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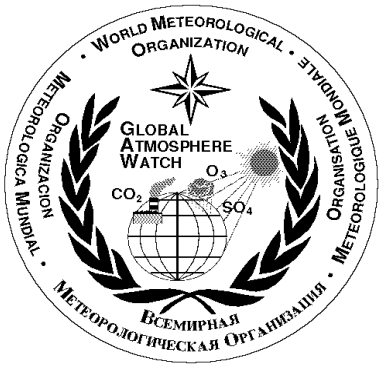

No. 149

COMPARISON OF TOTAL OZONE MEASUREMENTS OF DOBSON AND BREWER SPECTROPHOTOMETERS AND RECOMMENDED TRANSFER FUNCTIONS

MARCH 2003

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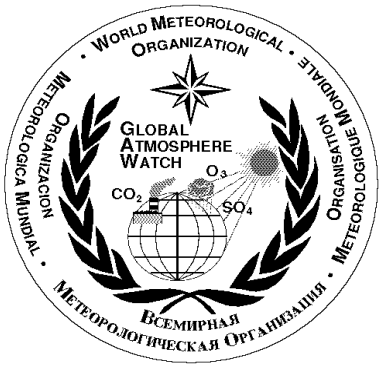

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COMPARISON OF TOTAL OZONE MEASUREMENTS OF DOBSON AND BREWER SPECTROPHOTOMETERS AND RECOMMENDED TRANSFER FUNCTIONS

Prepared by

J. Staehelin, J. Kerr, R. Evans and K. Vanicek

WMO TD No. 1147

Table of Contents

Abstract

The primary instruments used for measuring total column content of atmospheric ozone (TO_3) in the World Meteorological Organization's (WMO) Global Atmospheric Watch (GAW) program are the Dobson and the Brewer spectrophotometers. The Dobson instruments can be as old as 70 years, are specifically designed for TO_3 measurements, and are normally manually operated. The Brewer instruments are newer, can make measurements of other important parameters in atmospheric science and are fully automated. Much of what is known about TO_3 changes in time came from measurements with Dobson instruments at stations with long-term measurement programs. Many of these stations have added Brewer instruments to their measurement program. This report summarizes the available information about the differences between the instrument results and considers the requirements and transfer functions for replacing a Dobson instrument with a long history of measurements by a Brewer instrument. Many stations with both instruments show a seasonal cycle in the differences. At sites where profile measurements of temperature and ozone are available, much of the difference between the instrumental readings of the two types of instruments can be explained by incorporating the stratospheric temperatures and the vertical ozone distribution into the calculation of TO_3. At other sites, a more empirical approach is required to formulate a transfer function in order to allow the newer instrument's result to be used for the trend analysis. However, to obtain the required accuracy a period of three or more years of many (quasi) simultaneous measurements per day with both instruments is required. Changing from one instrument to the other is not recommended – the simultaneous operation of both instruments at a site increases the reliability of the long-term series. If any circumstance forces such a change, a careful construction of a transfer function as described in this paper is recommended to minimize the effect of the change on the long-term trend.

1. INTRODUCTION

1.1 Aims of the report

The development of a precise instrument to measure column (total) ozone (TO_3) with moderate manpower demand was a key step in atmospheric ozone research in the first half of the last century [Dobson and Harrison, 1926]. The instrument most widely in use was developed by G.M.D. Dobson [Dobson, 1931] in the 1920s and 30s and was fully refined by the International Geophysical Year (IGY) in 1957 [Dobson 1957a and 1957b; see also Komhyr, 1980]. Precise and long-term stable ozone measurements received a high priority since the beginning of the 1970s when the anthropogenic destruction of the ozone shield by ozone depleting substances become a topic of debate in science and public [Crutzen, 1971; Johnston, 1971; Stolarski and Cicerone, 1974; Molina and Rowland, 1974; see also Solomon, 1999]. Natural variability in TO_3 is large in the extratropical regions. The variation of TO_3 content from one day to another can be as large as ± 20%, while long-term trends by anthropogenic ozone depleting substances have been in the range of a few percent decrease per decade at mid-latitudes [e.g. Staehelin et al., 2001]. Well-maintained and calibrated Dobson spectrophotometers have proven suitable to monitor long-term changes with high reliability. This was not only demonstrated by the discovery of the ozone hole [Farmann et al., 1985] but also by monitoring the ozone shield at mid-latitudes and by checking the long-term stability of ozone instruments on-board satellites [WMO, 1992, 1995, 1999; Staehelin et al., 2001]. However, this requires a well-established and well-maintained data quality control program, which in this case runs under the auspices of WMO. During the last five years 76 Dobson stations have regularly reported data to the World Ozone and Ultraviolet Data Centre (WOUDC) at Toronto, Canada. The instrumental design, the calibration and data quality control program of the measurements by Dobson spectrophotometers are summarized in Section 2.1 as required for the subject of this report.

The Brewer spectrophotometer has been commercially available since the early 1980s [Kerr et al., 1981; 1985]. Like the Dobson spectrophotometer this instrument is based on sun photometry in the Huggins band but it uses more modern technology. The Brewer spectrophotometer is designed for completely automated operation implying smaller manpower demand. Furthermore it allows to measure simultaneously SO_2-column amount, which is an important interference for TO_3 measurements by Dobson spectrophotometers operated in polluted areas. During the last 5 years, measurements of 54 Brewer stations have been regularly sent to WOUDC. Also in the Brewer observing network, the data quality needs to be controlled. In Section 2.2 we briefly summarize the design and the operation of Brewer spectrophotometers, including calibration and data quality control, followed by a short summary of the differences between the two instrumental systems and the present operation of the networks (Section 2.3).

Since 1983 Brewer and Dobson instruments have been simultaneously operated at several sites showing small but consistent characteristics in the differences between the TO_3 measurements of the two instruments. This report aims to summarize the results of such studies. Section 3 lists the possible reasons for the observed differences and classifies different approaches to study the differences, which might be based on comparison of seasonal variation (using monthly means), daily means or single quasi-simultaneous measurements. In Section 4 we summarize the results of several selected studies. In Table 3 we list all the studies we obtained from our colleagues. From the experiences documented in the studies available to us we derive in Section 5 recommended procedures for the comparisons of Brewer and Dobson measurements and we present some conclusions in the last Section.

The simultaneous operation of Brewer and Dobson spectrophotometers offers the opportunity to strongly improve the reliability of the TO_3 monitoring of a station. The side by side operation of the two types of instruments calibrated from two independent sources allows to assess the reliability of the long-term stability of the involved instruments and networks. The careful construction of a transfer function can also be used to extend the number of TO_3 measurements of a Dobson series by measurements of the completely automated Brewer instrument, e.g. when restrictions in manpower costs do not allow to make Dobson observations during the weekend. Suitable transfer functions need to be developed and tested in order to make best use of this redundancy. However, we will show that the replacement of a Dobson by a Brewer instrument needs

a careful long-term comparison of simultaneous measurements and its analysis to avoid breaks in the TO_3 measurements of a particular station. Such breaks result in a TO_3 series of the station that is rather useless for long-term ozone trend analysis. There are no universal transfer functions between the two types of instruments of sufficient precision, which are independent of atmospheric condition.

Other instruments can also measure TO_3 amount. The comparison between Dobson and Brewer measurements and the more recently developed and well tested SAOZ instrument [Pommerau and Goutail, 1988] and the Russian filter instruments which provided valuable (but less precise) TO_3 measurements of the area of the former Soviet Union [Bojkov et al., 1994] is out of the scope of this report. Reliable ground based TO_3 observations are required for the validation of satellite TO_3 measurements, which allows to monitor the ozone shield with (quasi) global coverage. The necessity of this comparison including the assessment of the long-term stability of satellite instruments has been proven beyond any doubt, in particular because the satellite instruments have limited life times and ozone monitoring from space is based more and more on composite series. In this report we do not address the comparison of Dobson and Brewer measurements with TO_3 observations from space [comp. e.g. Fioletov et al., 1999]. However, the presented transfer functions based on simultaneous TO_3 measurements of Brewer and Dobson instruments can also help to improve the understanding of the difference between ground based (Dobson/Brewer) measurements and satellite ozone observations; therefore the presented results are relevant for satellite validation as well. Also Umkehr measurements (made with both Dobson and Brewer spectrophotometers) and UVB-measurements (made with Brewer spectrophotometry) are not discussed in this report.

2. DESIGN OF DOBSON AND BREWER SPECTROPHOTOMETERS, OPERATIONS AND DATA QUALITY CONTROL

This section is not meant as a manual of the instruments but only as a brief summary, which highlights the most important points necessary for the following discussion. Column ozone amount is determined by both spectrophotometers by the measurement of the differences between the intensities of the solar radiants reaching Earth's surface. The solar radiation is strongly attenuated by atmospheric ozone at the wavelengths in the region of 305 to 340 nm used in the instruments. The archive of the measurements of both types of instruments is the WMO/GAW World Ozone and Ultraviolet Radiation Data Centre (WOUDC) at Toronto, Canada.

2.1 Dobson spectrophotometer

The design of the Dobson spectrophotometer is shown in Figure 1 and the operational wavelength pairs are listed in Table 1. The instrument is a double monochromator with the dispersing spectrometer shown on the right side of Figure 1 and the recombining spectrometer on the left.

Table 1: Wavelengths of Dobson and Brewer instruments used for the measurement of TO_3, in nm.

Dobson spectrophotometer: Measured wavelength pairs: A[1)]: 305.5/325.4; C: 311.5/332.4; D[1)]: 317.6/339.8.
Brewer spectrophotometer: Measured wavelengths (photon counts): 306.3 (for SO_2); 310.1; 313.5; 316.8; 320.1.
Ratios of wavelengths pairs used in the Brewer TO_3 algorithm: MS4: 306.3/316.8; MS5: 310.1/316.8; MS6: 313.5/316.8; MS7: 320.1/316.8.

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1): The wavelength pairs are those used for standard (A and D wavelength pairs combined) measurements (see text). C and D pairs combined are also used when the sun is lower in the sky. In the past, other wavelength pairs were defined and used.

