the time of the annual ozone minimum. These are caused by the advection of ozone-poor air from the subtropics as well as from polar latitudes, when the polar vortex breaks up in springtime and air parcels with low ozone content due to CFC-caused ozone depletion are transported to the midlatitudes. The skin of the Central Europeans, which is very UV-sensitive after winter, is normally protected against the rapidly increasing UV-radiation by a thicker ozone layer during spring. This natural UV-shield has lost approx. 15 % of its effectiveness since the end of the sixties, when the Hohenpeissenberg ozone observations were started. It is expected, that this negative trend will continue at least the next two decades. Thus, a further enhancement of UV-B radiation is preprogrammed. At present it is impossible to predict, whether and how far mankind, but also fauna and flora, are able to adapt to these rapid changes of the environmental conditions. Other research projects within BayFORKLIM in the field of Biology might help with new knowledge, to predict and possibly to reduce or even avoid adverse effects of anthropogenic interventions in nature.

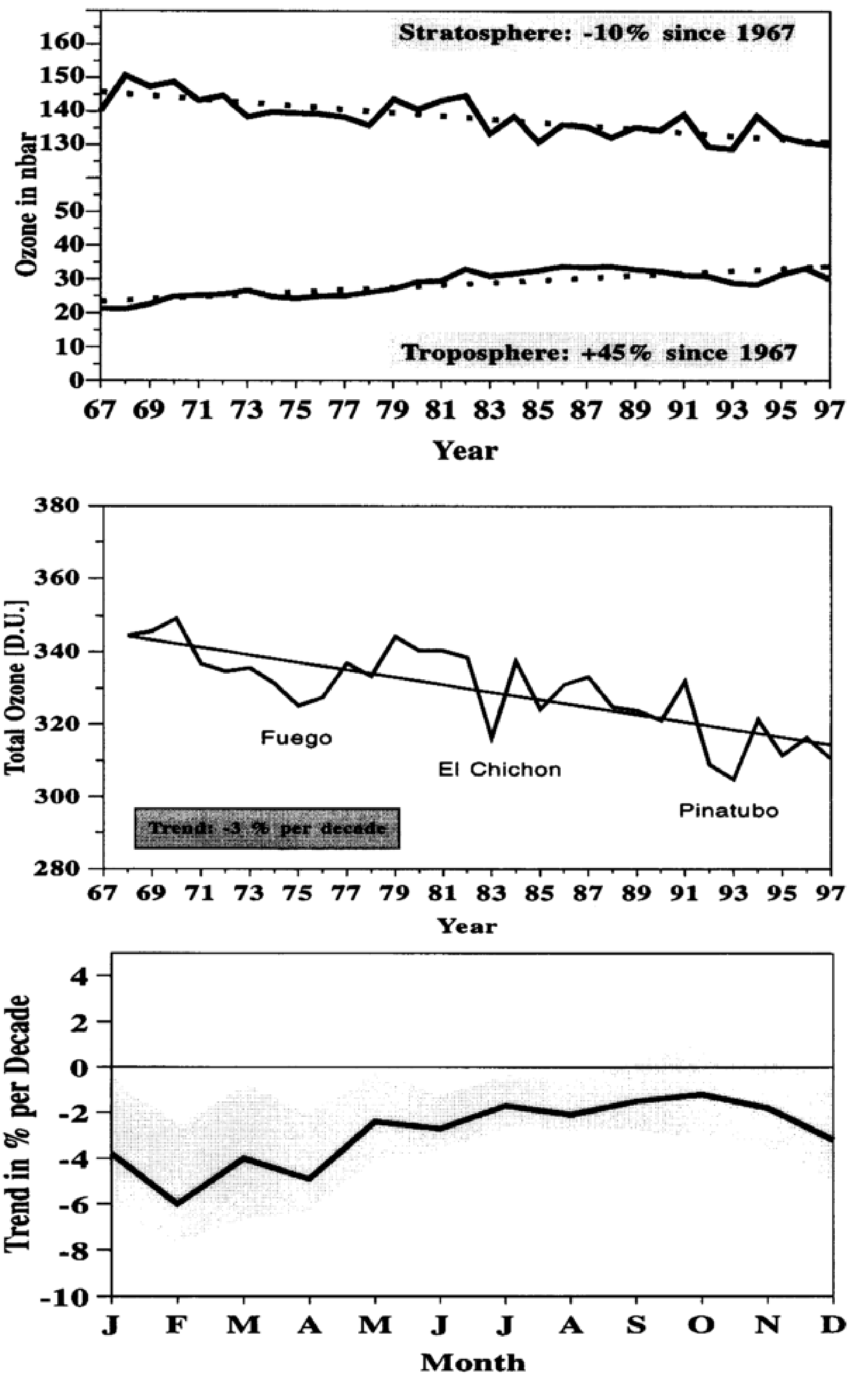


Figure 5.1 a,b,c: *Ozone trends at the Met. Obs. Hohenpeißenberg -*

a. Strato- und tropospheric trends deduced from Brewer/Mast-Ozonesondes

b. Trend of Dobson 104 - Total ozone incl. major volcanic eruptions

c. Annual course of the total ozone trend

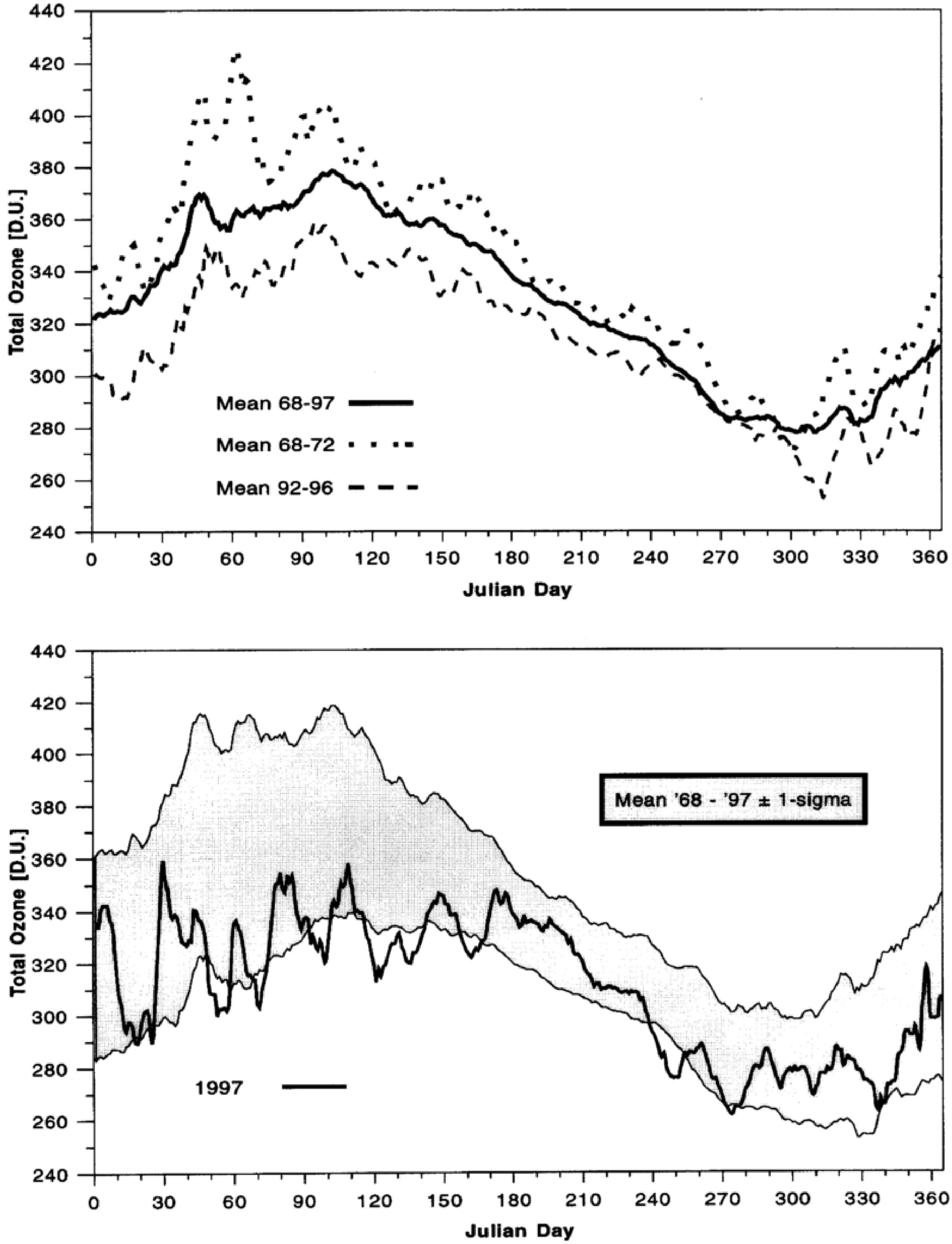