The wavelengths for the measurements are selected by the positions of the quartz plates Q1 and Q2 (see Figure 1). A spectrum is obtained by a prism (P1) and projected onto slits (S2-S3). The rotation of a disk by a chopper wheel (D) allows that one of two wavelengths alternatively passes to the photomultiplier (Mp). An optical wedge (W) is used to decrease the intensity of the light of the

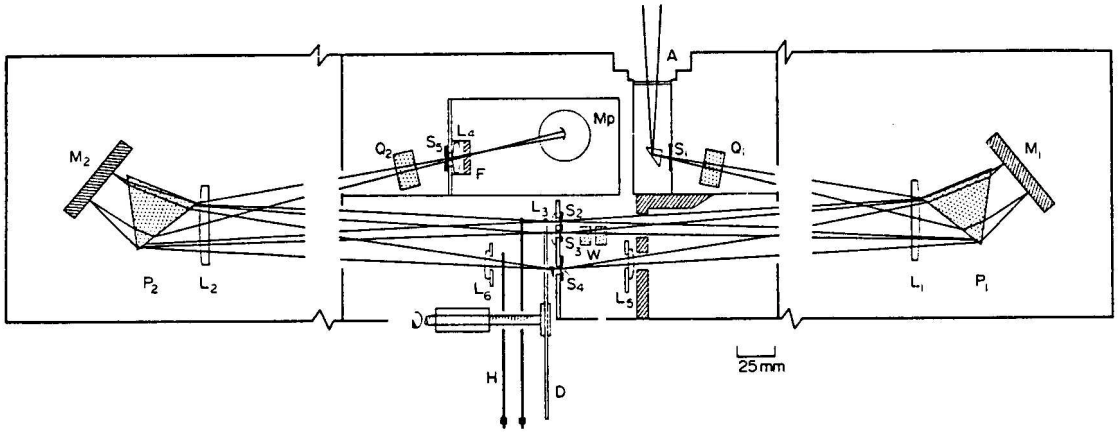

Figure 1: Schematic of the design of the Dobson spectrophotometer (see text) [Walshaw, 1989].

longer (higher intensity) wavelength until the difference in the intensities of the two wavelengths becomes zero (measured by Mp). The reading of the instrument is expressed as the position of W where the difference of the intensities measured at Mp is zero. A second prism (P2) recombines the dispersed radiation onto the exit slit (S5) where it is measured by Mp. The use of the double monochromator minimizes stray light scattered internally within the instrument. Thus, the difference of intensities of the wavelengths, and not the absolute intensities of the single wavelengths, is measured by Dobson spectrophotometers.

The basic formula to calculate the TO_3 amount by a Dobson spectrophotometer from a single wavelength pair observation is:

$$X = \frac{N - \tilde{\beta}\, m_p - \tilde{\delta}\, (\cos\vartheta)^{-1}}{\tilde{\alpha}\, \mu} = \frac{N}{\tilde{\alpha}\, \mu} - \left\{ \frac{\tilde{\beta}}{\tilde{\alpha}} \frac{m}{\mu} + \frac{\tilde{\delta}}{\tilde{\alpha}} \frac{(\cos\vartheta)^{-1}}{\mu} \right\} \qquad (1)$$

where:

- X: TO_3 (total ozone amount)

- $N = L_0 - L = \log \frac{I_0}{I_0'} - \log \frac{I}{I'}$

The symbol ' refers to the longer wavelength.
- I/I': ratio of intensities measured by the Dobson spectrophotometer at Earth's surface.
For meaningful measurements a Dobson spectrophotometer needs a wedge calibration.
- I_O/I_O': ratio of intensities outside the atmosphere, as it would be measured by the specific Dobson spectrophotometer (also called extraterrestrial constants (ETC)). This ratio can be directly determined by the Langley Plot method (see below) or indirectly by transfer from another (reference) instrument.

- $\tilde{\beta} = \beta - \beta'$; $\quad \tilde{\alpha} = \alpha - \alpha'$; $\quad \tilde{\delta} = \delta - \delta'$

where: β: Rayleigh scattering coefficient $\quad m_p$: relative optical air mass
δ: particle scattering coefficient $\quad \theta$: solar zenith angle
α: ozone absorption coefficient $\quad \mu$: optical air mass for the ozone layer

Two wavelength pairs (AD-wavelengths) for observations of TO_3 have been selected for the world standard measurements at the IGY in order to minimize the influence of aerosol interference

[Dobson, 1957a; 1957b; Komhyr, 1980]. The TO_3 amount from the AD-wavelength pairs is derived by the following formula:

$$X_{AD} = \frac{N_A - N_D}{\tilde{\alpha}_A - \tilde{\alpha}_D}\frac{1}{\mu} - \frac{\tilde{\beta}_A - \tilde{\beta}_D}{\tilde{\alpha}_A - \tilde{\alpha}_D}\frac{m_p}{\mu} - \frac{\tilde{\delta}_A - \tilde{\delta}_D}{\tilde{\alpha}_A - \tilde{\alpha}_D}\frac{(\cos\theta)^{-1}}{\mu} \quad (2)$$

The indices A and D relate to the wavelength pairs listed in Table 1. The last term of equation (2) can be neglected because particle scattering is only weakly dependent on the wavelength in this part of the spectrum yielding the following equation:

$$X = \left(\frac{N_A}{\mu_A} - \frac{N_D}{\mu_D}\right)\frac{10}{\tilde{\alpha}_{AD}} - A_{COR}\frac{m}{\mu_{AD}} \quad (3)$$

where the atmospheric correction (A_{COR}) is defined as:

$$A_{COR} = \frac{\tilde{\beta}_{AD}}{\tilde{\alpha}_{AD}} 1000 \frac{p}{p_o} \quad (4)$$

where p is the mean pressure at the measuring station and p_o is the standard pressure (1000 hPa).

The stability of the instruments is routinely checked by mercury and standard lamp tests (monthly). The standard lamp tests are also used to apply corrections to the readings if necessary [Komhyr, 1980]. The calibration of the Dobson instruments is based on the Langley plot method, which determines the instrumental (extraterrestrial) constants by plotting the readings against the solar zenith angle, and extrapolating it to outside the atmosphere. However, the Langley plot determination is problematic at mid and high latitudes because of the large natural daily variability of TO_3. The Langley plot method is applied to one single instrument in the Dobson network (the primary Dobson instrument, D83). The measurements are performed at the Mauna Loa Observatory at Hawaii. The primary world Dobson instrument is maintained at the Climate Monitoring and Diagnostics Laboratory (CMDL) of the National Atmospheric and Oceanic Administration (NOAA) at Boulder, Colorado, USA (World Dobson Calibration Center (WDCC)). The primary Dobson instrument (or recently usually the secondary instrument (D65) calibrated by the primary instrument through simultaneous measurements) is subsequently transported to selected sites, where the operationally used instruments are compared with the standard instrument in Dobson intercomparisons. The instrumental constants of the individual instruments are deduced from such intercomparisons with the standard instruments. The operational instruments are controlled and corrected (if necessary) by regular Dobson intercomparisons (e.g. wedge calibrations are performed if required). The procedure of these intercomparisons, which run under the control of the Global Atmospheric Watch program of WMO, is well established and the results are documented by reports available to the community [e.g. Basher, 1995; Komhyr et al., 1989a; Grass et al., 1994 and other GAW reports]. Recently this concept was modified. Regional Dobson Calibration Centres (RDCC) were introduced, which are responsible for the intercomparisons and the evaluation of the measurements. Their work also includes the processing of the data, the determination of corrections (if required) and the publication of the results. The European operational instruments are compared by the RDCC of Europe with the regional (German) reference instrument and not anymore directly with the primary or secondary Dobson instrument of CMDL. The Meteorological Observatory at Hohenpeissenberg of the German Weather Service (see 4.4) is now operating the RDCC of Europe in close collaboration with the Solar and Ozone Observatory of the Czech Hydrometeorological Institute at Hradec Kralove. The Ozone Layer Monitoring Unit of the Japanese Meteorological Agency (JMA) operates in the same way as RDCC for the Asian region. Similar RDCCs are created under the umbrella of the GAW program for South America (Buenos Aires, Argentina) and for Africa (Pretoria, South Africa).

Careful data analysis showed that the primary Dobson instrument, which is regularly calibrated by the Langley plot method at Hawaii, has a long-term stability of better than 1% [Komhyr

et al, 1989b]. The calibration of the individual Dobson spectrophotometers by comparison with the standard instrument introduces an additional uncertainty, which is also expected to be less than ±1% as documented in GAW reports.

The most precise measurements of TO_3 can be obtained by direct sun observations. TO_3 can also be determined from blue or cloudy zenith sky measurements, however with lower precision. For that purpose an empirical cloud sky chart based on quasi simultaneous direct sun and zenith sky measurements has to be constructed [De Backer, 1998, comp. Sect. 4.2 ; Stanek et al., 1998]. At many sites zenith sky observations under cloudy conditions are required to obtain a sample of observations, which is representative enough for reliable long-term monitoring.

2.2 Brewer spectrophotometer

The design of the Brewer spectrophotometer is shown in Figure 2 and the wavelengths used for measurements are listed in Table 1. Holographic gratings are used to disperse (solar) radiation passing through the entrance slit [Kerr et al., 1981; 1985]. The measurements of column ozone (and of column sulfur dioxide (SO_2) and nitrogen dioxide (NO_2), see below) are based on the measurements of the photocounts at the selected wavelengths of the solar light. An automated sun tracker aligns the instrument into the proper position for the measurement. The instrument is designed for fully automated operation. The type of measurement (direct sun or other type of TO_3 measurements, Umkehr or UV-B) and its sequence can be programmed by the operator. The Brewer instrument allows the simultaneous determination of column ozone and of column sulfur dioxide (SO_2). Most Brewer instruments (Mk II) use one single holographic grating and therefore only one dispersive element ("single Brewer"). Mk III Brewer instruments are double monochromators that use two holographic gratings ("double Brewers"). The Mk IV Brewers are based on one holographic grating and have the option to measure column NO_2 amount in addition.

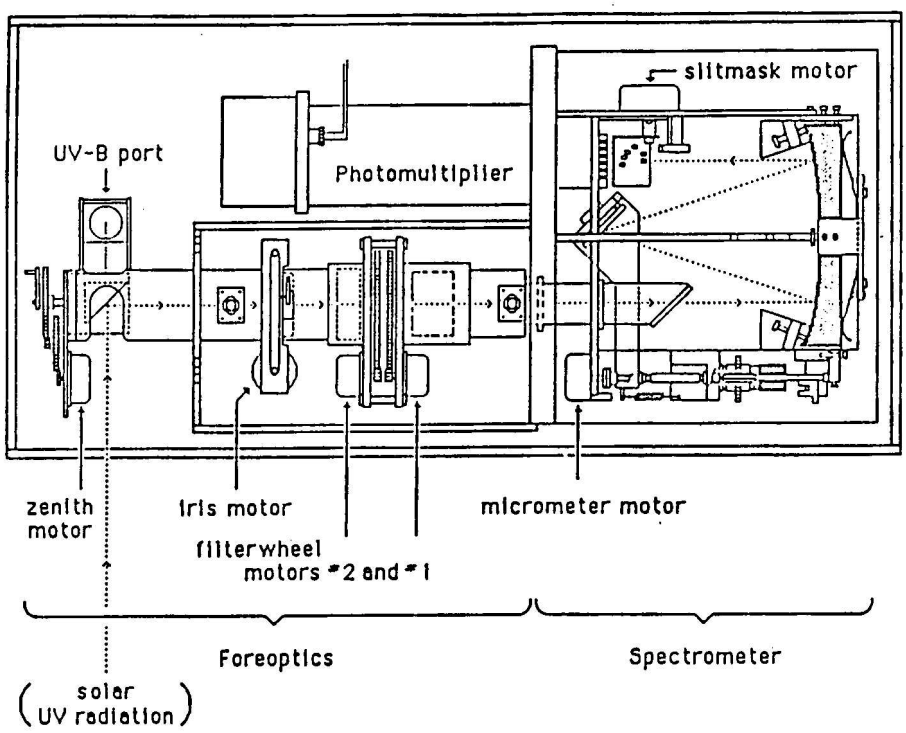

Figure 2: Design of the Brewer spectrophotometer, type MK II [from Evans et al., 1987].

Atmospheric SO_2 and NO_2 are interferences in TO_3 measurements by Dobson spectrophotometers [Komhyr and Evans, 1980; De Backer and De Muer, 1991]. In order to correct Dobson spectrophotometric TO_3 measurements one has to subtract the SO_2 amount (measured by a Brewer instruments) times a correction factor from the Dobson readings. Somewhat different values of these correction factors have been used, based on theoretical considerations [1.53:

Komhyr and Evans, 1980] or field measurements [1.41: De Backer and De Muer, 1991; 1.06, Kerr et al., 1988, comp. 4.3].

TO_3 amount is calculated by the following formula from the Brewer measurements:

$$X = MS11 = \frac{MS9 - B1}{A1\,M2} \tag{5}$$

where:
- *MS9 = MS5 - 0.5 MS6 - 1.7 MS7*
- *MS5*, *MS6*, *MS7* are the measurements of the intensities at the different wavelengths (see Table 1)
- *M2* is the optical air mass, determined by:

$$M2 = \sec(\arcsin(\frac{R}{R+Z}\sin(SZA)))$$

where:
- R: Earth's radius (6370 km) and Z is the ozone layer height (22 km)
- SZA the solar zenith angle
- *B1* is the extraterrestrial constant for the wavelengths used for ozone measurements
- *A1* is the differential ozone absorption coefficient for the ozone measurements determined by a linear combination of ozone absorption coefficients of different wavelengths selected by the slit mask for ozone measurements.

B1 and *A1* are instrumental constants that are determined by comparisons with a standard instrument and checked or updated by the intercomparison with the traveling standard instrument. Lamp tests are performed every day as part of the recommended program of automatic measurements, which can be adapted by the operators.

The calibration of the Brewer instruments is based on the Langley plot calibration at the Mauna Loa Observatory at Hawaii as well as in the Dobson network, but the operating procedures differ from those used in the Dobson network. A triad of Brewer instruments is maintained by MSC (Meteorological Service of Canada) at Toronto, Canada, and one of them is shipped in regular intervals to the Mauna Loa Observatory at Hawaii for Langley plot calibration [Kerr et al., 1998]. The WMO travelling standard instrument is calibrated with the Brewer triad through side by side measurements. The WMO standard instrument is subsequently transported to the operational instruments at the measuring stations for regular calibrations and check of the calibrations. This service is offered by a private company (International Ozone Service Inc. (IOS)) and the manufacturer of the instruments (Kipp and Zonen).

2.3 Summary of differences between Dobson and Brewer measurements

Instrument design. Measurements by both types of instruments are based on sun photometry and the TO_3 is derived from the absorption of solar light in the Huggins band. However, the Dobson spectrophotometer is based on the measurements of the ratios of two wavelength pairs, while the Brewer spectrophotometer measures photocounts at 5 wavelengths allowing the simultaneous measurement of ozone and of SO_2 column amount. For the separation of the wavelengths the Dobson instruments use 2 and the Brewer 5 slits. The field of view is 8^o for Dobson and 3^o for Brewer instruments. Dobson instruments have two prisms to separate the respective wavelengths, while Brewer instruments use one or two dispersive elements (holographic gratings). The Brewer instruments are commercially available and designed for completely automated operation.

Wavelengths pairs and their dependence on temperature. The ozone absorption in the Huggins band depends on temperature [Komhyr et al., 1993]. The operational algorithms for retrieval of column ozone for both instrument types (equations (3) and (5)) ignore the temperature dependence of the ozone spectrum. They are based on the absorption cross sections at -46.3^o C. However, during the annual cycle temperature in the stratosphere varies together with the vertical ozone

distribution. In addition to the typical seasonal variation temperature and ozone profiles at mid and high latitudes can strongly change from one day to another. Since the total ozone measured from ground is the integral over the atmospheric profile weighting over the temperature and the ozone profile is required to fully account for this variability. (This approach is explored in Section 4.5.) Komhyr et al. [1993] discussed several problems that limit the accuracy of Dobson direct sun observations such as slit functions, μ-dependence and others including the temperature dependence of ozone absorption cross sections. For averaged ozone/temperature variability at mid-latitude stations they calculated an impact of 0.13% ozone change per degree Celsius temperature change. (This approach was used for TO_3 comparison of Dobson and Brewer instruments in Section 4.4).

The wavelengths used in the two types of instruments are different (see Table 1). The temperature sensitivity in the Huggins band varies with wavelength. The ozone cross sections of the wavelengths used in Dobson and Brewer instruments are shown in Table 2 for different temperatures (as used in the algorithm of the GOME satellite instrument from Burrows et al., [1999]). In Figure 3 and 4 the ratios of the absorption cross sections of the ozone spectrum (smaller wavelength divided by longer wavelength) are shown as a function of temperature for the wavelength pairs of the Dobson instrument in Figure 3 and for the wavelengths used in Brewer spectrophotometry in Figure 4. (e.g. for wavelength pair A in Dobson spectrophotometry σ(305.5 nm/σ(325 nm) was calculated for the individual temperatures) (from Lehmann [2001]). The comparison indicates that the wavelengths used in TO_3 measurements in Dobson spectrophotometry are more susceptible to stratospheric temperature variation than those of the Brewer instrument, in particular because of the wavelength pair D. Temperature and ozone measurements over the station are needed to account for the temperature effect of the ozone spectrum for calculation of the TO_3 amount.

Table 2: Ozone absorption cross sections σ [cm^{-2}] for the wavelengths used in Dobson and Brewer spectrophotometers at five temperatures as used in the GOME flight model (FM) [from Burrows et al., 1999].

Wavelength (nm)	Temperature (K) 202	221	241	273	293
Dobson instruments					
A: 305.5	$1.56\ 10^{-19}$	$1.59\ 10^{-19}$	$1.64\ 10^{-19}$	$1.75\ 10^{-19}$	$1.84\ 10^{-19}$
325.4	$1.14\ 10^{-20}$	$1.17\ 10^{-20}$	$1.22\ 10^{-20}$	$1.34\ 10^{-20}$	$1.45\ 10^{-20}$
D: 317.6	$3.43\ 10^{-20}$	$3.47\ 10^{-20}$	$3.56\ 10^{-20}$	$3.81\ 10^{-20}$	$4.05\ 10^{-20}$
339.8	$7.29\ 10^{-22}$	$8.00\ 10^{-22}$	$9.25\ 10^{-22}$	$1.28\ 10^{-21}$	$1.57\ 10^{-21}$
Brewer instruments					
303.2	$2.15\ 10^{-19}$	$2.19\ 10^{-19}$	$2.26\ 10^{-19}$	$2.39\ 10^{-19}$	$2.50\ 10^{-19}$
306.3	$1.51\ 10^{-19}$	$1.53\ 10^{-19}$	$1.57\ 10^{-19}$	$1.66\ 10^{-19}$	$1.73\ 10^{-19}$
310.1	$8.29\ 10^{-20}$	$8.50\ 10^{-20}$	$8.81\ 10^{-20}$	$9.49\ 10^{-20}$	$1.00\ 10^{-19}$
313.5	$5.93\ 10^{-20}$	$5.99\ 10^{-20}$	$6.15\ 10^{-20}$	$6.33\ 10^{-20}$	$6.91\ 10^{-20}$
316.8	$2.96\ 10^{-20}$	$3.09\ 10^{-20}$	$3.25\ 10^{-20}$	$3.62\ 10^{-20}$	$3.91\ 10^{-20}$
320.1	$2.55\ 10^{-20}$	$2.58\ 10^{-20}$	$2.65\ 10^{-20}$	$2.84\ 10^{-20}$	$3.03\ 10^{-20}$

Calibration. The primary reference instruments of both networks are calibrated by the Langley plot method performed at the Mauna Loa Observatory at Hawaii. Dobson instruments require wedge calibrations. The Dobson network relies on one single instrument, the primary Dobson instrument, which is maintained by the group of CMDL (WDCC). The measurements of this instrument (D83) are used to calibrate a secondary instrument (D65), which is (was) mostly used for side by side calibration of the instruments operated at the stations. Such intercomparisons are organized by WMO. The operational instruments are checked after the initial side by side calibration in regular intervals. The periods between these calibrations should not exceed 4 years. The procedure of these intercomparisons has been highly standardized and resulted in a gradual improvement of the data quality of the Dobson network [Basher, 1995]. All calibration measurements were processed by CMDL in the past and the results of these intercomparisons were published in WMO/GAW reports or other publications, which are open to all interested scientists. The intercomparisons usually last for 3

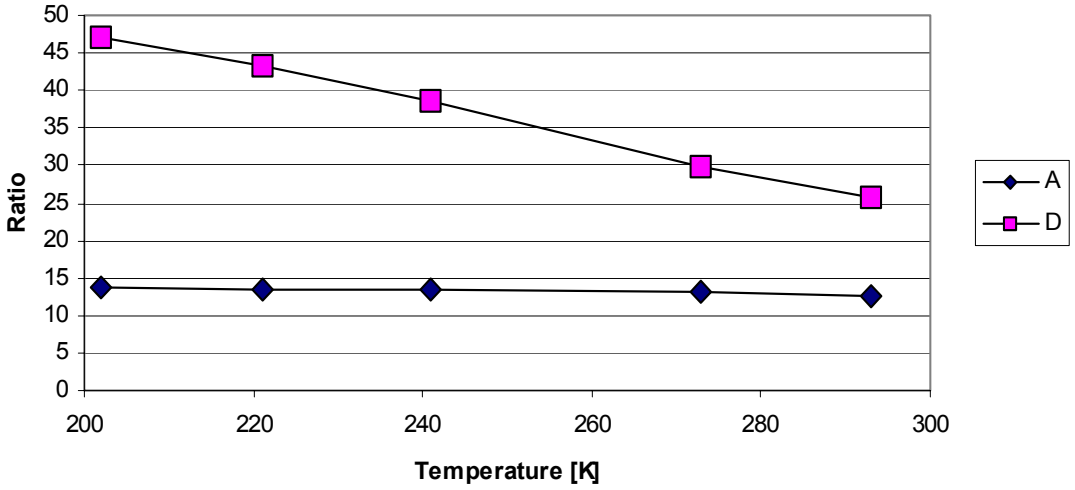

Figure 3: Ratios of the cross sections of the ozone absorption of the wavelength pairs used in Dobson spectrophotometry as a function of temperature [see. Table 2; from Lehmann, 2001]. The ratios were calculated by division of the cross section at the lower wavelength by those at the higher wavelength. For abbreviations of wavelength pairs A and D see Table 1.