Figure 5.2a-b: Annual course of total ozone: mean(68-97), 68-72, 92-96 (a) and 1997 incl. mean ± σ (b)

6 ACKNOWLEDGEMENT

Our first thanks is dedicated Dr. K. Wege who as former director of the observatory got this project under way inspite of some problems. We are grateful to Mr. L. Erbertseder and the colleagues from the ozone group (S. Steiner, F. Strommer und M. Adelwart) for their hard work in order to produce the reliable long term series of ozone (total ozone, vertical profile) and UV-B. The support of the workshop group (F. Schönenborn, A. Stögbauer and J. Eding) was absolutely necessary for the success of the project. Thanks also to K. Schönenborn who always requested the necessary funds in time.

Dear Fiona and Wolfgang Steinbrecht, thank you very much for your valuable support. Your improvements to our first English draft have made this report legible for native English speakers.

Many thanks to the radiation group of the Meteorological Institute of Munich University. The co-operation with this group can surely be described as exemplary in the sense of the BayFORKLIM stipulations. Also, many thanks to other scientists of various institutions including Dr. K. Dehne and Dr. G. Seckmeyer, who kindly put their valuable calibration lamps at our disposal. They proved with their willingness to co-operate, that this behaviour is of more benefit for science than rivalry.

We would like to express our gratitude to all responsible persons within the Bavarian Climate Research Programme for their benevolent obligingness and active support concerning the administrative realization of this project.

Last but not least we would like to thank the Bavarian Ministry of Economy and Transportation as well as the Government of Upper Bavaria, who alone made this project possible providing considerable funds under grant B I 10 in the Bavarian Climate Research Programme (BayFORKLIM).

In memory of Dr. W. Attmannspacher, who was the director of the observatory from 1967 to 1986, his creative urge and authority should be appreciated. He founded worldwide recognized, long term series of total ozone and ozone vertical profiles in such high quality, which is absolutely necessary for the following investigations.

7. References

Ambach W., M. Blumthaler, Ozon-Abnahme und UVB-Zunahme. In: OeGM-Bulletin, Nr.1, p. 5-6, 1992.

Ambach W., M. Blumthaler, Characteristics of Solar UV Irradiance. Meteorol. Zeitschrift, N.F. 3, p. 211-220, 1994.

Bais, A., C. Zerefos, C. Meleti, I. Ziomas, Comparison of UV-B Measurements Performed with a Brewer Spectrophotometer and a new UVB-1 Broad Band Detector. In: Ozone in the Troposphere and Stratosphere Part 2, p. 786-789, NASA Conference Publication 3266 zum Quadrennial Ozone Symposium 1992 in Charlottesville, USA, 1994.

Bais, A., UV-B Observations with a Brewer Spectrophotometer. Talk at the Third WMO Consultation on Brewer Ozone Spectrophotometer - Operation, Calibration and Data Reporting, Puerto de la Cruz, Tenerife, 1994a.