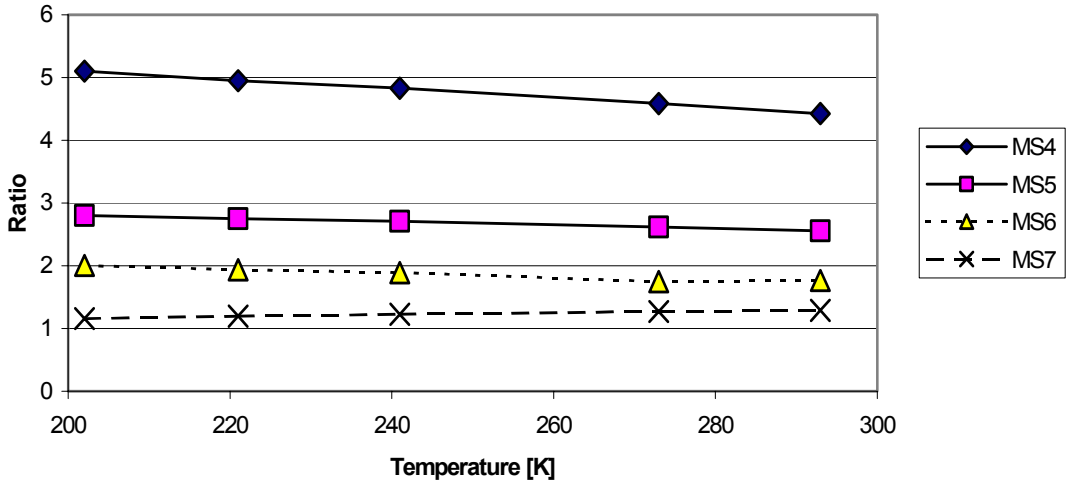

Figure 4: Ratios of the ozone absorption cross sections of the wavelength pairs used in TO_3 determination of Brewer instruments as a function of temperature [see Table 2, from Lehmann, 2001], calculated in the same way as in Figure 3. For abbreviations of wavelength pairs see Table 1.

weeks leaving room for training of the operators and staff persons. This procedure has been changed recently in the GAW Dobson network. The European standard instrument (D64) is currently used for comparison with the European operational instruments and the Meteorological Observatory Hohenpeissenberg acts as Regional Dobson Calibration Centre (RDCC) of Europe in close collaboration with the Solar and Ozone Observatory Hradec Kralove (Czech Republic). The results of the intercomparisons of 2000 and 2001 including 13 tested instruments were published recently [Köhler, 2001]. Instrument D116 will be used for the comparison of the operational instruments of Asia (RA-II) and the Ozone Monitoring Unit of JMA is responsible for the RDCC of Asia. Instrument D116 was compared and calibrated by the world standard instrument (D83) at Mauna Loa Observatory in 2001 and it will be used for regular regional calibration campaigns of RA-II at the observatory of JMA at Tskuba starting in 2003.

The Brewer network is based on a triad of instruments, operated by MSC at Toronto, Canada, from which one of the instruments is periodically selected for Langley plot calibration at Mauna Loa Observatory at Hawaii. The side by side comparison of the station Brewer instruments with the WMO Brewer traveling standard instrument is more dependent on the individual initiative of

the operating institutions that also have to fund this service. No comparison of a large number of instruments is usually done, since the standard instrument is transported from one to another field instrument. This avoids the transport of the operational instruments, which needs to be carefully positioned because of the automatic sun tracking of the Brewer spectrophotometers. The intercomparisons are performed by a private company (International Ozone Service Inc. (IOS) or by the manufacturer (Kipp and Zonen)), which only reports to the owner of the instruments. No official procedure of reporting the results of the intercomparison of the operational instruments with the standard instruments is presently adopted in the Brewer network. The lack of such a central archive limits the traceability of the long-term stability of the worldwide Brewer ozone network.

3. POSSIBLE FACTORS CONTRIBUTING TO THE DIFFERENCES BETWEEN DOBSON AND BREWER MEASUREMENTS AND APPROACHES FOR COMPARISON

3.1 Possible factors for the differences

Figure 5 shows the typical features when the seasonal variation of TO_3 measurements of a Dobson and a Brewer instrument of a mid-latitude station are compared. In this and the following discussion we assume well-calibrated and maintained instruments. Any technical problem including robustness of the instruments, manpower and other costs are ignored. The Dobson and the Brewer readings are assumed to be calculated by the Bass-Paur scale as recommended by WMO [Komhyr et al., 1993]. On annual average, Brewer and Dobson readings only differ from each other by a small amount but the calculated TO_3 amounts show a typical seasonal variation. Different factors possibly contribute to these differences, which can exceed the precision of the single measurement. They might include:

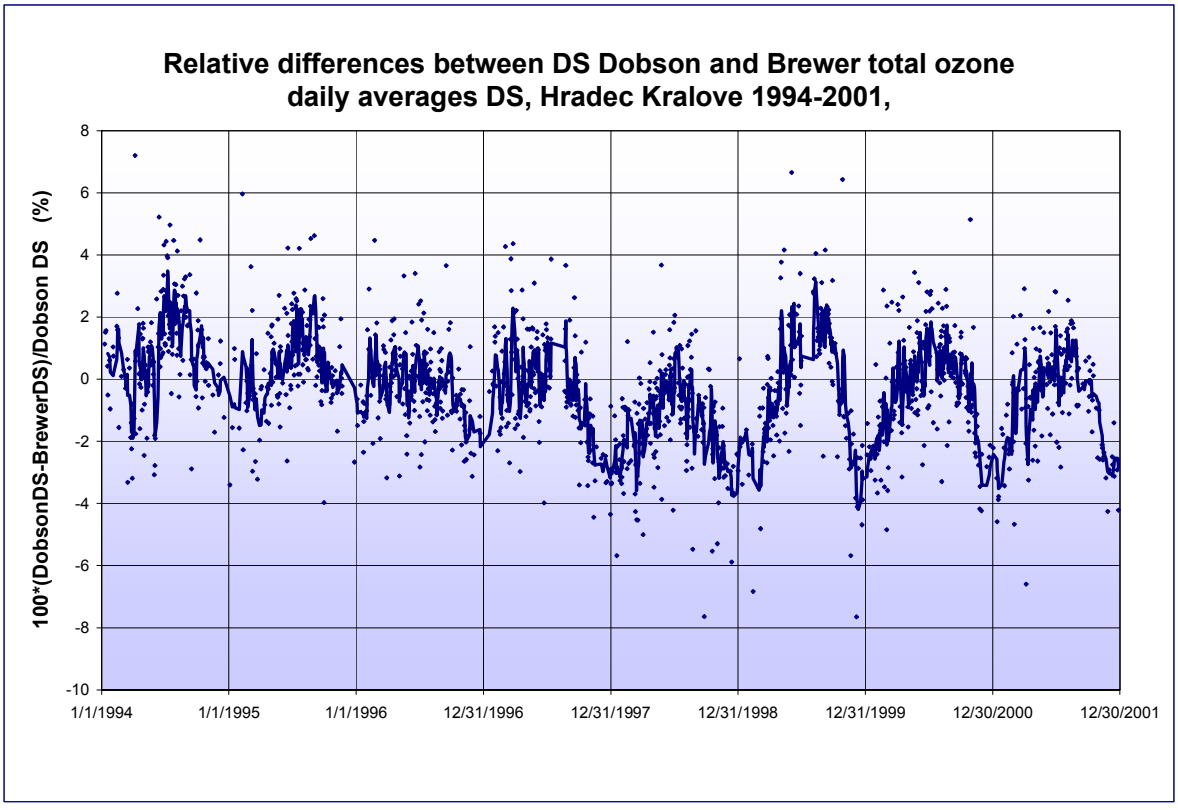

Figure 5: Typical seasonal variation of the relative differences of direct sun TO_3 daily mean measurements of a Dobson (D74) and a Brewer (B98) instrument, operated at Hradec Kralove, Czech Rep. [comp. Table 3 and Vanicek, 1998]; if zenith sky observations are also included the amplitude of the seasonal variation of the difference becomes much smaller.

1. Sulfur dioxide is known to interfere with TO_3 measurements in Dobson spectrophotometry by absorbing UV at the same wavelengths as ozone. For the proper comparison of column ozone, SO_2 amount measured by the Brewer spectrophotometer needs to be subtracted from the TO_3 amount measured by the Dobson instrument (comp. Sect. 2.2), which is significant at polluted areas [De Muer and De Backer, 1992]. However, at remote and Alpine sites the pollution by SO_2 is very small and can be neglected [Staehelin et al., 1998].

2. Since TO_3 measurements are not based on the same wavelengths in both instruments, different seasonal variations of TO_3 are expected. Temperature in the stratosphere has a typical seasonal variation that affects TO_3 readings of Dobson spectrophotometers more strongly than those of Brewer instruments (compare Figures 3 and 4).

3. The design of the instruments is different, which has to be considered when comparing the results of the two types of instruments (e.g. potential internal stray light problems, possibly affecting the measurements at low solar angles). Furthermore, differences in the retrieval algorithms used for TO_3 determination need to be considered (e.g. the calculation of the air mass of ozone is different in the algorithms of the two types of instruments) and the field of the view of the instruments is different. Dobson instruments ”see” light that was scattered into the view more readily than the Brewer instrument. This scattered light affects the calculated ozone value from the Dobson measurements at high TO_3 values and low sun angles. Such a dependence of an instrument can introduce a seasonal bias to the TO_3 measurements, which can be particularly important at mid and high latitude stations.

4. Both instrument types are calibrated by the Langley plot method at the Mauna Loa Observatory at Hawaii, but the calibrations are organized differently including different institutions (comp. Section 2.3). Therefore, problems in the calibration of one or the other network leading to inconsistencies cannot be ruled out a priori. Every calibration of an instrument introduces some uncertainty and every instrument has its own characteristics. However, if the features of the single instruments and its calibrations would completely dominate such comparisons, no general characteristics of the instrumental comparisons could be expected.

5. Instrumental temperature can influence solar UV radiation measurements by Brewer instruments as shown by Weatherhead et al. [2001]. However, this temperature dependence is corrected in the discussed measurement of TO_3.

3.2 Approaches for the comparison

Different approaches for the comparisons of the measurements of the two instrument types can be selected. Typical features when plotting the time series of differences between Dobson and Brewer measurements at mid-latitudes are shown in Figure 5. For polluted sites, SO_2 amount should be subtracted from the Dobson measurements to make the measurements of TO_3 more comparable (see Section 2.2).

Monthly mean values can be used for comparison, which could be obscured by the large day to day variability of ozone at extratropical sites if the measurements are not available from the same days. A comparison of daily means is another option. Daily mean comparison could lead to some scatter in the data, if TO_3 significantly changes during the day and if observations of Brewer and Dobson instruments are performed at different times. This could make the comparison more susceptible to the representativity of the daily mean values introducing additional uncertainty.

The comparison of quasi-simultaneous measurements, using small intervals in solar zenith angle and time, is most suitable for more detailed investigations. By this procedure the variability in atmospheric ozone can be excluded as reason for differences in the readings of the instruments (ignoring differences in the field of view of the two types of instruments, see 3.1). The effect of the stratospheric temperature on the measurements can be estimated, if atmospheric temperature and ozone profile information is available (see 4.4. and 4.5.). Ozonesonde measurements are suitable for a detailed comparison, if regularly launched from the respective sites. Plots of the differences as a function of the solar zenith angle have been used to characterize the instrumental differences (see

4.3). Such comparisons need an extended data set of quasi-simultaneous measurements (including many more measurements than one single Dobson observation per day) for construction of a precise transfer function of the two types of instruments.

Table 3: TO_3 measurements of collocated Dobson (D) and Brewer (Br) instruments. Mark III Brewer instruments are specially marked

Station and instruments	**Start of simult. measurements** [1)]	**Remarks and documentation**
Toronto (Canada) (43.8°N) (D77, Br8)	1983	simultaneous measurements for Toronto [Kerr et al., 1988; Kerr, 2002]
Uccle (Belgium) (50°5'N) (D40, Br16)	1983	strong interference by local SO_2 pollution in the 1980s [De Backer and De Muer, 1991; De Muer and De Backer, 1992; De Backer, 1998]
Hohenpeissenberg (Germany) (47.8 °N) (D104, Br10)	1983	rural site [Köhler and Attmannspacher, 1986; Köhler et al., 1989; Köhler, 1995].
Potsdam (Germany) (52.2°N) (D71		[Feister, 1991; Spänkuch et al., 1999]
Br30	1987	
Br118 (Mk III))	1996	
Arosa (Switzerland) (46.5°N) (D101, D62 (since 1992),		Alpine site [Staehelin et al., 1998; Hoegger et al., 1992, Lehmann, 2001]
Br40	1988	
Br72	1991	
Br156(MkIII))	1998	
Boulder (Co., USA) (40.0°N)	Nov. 1988 - March 1989	only restricted simultaneous measurements from November 1988 to March 1989 [Diaz et al., 1990a and b]
Lisbon (Portugal) (38.8°N) (D13, Br47)	June 1989-June 1992, since July 2001	[pers. commun. D. Henriques, 2002]
Reykjavik (Iceland) (64.1°N) (D50, Br"001", instr. of Univ. Thessaloniki Greece)	Nov. 1991-Aug. 2001	[pers. commun. B. Thorkelsson]
Scott Base (Antarctica) (78° S) (D17, Br50)	Sept.-Oct. 1991	during formation of ozone hole [Nichol and Valenti, 1993]
Belsk (Poland) (51.8°N)	1992	[pers. commun. M. Degorska and B. Rajewska, 2001]
Hradec Kralove (Czech. Rep.) (50.2°N) (D74, Br98)	1994	see Figure 5 [Vanicek, 1998]
Vindeln (Sweden) (64.2°N) (D30, Br06)	1996	High latitude station [Josefsson, 2000; Josefsson, 2002]
Troms (Norway) (69.7°N) (D14, Br104 (Mk III))	June 1994-Oct. 1999	[pers. commun. K. Edvardsen]
Bankok (Thailand) (13.7°N) (D90, Br121)	1996	[pers. commun. S. Sudhibrabha]
El Arenosillo (Spain) (37.1°N) (D120, Br150(Mk III))	1997	[pers. commun. J.M. Vilaplana, 2002]
Camborn (50.2°N) **and Lerwick** (60.1°N) **(UK)**		simultaneous Brewer and Dobson data of several years [Moore, pers. commun., 2001]
Lauder (New Zealand) (45°S) (D72, Br171)	Nov. 2001-Febr. 2002	[G. Bodeker, pers. commun., 2002]
Fairbanks (Alaska, USA) (64.7°N) (D83, D63, B7 and B85 (MkIII))	March-April 2002	Total Ozone Measurements by Satellites, Sondes and Spectrometers at Fairbanks field campaign (TMS3-F)

[1)] Period of measurements if simultaneous measurements are not continuously ongoing

4. SUMMARY OF REPORTED RESULTS

4.1 Overview of simultaneous Dobson and Brewer measurements

In this section we show examples of different approaches of comparison for TO_3 measurements of Dobson and Brewer instruments, which have been documented in the literature or in reports. An overview of the sites where simultaneous Dobson and Brewer measurements are available and the reports of studies and papers available to us are given in Table 3. Table 3 shows that a large number of long-term simultaneous measurements known to us originate from European stations. (Note that the results of Dobson-Brewer comparisons from individual stations given in the following sections are deduced from different periods of measurements and calibrations of instruments. For other periods the differences can be significant – see for example monthly means of TO_3 deposited in WOUDC for Toronto 1988-1995 and 1996-2001, Arosa 1988-1989 and 1990-2001, Belsk 1993-1994 and 1995-2001; such differences might originate from calibration problems).

4.2 Comparison of measurements at Uccle (Belgium): SO_2 influence

Simultaneous Brewer and Dobson measurements started at Uccle in Belgium in 1983 [De Backer and De Muer, 1991]. Uccle is close to the capital Brussels, which was strongly affected in the past by the primary pollutant sulfur dioxide. SO_2 column amount from the Brewer measurements was subtracted from the TO_3 amount measured by the Dobson spectrophotometer yielding much better agreement between the readings of the Dobson and the Brewer instrument [see Figure 6 and De Muer and De Backer, 1992]. Brewer SO_2 column amount strongly decreased during the 1980s because of more stringent air pollution legislation. De Muer and De Backer [1992] were able to subtract a fictitious trend in the Dobson series by using a model connecting SO_2 column readings with long-term surface SO_2 monitoring measurements. The operational measurements at this station also include zenith sky observations, both with Dobson and Brewer instruments which are required because of many temperature inversions in this region preventing direct sun observations [De Backer, 1998]. The zenith measurements are separated into zenith blue and zenith cloudy observations. For the zenith blue values a polynomial is fitted by a least square method based on quasi-simultaneous direct sun and zenith observations. For the observations with clouds a correction depending linearly on TO_3 is introduced. By this empirical correction the mean differences between daily mean values of direct sun and zenith observations are -(0.1+/-1.6)% for the Dobson and -(0.1+/-1.5)% for the Brewer observations [De Backer, 1998].

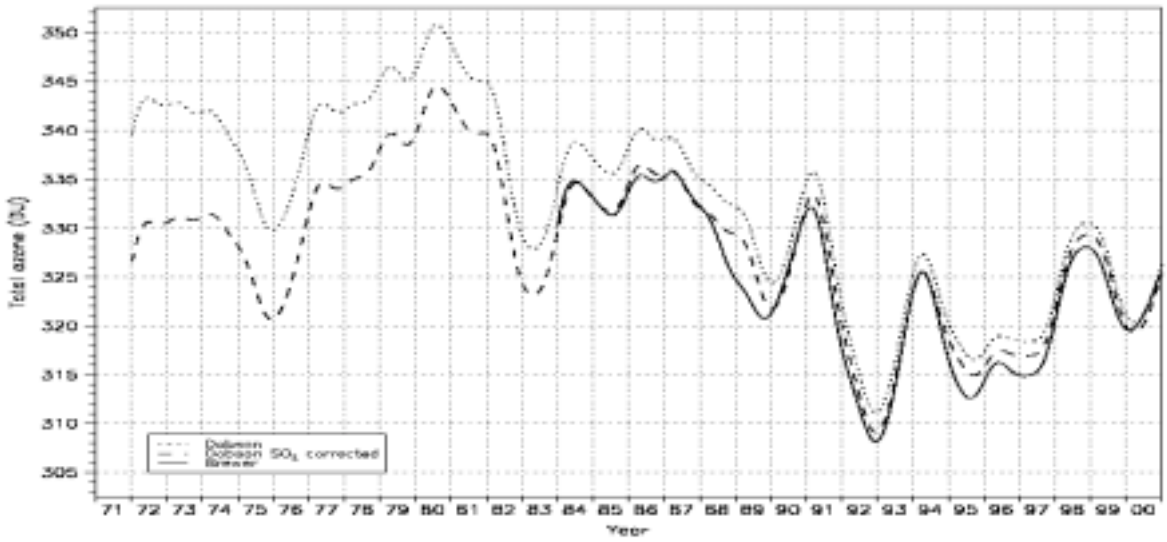

Figure 6: Time series of TO_3 measurements of a Dobson (D40) and Brewer (Br16) instrument operated at Uccle (Belgium), including Dobson observations without correction and Dobson measurements with correction of SO_2 column amount (by subtraction of 1.41 times SO_2 measurements of the Brewer instrument) compared with TO_3 measurements of a Brewer spectrophotometer [pers. commun. H. De Backer, 2002].

4.3 Comparison of measurements at Canadian stations: Removal of SO_2 interference, differences in μ-dependence and effective ozone temperature

In the Canadian network, Brewer instruments replaced almost all Dobson spectrophotometers in 1988 after simultaneous measurements of both types of instruments, which started in 1983 [Kerr et al., 1988]. The longest series of simultaneous measurements stems from Toronto, where a Dobson spectrophotometer is still in operation. The simultaneous Brewer and Dobson measurements of Toronto were carefully analyzed for the period of 1983 to 1987 [Kerr et al., 1988]. The measurements were treated first by removing SO_2 amount from the Dobson data. In the second step the differences of the quasi-simultaneous measurements were characterized by plotting their differences against μ , yielding a linear dependence (see Figure 7). The authors pointed out that such a μ dependence would be expected in case of an erroneous calibration of one of the instruments. However, this was very unlikely in case of these measurements, because the Dobson instrument was calibrated by the Langley plot method at the Mauna Loa Observatory at Hawaii in July-August 1980 and the Brewer spectrophotometer in May-June 1983 and again in March-April 1987. The Brewer instrument is part of the Brewer triad operated by MSC at Toronto. In the next step of the analysis the μ difference was removed. The different temperature sensitivities of the wavelengths of the two instruments was believed to be the most likely cause for the systematic differences between the readings of the two instruments because of the simultaneous seasonal variation of stratospheric temperature.

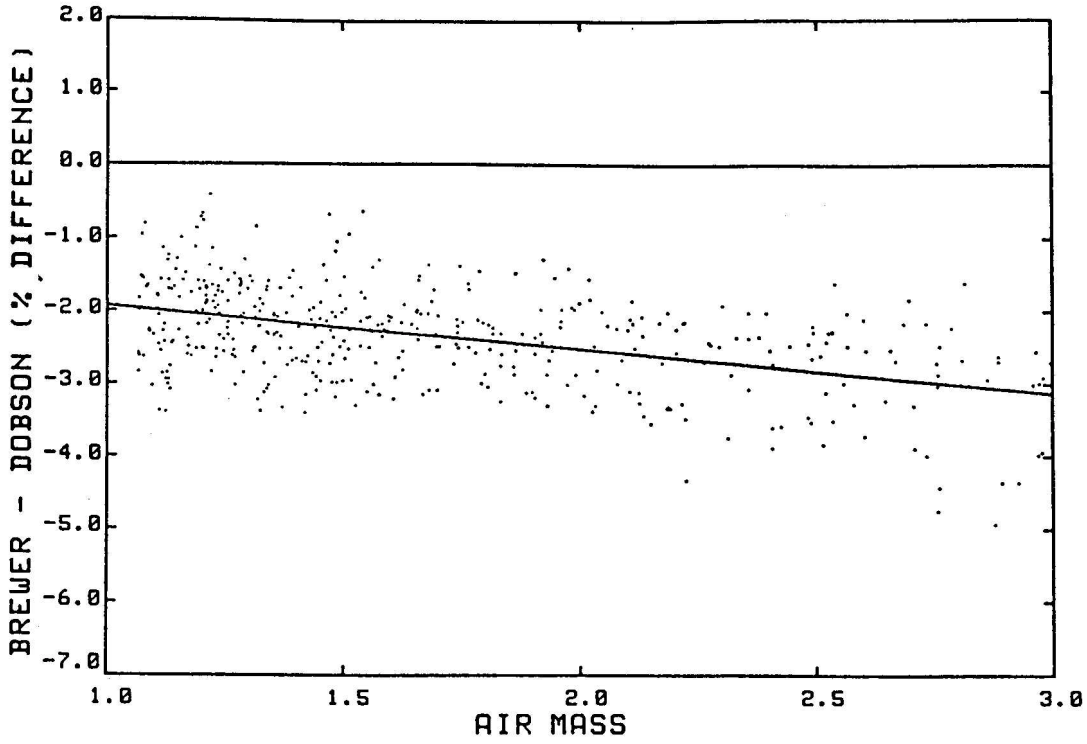

Figure 7: Relative differences of TO_3 measurements of a Dobson (D77) and a Brewer (Br8) instrument at Toronto (Canada) plotted as a function of the air mass [Kerr et al., 1988] (note: Dobson data are given in the old (Vigroux) scale whereas Brewer data are presented in the Bass Paur scale).