Bais, A., Re-evaluation of Brewer #005 Ozone Data 1982-94 to the Present. Talk at the Third WMO Consultation on Brewer Ozone Spectrophotometer - Operation, Calibration and Data Reporting, Puerto de la Cruz, Tenerife, 1994b.

Barnard, W., The United States UV-B Program. Talk at the Third WMO Consultation on Brewer Ozone Spectrophotometer - Operation, Calibration and Data Reporting, Puerto de la Cruz, Tenerife, 1994.

Basher, R., Upward Trend Detected in Solar UV-B in New Zealand. Talk at the Third WMO Consultation on Brewer Ozone Spectrophotometer - Operation, Calibration and Data Reporting, Puerto de la Cruz, Tenerife, 1994.

Basher, R., X. Zheng, S. Nichol, Ozone-Related Trends in Solar UV-B Series. Geophysical Research Letters, Vol. 21, No. 24, p. 2713-2716, 1994.

Blumthaler, M., W. Ambach, Indication of Increasing Solar Ultraviolet-B Radiation Flux in Alpine Regions. Science, Vol. 248, p. 206-208, 1990.

Bojkov, R.D., Personal communication, Third WMO Consultation on Brewer Ozone Spectrophotometer - Operation, Calibration and Data Reporting, Puerto de la Cruz, Tenerife, 1994.

Brewer, A.W., A Replacement for the Dobson Spectrophotometer?. Pure and Applied Geophysics (PAGEOPH), Vol. 106-108, p. 919-927, 1973/V-VII.

Brühl, C., P.J. Crutzen, On the Disproportionate Role of Tropospheric Ozone as a Filter Against Solar UV-B Radiation. Geophysical Research Letters, Vol. 16, No. 7, p. 703-706, 1989.

Claude, H., W. Vandersee, K. Wege, On Long-Term Ozone Trends at Hohenpeissenberg. In: Ozone in the Troposphere and Stratosphere Part 1, p. 190-194, NASA Conference Publication 3266 zum Quadrennial Ozone Symposium 1992 in Charlottesville, USA, 1994a.

Claude, H., F. Schönenborn, W. Steinbrecht, W. Vandersee, New Evidence for Ozone Depletion in the Upper Stratosphere. Geophysical Research Letters, Vol 21, No. 22, p. 2409-2412, 1994b

Cuevas, E., A. Redondas, Measurements of Total Ozone and Sulphur Dioxide with Brewer #033

Izaña Observatory. A Contribution to the Global Atmospherie Watch. Publication of the Instituto Nacional de Meteorologia, Observatorio Especial de Izaña, Santa Cruz de Tenerife, Spain, 1993.

De Backer, H., D. De Muer, Intercomparison of Total Ozone Data Measured with Dobson and Brewer Ozone Spectrophotometers at Uccle (Belgium) from January 1984 to March 1991, Including Zenith Sky Observations. Journal of Geophysical Research, Vol. 96, No. D11, p. 20711-20719, 1991.

Dehne, K., Zur Variation von Absolut- und Relativwerten der UV-Globalstrahlung. In: Laufener Seminarbeiträge 3/88, Wirkungen von UV-B-Strahlung auf Pflanzen und Tiere, 1989.

DIN 5031, Strahlungsphysik im optischen Bereich und Lichttechnik. Größen, Formeln und Kurzzeichen für photobiologisch wirksame Strahlung, Teil 10, 1975.

DIN 5050, Solarien und Heimsonnen. Meßverfahren, Typverteilung, Kennzeichnung, Teil 1, 1992

Entzian, G., K. H. Grasnick, J. Taubenheim, Seasonal Variations of Ozone Trends. Adv. Space Res., Vol. 10, No. 10, p. 265-268, 1990

Feister, U., Field Performance of a Brewer Spectrometer and a Filter Ozonometer M 124 as Compared to a Dobson Spectrophotometer. Z. Meteorol. 41, p. 291-305, 1991.

Feister, U., Comparison between Brewer Spectrometer, M 124 Filter Ozonometer and Dobson Spectrophotometer. In: Ozone in the Troposphere and Stratosphere Part 2, p. 770-773, NASA Conference Publication 3266 zum Quadrennial Ozone Symposium 1992 in Charlottesville, USA, 1994a.