The authors used the following formula for simulation of the Dobson from the Brewer measurements:

$$X_{Dob} = K\, X_{Br} + \frac{\varepsilon}{\mu} \qquad (6)$$

where: - X_{Dob}: Dobson TO_3 observations corrected for SO_2

- X_{Br}: Brewer TO_3 observations
- K: constant
- μ: air mass of ozone
- ε: air mass dependent difference of the measurements of the two instruments.

By dividing equation (6) by X_{Br} the ratios of the readings of the two instruments are described. By a regression of X_{Dob}/X_{Br} against $1/\mu X_{Br}$, the slope (ε) and intercept (K) is obtained:

$$\frac{X_{Dob}}{X_{Br}} = K + \frac{\varepsilon}{\mu X_{Br}} \tag{7}$$

The regressions were calculated for the individual months between April and August, in which the μ-range is large enough to obtain a reliable fit. Finally the following transfer function was used to simulate Dobson from the Brewer values:

$$X_{simD} = K\,[1 - 0.005 \cos(JD)]\, X_{Br} - 8.1/\mu + 0.106\, SO_2 \tag{8}$$

Where:

- X_{simD}: Dobson TO_3 value simulated from Brewer TO_3 measurements.
- JD: Julian day
- X_{Br}: Brewer TO_3 value
- μ: air mass of ozone
- SO_2: Brewer column measurements of SO_2.

Kerr [2002] recently introduced a new method (group-scan method) in which the rapid sampling (by a mask) of the 5 wavelengths of a Brewer instrument (see Table 1) is combined with a slower spectral scanning (carried out by rotation of the grating). This yields one scan over 45 wavelengths, which are treated by a modified DOAS (Differential Optical Absorption Spectroscopy) technique. The rather sophisticated data analysis allows the calculation of the mean effective ozone temperature (together with the Aerosol Optical Depth), which describes the integral over the ozone profile weighted over the stratospheric temperatures and taking into account the temperature sensitivities of the ozone cross sections of the used wavelengths (see Section 2.3). The effective ozone temperatures derived from Brewer measurements at Mauna Loa Observatory (Hawaii) showed good agreement with ozone and temperature profiles measured by (single) ozone sondes from Hilo (Hawaii). The effective ozone temperatures calculated from the Brewer measurements of Toronto from 1997 to 2001 show good agreement with the expected temperature and ozone variation over the station [Kerr, 2002]. This analysis provides further evidence, that the different temperature sensitivities of the wavelengths of the Brewer and the Dobson instrument are the primary cause of the seasonal variation of the differences between TO_3 measurements of the two instruments (see Figure 5) and that the wavelengths used in Brewer spectrophotometry are much less sensitive to the stratospheric temperature variation.

4.4 Comparison of measurements at Hohenpeissenberg (Germany): Approximate correction for temperature influence and determination of air mass

Simultaneous Brewer and Dobson measurements have been available at Hohenpeissenberg since 1983 [Köhler and Attmannspacher, 1986; Köhler et al., 1989] and at Potsdam since 1987 [Feister, 1991; Spänkuch et al., 1999] (see Table 3). The Observatory at Hohenpeissenberg is now part of the RDCC of Europe and most of the side by side comparisons of European Dobson instruments take place at Hohenpeissenberg (comp. Section 2.1).

The seasonal variation of the difference between the two types of instruments at Hohenpeissenberg shows typical features (see Figure 8), similar to Figure 5. SO_2 column amount at Hohenpeissenberg is expected to be usually small. The different influences of the temperature on the two instruments has been removed by the following procedure [U. Köhler, pers. commun., 2001].

The sensitivity of the ozone absorption cross sections on temperature is for averaged profiles 1.3% per 10K for Dobson spectrophotometers ([Komhyr et al., 1993], comp. Section 2.3) and 0.7% per 10K for Brewer instruments, leaving 0.6% per 10K for the difference between the two types of instruments [Kerr et al., 1988]. A mean temperature correction was applied using the ozone and the temperature profiles from the ozonesondes launched from Hohenpeissenberg. The calculations are based on the deviations from the monthly mean profiles using a vertical resolution of 1 km. The temperature effect of TO_3 amount depends not only on the temperature but also on the ozone profiles requiring the respective weighting. The results show that approximately 1/3 of the difference can be explained by the temperature effect by this approach (see Figure 8).

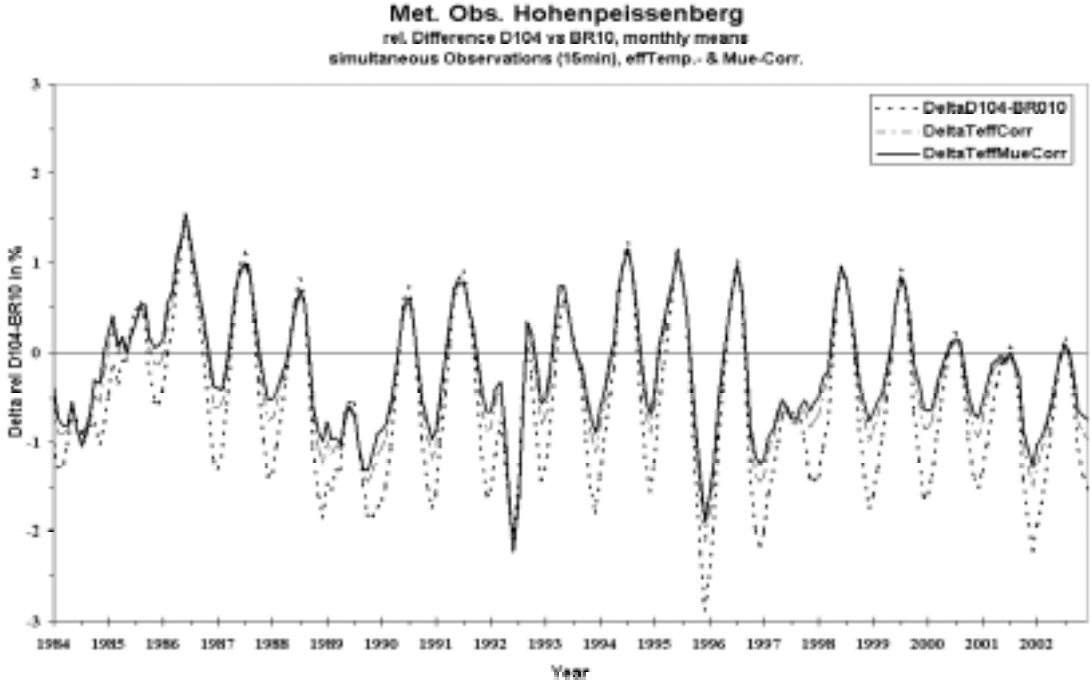

Figure 8: Relative differences (in %) of TO_3 of a Dobson (D104) and a Brewer (Br10) instrument at Hohenpeissenberg (Germany). The plot shows monthly means based on quasi simultaneous measurements ($\Delta t \leq 15$ min) without correction, data with averaged temperature correction (see text), and correction with averaged temperatures plus additional correction taking into account the differences in the calculation of μ (see text) [pers. commun. U. Köhler, 2002].

The relative stability of the two series was good if the knowledge from the different calibrations was taken into account, i.e. if homogenized series [Köhler, 1995] were used. The optical air mass of O_3 (μ) is calculated in a different way in the retrieval algorithms of Brewer and Dobson instruments. Köhler calculated the μ-values of both algorithms (for every 15 min for the days at the beginning of the four seasons) and he approximated the differences by a quadratic polynom, yielding the following (small) corrections: $0.99968 + 0.00081\ \Delta\mu + 0.000265\ \Delta\mu^2$. These values can be directly used for the comparison of the TO_3 of two types of instruments (comp. eq. (1)). This correction was applied on monthly mean values (as in case of the temperature influence). This correction diminishes the differences between the TO_3 values of the Dobson and the Brewer instrument, but the effect is rather small (see Figure 8).

4.5 Comparison at Arosa (Switzerland): Detailed correction for temperature influence

Arosa is located at 1860 m amsl. in the Swiss Alps far away from large primary air pollutant emission sources. Therefore, SO_2 measurements of the Brewer spectrophotometer only occasionally exceed its detection limit. Since 1988, Brewer instruments are operated at Arosa [Hoegger et al., 1992; 1994]. Today, the instrumentation of the station allows comparing the measurements of two Dobson spectrophotometers, two Brewer Mk II and one Brewer Mk III instrument (see Table 3). Because Arosa is above the inversion layer of the Swiss plateau direct sun observations are possible during about 70% of the days of the whole year. Zenith sky TO_3

observations are not performed because they are not required for representative measurements necessary for long-term trend analysis. The Dobson program includes many TO_3 observations (up to 12 or even more on days with favourable weather conditions in summer, except during weekends). This yields a large sample of quasi-simultaneous measurements of Dobson and Brewer instruments. The first approach of the data comparison was similar to the earlier Canadian study (see 4.3) [Staehelin et al., 1998]. In the first step the Dobson data were corrected for the SO_2 column amount measured by the Brewer instrument (which changed the Dobson data only slightly). In the next step, the differences between the quasi-simultaneous Dobson and Brewer data were plotted against the μ-values. Thereafter, the apparent μ-difference was removed from the data. The difference of these data corrected for different behaviour in μ still showed a seasonal variation, which was, however, much smaller. It was believed, that this seasonal difference might be caused by the different wavelengths used for TO_3 measurements in the two instruments.

The data analysis also indicated that the differences between the two Dobson and between the three Brewer instruments were much smaller than those between instruments of different types. The similar behaviour between the measurements of the Brewer instruments of type Mk II and Mk III with respect to the μ-values provides strong evidence that the difference in Dobson and Brewer measurements cannot be attributed to the fact that Dobson instruments are double monochromators leading to less stray light than the single dispersal Mk II Brewer instruments, because Mk III Brewers are also double monochromators. The differences between the TO_3 measurements of one Dobson and one Brewer series at Arosa (see Figure 9) are showing again the seasonal variation typical for mid-latitude stations with an averaged maximum to minimum difference of approximately 3%. The differences between the quasi-simultaneous measurements of the two types of instruments depend almost linearly on the air mass μ which is up to 3.5 (see Figure 10). This was documented earlier (comp. Staehelin et al. [1998]).