Feister, U., Model Calculations and Measurements of Chemically and Biologically Effective UV Radiation Reaching the Ground. Berichte des Deutschen Wetterdienstes Nr. 190, 1994b.

Feister, U., R. Grewe, K. Gericke, A Method for Correction of Cosine Errors in Measurements of Spectral UV Irradiance. Solar Energy, Vol. 60, No. 6, 1997.

Gardiner, B. G., P. J. Kirsch, Second European Intercomparison of Ultraviolet Spectroradiometers. Report to the Commission of the European Communities, STEP Project 76, p. 1-21, 1993.

Gardiner, B. G., P. J. Kirsch, Setting Standards for European Ultraviolet Spectroradiometers. Report to the Commission of the European Communities, STEP Project 76, 1994.

Ito, T., Y. Sakoda, K. Matsubara, R. Kajihara, T. Uekubo, M. Kobayashi, M. Shitamichi, T. Ueno, M. Ito, UV-B Radiation Amplification Factor Determined Based on the Simultaneous Observations of Total Ozone and Global Spectral Irradiance. In: Ozone in the Troposphere and Stratosphere Part 2, p. 657-662, NASA Conference Publication 3266 zum Quadrennial Ozone Symposium 1992 in Charlottesville, USA, 1994.

Josefsson, W., Solar Ultraviolet Radiation in Sweden. SMHI-Report RMK Nr.53, 1986.

Josefsson, W., Personal communication, 1995.

Kerr, J. B., I. A. Asbridge, W. F. J. Evans, Intercomparison of Total Ozone Measured by the Brewer and Dobson Spectrophotometers at Toronto. Journal of Geophysical Research, Vol. 93, No. D9, p. 11129-11140, 1988.

Kerr, J. B., I. A. Asbridge, W. F. J. Evans, Long Term Intercomparison between Brewer and

Dobson Spectrophotometers at Edmonton. In: Ozone in the Atmosphere, Hrsg.: R.D. Bojkov and P. Fabian, p. 105-108, A. Deepak, Hampton, Va, 1989.

Kerr, J.B., C.T. McElroy, Evidence for Large Upward Trends of Ultraviolet-B Radiation Linked to Ozone Depletion. Science Vol. 262, p. 1032-1034, 1993.

Kerr, J.B., The Measurement of UV-B in Canada. Talk at the Third WMO Consultation on Brewer Ozone Spectrophotometer - Operation, Calibration and Data Reporting, Puerto de la Cruz, Tenerife, 1994.

Kerr, J.B., C.T. McElroy, Personal communication, 1995.

Köhler, U., R. Hartmannsgruber, W. Attmannspacher, Experiences with a Brewer Spectrophotometer and Intercomparison Measurements with a Dobson Spectrophotometer. In: Atmospheric Ozone, Proceedings of the Quadrennial Ozone Symposium 1984 in Halkidiki, Greece, D. Reidel Publ. Comp., 1985.

Köhler, U. W. Attmannspacher, Long Term Intercomparison between Brewer and Dobson Spectrophotometer at the Hohenpeissenberg. Beitr. Phys. Atmosph., Vol. 59, p. 85-96, 1986.

Köhler, U., K. Wege, R. Hartmannsgruber, H. Claude, Vergleich und Bewertung von verschiedenen Geräten zur Messung des atmosphärischen Ozones zur Absicherung von Trendaussagen. BPT-Bericht 1/88, 1988.

Köhler, U., H. Claude, First results of the re-evaluation of the long term ozonesonde records at Hohenpeissenberg. Polar stratospheric ozone, Proceedings of the third European workshop 18 to 22 September 1995, Schliersee, 1996.

Köhler, U., Re-evaluation of Hohenpeissenberg Ozone Records. In Atmospheric Ozone Dynamics: Observation in the Mediterranean Region. Proceedings of ARW, Athens (Greece), Nov. 1995, 1997.