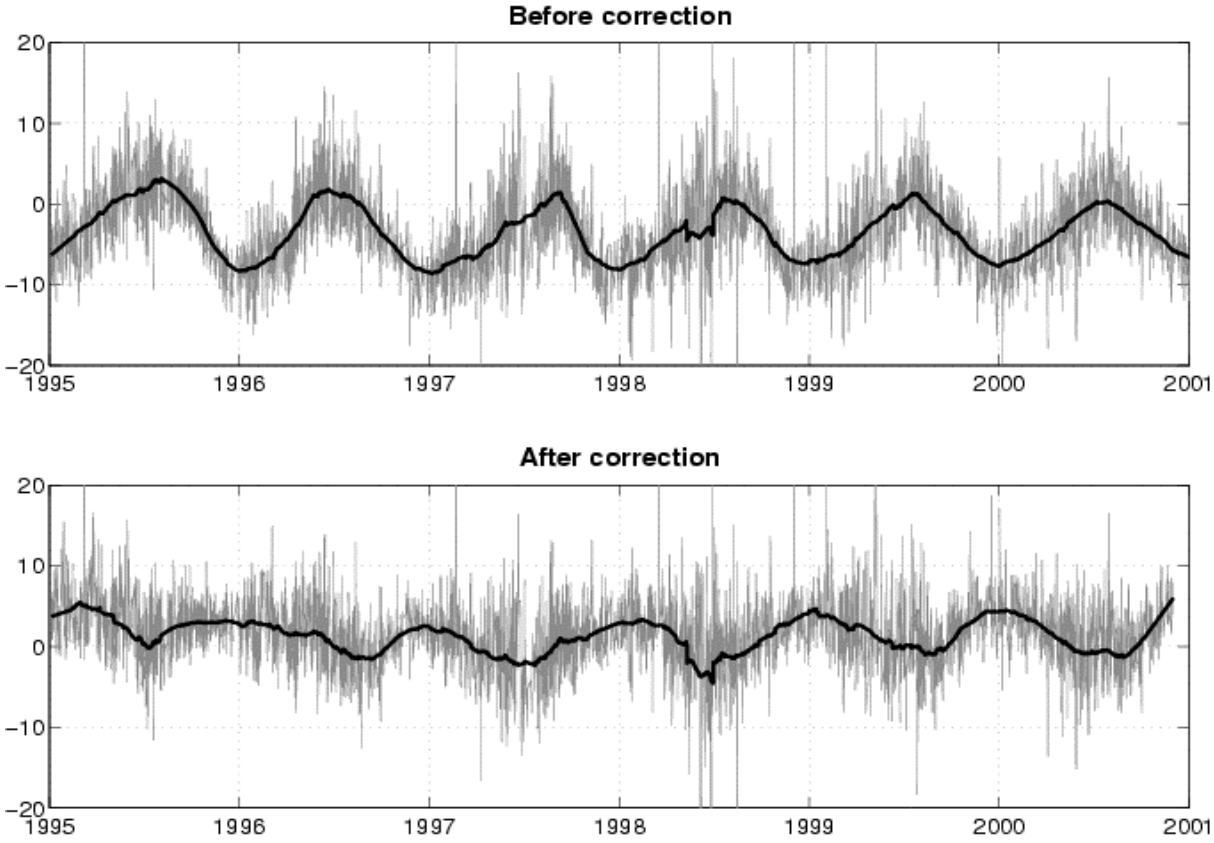

Figure 9: Time series of differences in TO_3 measurements (given in Dobson units) of Dobson instrument D101 and of Brewer instrument Br40 operated at Arosa (Switzerland). Only measurements performed within one hour are included. Before correction (top): Measurements without temperature correction; after correction (bottom): Same measurements after temperature correction (see text), from Lehmann [2001].

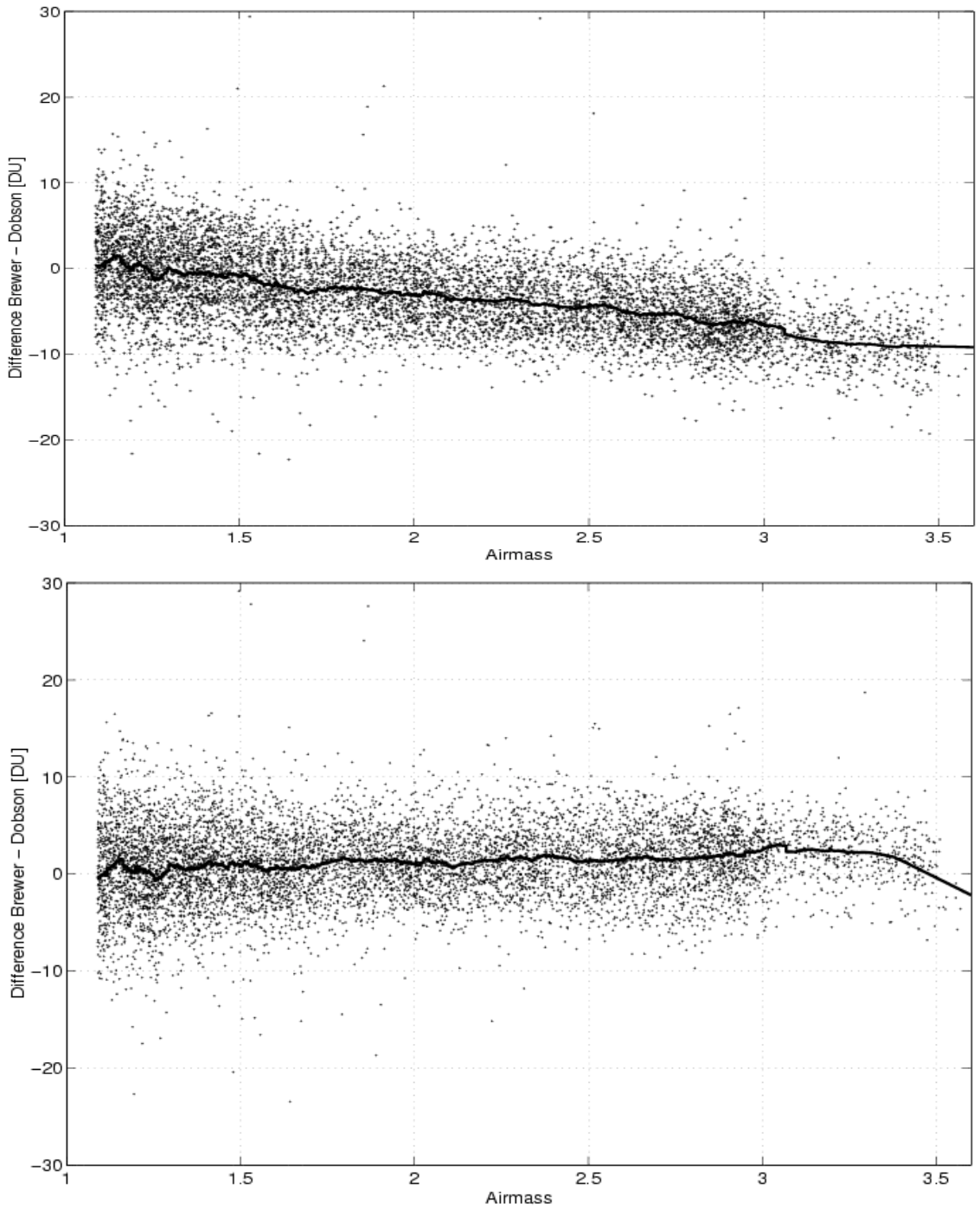

Figure 10: Difference in TO_3 measurements of Arosa, Switzerland shown in Figure 9 as a function of the ozone air mass μ. Before correction (top): Measurements without temperature correction; After correction (bottom): Same measurements after temperature correction (see text), from Lehmann [2001].

In order to evaluate more precisely the influence of the variability of the profiles of temperature and ozone on the ground based TO_3 measurements at Arosa Lehmann [2001] used single ozonesonde measurements launched from Payerne (used e.g. by Weiss et al. [2001]). Payerne is located in the Swiss plateau at a distance of approximately 200 km from Arosa. The ozonesonde measurements are regularly performed three times per week and at that time Brewer-Mast sensors were operationally used. The ozone profiles are scaled by Dobson TO_3 measurements of Arosa using the standard WMO procedure. The balloon typically bursts at elevations of 30 km asl., and a satellite ozone climatology was used to estimate ozone above the burst level. Lehmann selected as arbitrary reference for the description of the temperature effect the summer values of the ozone climatology deduced from the ozonesonde record of

Hohenpeissenberg (Germany). Against this climatology the ozone/temperature effect was calculated by weighting over the ozone and temperature profiles of the individual ascents. In the comparison only TO_3 values measured during the ascents of the sondes were included. The temperature dependencies of all involved wavelengths were calculated.

The temperature dependence of the measured signals NA of the wavelength pair A (see Table 1) of the Dobson measurements for a temperature T2 was described relative to a reference temperature T1 by

$$\boldsymbol{NA_{sens}} = \frac{NA(T2) - NA(T1)}{NA(T1)} \tag{9}$$

The same approach was used for the description of the temperature sensitivity of the signal ND of the wavelength pair D. The temperature influence on the Dobson measurements was described by:

$$X_{ADsens} = \frac{\left(\frac{N_A\, NA_{sens}}{\mu_A} - \frac{N_D\, ND_{sens}}{\mu_D}\right)\frac{10}{\tilde{\alpha}_{AD}}}{\left(\frac{N_A}{\mu_A} - \frac{N_D}{\mu_D}\right)\frac{10}{\tilde{\alpha}_{AD}} - A_{COR}\frac{m}{\mu_{AD}}} \tag{10}$$

The temperature sensitivities of the ozone absorption cross sections were quantified by the values presented in Table 2 and the ozone absorption cross sections at the temperatures between the values of Table 2 were calculated by linear interpolation [Lehmann, 2001].

For the description of the temperature sensitivities of the wavelengths used in Brewer TO_3 measurements (see Table 1) he used the same approach. First the temperature sensitivities of the primary ratios (MS4 - MS7, see 2.2) were defined as:

$$MSx_{sens} = \frac{MSx(T2) - MSx(T1)}{MSx(T1)} \tag{11}$$

where:

MSx_{sens} is the temperature sensitivity of the respective wavelength pair (see Table 2).

The temperature sensitivity of MS9 ratio used in the TO_3 determination (see equation (5)) is described by:

$$MS9_{sens} = \frac{MS5\, MS5_{sens} - 0.5\, MS6\, MS6_{sens} - 1.7\, MS7\, MS7_{sens}}{MS5 - 0.5\, MS6 - 1.7\, MS7} \tag{12}$$

Finally, the temperature sensitivity used for TO_3 is calculated by:

$$MS11_{sens} = \frac{MS9\, MS9_{sens}}{MS9 - B1} \tag{13}$$

The following formula was used to describe the ozone-temperature profile influence based on the information of the ozonesondes of Payerne:

$$\overline{\overline{O_3 x \sec t(wl, profile)}} = \frac{\int_{heigth=0}^{100km} O_3(height)\, O_3 x \sec t(wl, T(height))\, \partial height}{\int_{height=0}^{100km} O_3(height)\, \partial height} \qquad (14)$$

The temperature is linearly interpolated with elevation and an exponential decrease of the ozone concentrations above the burst level of the ozonesondes is assumed.

From this analysis he obtained the correction factors for the different wavelength pairs used in the Dobson and the Brewer algorithm, confirming the large temperature sensitivity of Dobson wavelength pair D. Finally these corrections were applied to one Dobson and one Brewer series of Arosa yielding much smaller seasonal differences (see Figure 9). After this procedure, the apparent dependence of the differences of the TO_3 measurements on the airmass (μ), which is typically found in such comparisons, becomes much smaller (see Figure 10). This procedure removes approximately 2/3 of the observed differences in the simultaneous Dobson and Brewer measurements of Arosa. However, it has a tendency for an overcorrection, which remains to be explained. It is planned to adopt this procedure to all measurements at Arosa for data quality control and early detection of problems or drifts in the measurements of one of the instruments.