Köhler, U., H. Claude, Homogenized Ozone Records at Hohenpeissenberg. Submitted to and accepted for the Proceedings of the Quadrennial Ozone Symposium, 11.-22.9.1996 in L'Aquila, Italy, 1998.

Liepert, B., P. Fabian, H. Grassl, Solar Radiation in Germany – Observed Trends and an Assessment of their Causes, Part I: Regional Approach. Beitr. Phys. Atmosph., Vol. 67, No. 1, p. 15-29, 1994.

Nagel, D., U. Leiterer, Brewer Spektrometer MK IV, BMFT-Projekt Optische Feldmeßmethoden – Final Report. In: DWD Abteilung Forschung, Arbeitsergebnisse Nr. 22, 1995.

Nichol, S.E., C. Valenti, Intercomparison of Total Ozone Measured at Low Sun Angles by the Brewer and Dobson Spectrophotometers at Scott Base, Antarctica, Geophysical Research Letters, Vol. 20, No. 19, p. 2051-2054, 1993.

Ruggaber, A., Modellierung Photolytischer Prozesse in der Troposphäre. Thesis, München, 1994.

Ruggaber, A., R. Dlugi, T. Nakajima, Modelling Radiation Quantities and Photolysis Frequencies in the Troposphere. Journal of Atmospheric Chemistry, Vol. 18, p. 171-210, 1994.

Seckmeyer, G., Spektralradiometer für die ökologische Pflanzenforschung. Licht 41, p. 501-506, 1989.

Seckmeyer, G., S. Thiel, M. Blumthaler, P. Fabian, S. Gerber, A. Gugg-Helminger, D.-P. Häder, *M. Huber, C. Kettner, U. Köhler, P. Köpke, H. Maier, J. Schäfer, P. Suppan, E. Tamm, E. Thomalla*, Intercomparison of spectral-UV-radiation measurement systems. Applied Optics, Vol. 33, No. 33, p. 7805-7812, 1994.

Tamm, E., E. Thomalla, Personal communication, 1994

Tamm, E., E. Thomalla, Personal communication, 1995

Tevini, M., D.-P. Häder, Allgemeine Photobiologie. G. Thieme Verlag, Stuttgart, 1985

Thomalla, E., E. Tamm, U. Köhler, P. Köpke, W. Vandersee, Variability of UV Irradiance with Actual Hohenpeissenberg Ozone Data and other Atmospheric Parameters. Abstract on a talk at the European Symposium on Effects of UV Radiation, GSF Neuherberg, 1993.

Vandersee, W., U. Köhler, UV-Observations With A Brewer Spectrophotometer At Hohenpeissenberg. In: Ozone in the Troposphere and Stratosphere Part 2, p. 742-745, NASA Conference Publication 3266 on the Quadrennial Ozone Symposium 1992 in Charlottesville, USA, 1994.

Vandersee, W., UV-B Measurements with a Brewer at Hohenpeissenberg. Talk at the Third WMO Consultation on Brewer Ozone Spectrophotometer - Operation, Calibration and Data Reporting, Puerto de la Cruz, Tenerife, 1994.

Wang, P., J. Lenoble, Comparison between Measuring and Modelling of UV-B irradiance for Clear Sky: A Case Study. Applied Optics, Vol. 33, No. 18, p. 3964-3971, 1994

Wardle, D. J., C. D. Walshaw, T. W. Wormell, A New Instrument for Atmospheric Ozone. Nature 199, p. 1177-1178, 1963.

WMO, Scientific Assessment of Ozone Depletion: 1991.

WMO, Second WMO Consultations on Ozone Measurements by Brewer Spectrophotometer, Global Atmosphere Watch, WMO Global Ozone Research and Monitoring Project Report No. 30, 1994.

Zerefos, C. S., A. F. Bais, I. C. Ziomas, Monochromatic UV-Magnification Factors and Total Ozone. In: Atmospheric Ozone, Proceedings of the Quadrennial Ozone Symposium 1984 in Halkidiki, Greece, D. Reidel Publ. Comp., p. 686-690, 1985.