4.6 Comparison of Dobson and Brewer measurements at Boulder (Colorado, USA)

Simultaneous direct sun measurements of a Dobson and a Brewer instrument performed from November 1988 to March 1989 at Boulder, CO., USA, were analyzed by Diaz et al. [1990a and b]. They found a good correlation between the R6 (weighted counting rate combined for ozone measurement) values of the Brewer measurements and the TO_3 measurements of the Dobson instrument multiplied by the ozone air mass factor μ . The approach in this study was to consider whether the instruments are attempting to measure the same thing: Total ozone. If all assumptions and parameters were correct for both instruments the resultant calculated ozone would be identical for these simultaneous (within 15 seconds) measurements. The equations at the end of the manipulations which convert counting rates or attenuator position to ozone are very similar and can be set equal to each other for simultaneous measurements. The relation between (R6-ETC) and N-values was examined. The main result was that (R6-ETC) and N-values were very highly correlated, with the slope of the relationship dependent on the season. Mathematically, the slope should be the ratio of the cross-sections used for the instruments and the seasonality of the slope implies a temperature of the stratospheric effect. The restricted data set consists mainly of wintertime data covering only part of the stratospheric temperature range. The method used in this comparison, if conducted over a time period long enough, could produce a useful transfer function which allows one instrument to operate as a proxy for the other for direct sun measurements. This was a highly ”labor intensive” method that was only easily done in this case with the aid of an automated Dobson instrument.

4.7 Comparison of measurements of high latitudes (Vindeln, Sweden), polar sites (Scott Base, Antarctica) and TOMS3-F (Fairbanks, Alaska) campaign

At polar sites direct sun observations are not feasible during polar night and restricted to large air masses in the periods surrounding the polar night. With large air masses the proportion of scattered light increases compared to the direct radiation and therefore the measurements are more difficult. Josefsson [1992] developed a method which uses focused sun measurements for Brewer instruments. This technique was also used in a study of Nichol and Valenti [1993], in which simultaneous TO_3 measurements of a Brewer and a Dobson instrument at Scott Base (78°S) (see Table 3) during the development of the Antarctic ozone hole were carefully analyzed. The daily mean values agreed usually within 5%, which is an encouraging result. At Vindeln in Sweden (64.24°N), TO_3 has been measured by a Dobson and a Brewer instrument since 1994 (see Table 3). The possibilities for measurements are strongly restricted during winter conditions. The data quality of the Brewer total ozone measurements by the focused sun method was carefully tested [Joseffson, 2002]. From the measurements at Vindeln no seasonal variation of the difference between Dobson

and Brewer measurements typically observed at mid-latitudes is obvious, which is surprising. The measuring uncertainties at low sun are of the same order as the expected effect from stratospheric temperature variation. Some of them are systematic, which may cancel the effect (i.e. counteracting μ-dependence) [pers. commun. Joseffson, 2002].

The recent study of Total Ozone Measurements by satellites, sondes and spectrometers at high latitudes (TOMS3-F) was planned to compare ozone measurements at high latitudes. TOMS3-F was held mid March to mid April 2001 at the University of Alaska, Fairbanks (UAF) (64.7°N). The goal of this campaign was to understand as much as possible the differences between the ground based and satellite instruments and to determine the causes of those differences. To fully understand causes of these differences, it is necessary to know the specific atmospheric conditions under which the measurements were made. For that purpose a great number of balloon ozonesondes were flown. The ground instruments used in TOMS3-F were the World Standard Dobson D83 (CMDL), UAF station instrument D63 (CMDL/UAF), single monochromator Brewer Br7 (MSC) and double monochromator Brewers Br85 (MSC) and Br171 (Goddard Space Flight Centre, GSFC) (see Table 4). The balloon instruments were Electro-Chemical Cell ozonesondes. The space instrument was the Earth Probe Total Ozone Mapping Satellite (EPTOMS). This report concentrates on the results from the Dobson and Brewer instruments.

Table 4: Overview of results of the spectrophotometric TO_3 measurements of TOMS3-F (Total Ozone Measurements by Satellites, Sondes and Spectrometers at the Fairbanks field campaign), compare text.

Measurement Daily Average	Percent Difference from D83 (AD Direct Sun)	Comments
D63 UAF instrument (AD Direct Sun)	-1.3 +/- 2.0	Near-Simultaneous measurements show a calibration offset of almost -3% at 300 DU (Standard Definition of Calibration Difference)
D63 UAF instrument (CD Direct Sun, $5<\mu<2.4$)	+3.5 +/-1.3	As CD observations are made mostly at lower sun, these averages are not on the same time periods as the other measurements. The values are both corrected for historic AD-CD difference and actual ozone weighted stratospheric temperature
Brewer B7	+3.1 +/- 1.6	Single Pass Brewer (MK II)
Brewer B85	+3.3 +/- 1.2	Double Pass Brewer (Mk III)
Brewer B171	+3.2 +/- 1.4	NASA Double Pass Brewer (Mk III) with internal scattered light determined
ECC Sonde (SBUV)	+3.8 +/- 5.4	SBUV refers to the method used to account for the unmeasured ozone above balloon burst.
EPTOMS	+0.3 +/- 6.0	EPTOMS has had instrument mechanical problems -- the values published in spring 2002 were used for this comparison

The TO_3 amount varied between 360 and 480 Dobson Units (DU). The combination of high ozone and low sun made the observing conditions quite different than those during other typical intercomparisons. The μX (TO_3 times the optical path length through the ozone layer) range was about 600-1800 DU, whereas the normal range for intercomparisons at mid-latitudes is about 300-900 DU. The ozone weighted temperature of the stratosphere during TOMS3-F were - 53.0 to -57.5°C, compared to - 46.3°C at mid-latitudes which is the value of the ozone cross-sections used to calculate ozone from the Dobson measurements. An extensive study [Kerr, 2002] of the Brewer instrument's response to stratospheric temperature over Toronto showed no significant temperature dependence of the wavelength cross-sections used to reduce the Brewer measurements (comp. Section 4.3).

The station Dobson instrument (D63) is automated and it makes direct sun observations at high μ values (>2.4) on all three of the wavelength pairs used by the Dobson instrument (comp. Table 1). The station instrument made many more CD observations than the standard instrument. There is a historic difference in the TO_3 results between the AD and CD combinations that are used to produce a "multiplying factor" for the CD results. (This is a standard operating procedure as described by Komhyr, 1980).

Table 4 summarizes the differences between the instruments. Some conclusions:

- The Dobson instruments using AD pairs underestimated the ozone amount at high μX values compared to the Double Pass Brewer (Mk III) instruments.
- Some (~1%) of the underestimation can be corrected by using the correct ozone cross-sections for the stratospheric temperature.
- The μX dependence of the underestimation can be explained as a combination of internal stray light at the A wavelength and forward-scattered light in the instrument's field of view.
- Single Pass Brewer instruments show some of the same problems, but as the field of view of the Brewer is much smaller the effect is likely due to internal stray light.
- Results from the CD pairs when adjusted by the normal procedures for historic AD differences and for the stratospheric temperature are similar to the results from the Brewer instrument. The Dobson instrument's internal configuration and the C pair higher intensity combine to reduce the effect of scattered light both in the instrument and in the field of view.

Note: In November-December 2001 Dobson D83 and Brewer B171 were operated at Lauder, New Zealand (comp. Table 3) – a temperate site at lower ozone, and with stratospheric temperatures in the – 43.2 to – 47.4^{o}C range. The Brewer results were approximately 0.5% higher than D83 AD results, with a limited number of overlapping measurements.

5. RECOMMENDED PROCEDURES FOR COMPARISON OF DOBSON AND BREWER MEASUREMENTS

Most of the available studies indicate that the difference between the TO_3 measurements of Dobson and Brewer instruments at mid-latitudes depends on:

(1) Column sulfur dioxide, which needs to be considered in particular when the measurements are performed in polluted areas.

(2) A seasonal bias, which probably originates from the different wavelengths included in the measurements of the two types of instruments.

Empirical studies based on quasi-simultaneous measurements revealed a systematic bias that can be characterized by different dependencies of the instruments on the air mass factor μ . A recent study suggests, that 2/3 of the difference between Dobson and Brewer measurements can be attributed to the different temperature response of the wavelengths included in the measurements of the two types of instruments. No unique simple transfer function without information on temperature and ozone profiles can be deduced for the comparison of the TO_3 measurements of the two types of instruments.

The data to construct the transfer function need to be of high quality, i.e. data obtained from an instrument with technical problems cannot be included in such a data set. We propose the following data selection for comparison of the measurements of Dobson and Brewer spectrophotometers:

(i) All observations used in such a comparison must be re-evaluated and updated with respect to well known and documented calibration history and regular standard lamp tests of instruments tied to world Dobson and Brewer standard instruments.

(ii) We recommend to use only direct sun observations because they are more precise than the other types of TO_3 observations (compare also legend of Figure 5).

(iii) We recommend to use only quasi-simultaneous measurements to avoid problems with ozone changes caused by changes in meteorological conditions. This also implies that we do not recommend to use daily mean values because this could introduce a further uncertainty.

Based on the still limited experience of such comparisons we propose two types of procedures, which have been used for comparison for mid-latitude stations. If temperature and ozone profile information is available at (or from a nearby) station, the temperature effect can be removed based on physical principles whereas at other sites only an empirical statistical transfer function can be constructed.

5.1 Procedure for comparison of Dobson and Brewer measurements based on detailed profile information

The approach described in Section 4.5. requires temperature and ozone profile information from a collocated ozonesonde station (or other such profile information, if a sufficient number of observations with sufficient vertical resolution is available). The procedure includes the following steps:

(1) Remove SO_2 column amount of Brewer measurements from the Dobson data, which is particularly important at polluted sites.

(2) Calculate temperature sensitivities of Dobson and Brewer wavelenghts according to equation (10) and (13).

(3) Use equation (14) for the comparison based on the information of the ozonesonde measurements.

(4) Compare seasonal variation of the differences before and after temperature correction (see Figure 9).

(5) Compare μ -dependence of the difference between Dobson and Brewer data before and after temperature correction (comp. Figure 10). By this comparison the effectiveness of the approach can be tested resulting in a much smaller dependence of the difference between the two types of instruments on ozone air mass μ. In case of good results, the respective data can be used to construct a transfer function.

By this approach, the comparison of the data of the two instruments can be derived based on the temperature dependence of the ozone spectrum.

5.2 Procedure for comparison of Dobson and Brewer measurements by statistical approach

In case of absence of detailed ozone and temperature profile information over the station only a statistical approach is feasible, while in case of profile information both approaches can be used. The proposed procedure is based on the analysis presented in Section 4.3. An extended database of quasi-simultaneous measurements is required. The minimal requirements of such a data set for a mid-latitude station are listed in Table 5. This clearly shows that one single Dobson observation per day is not adequate. The recommended procedure is inherently based on a climatological concept, assuming equal seasonal variation in temperature and vertical ozone distribution every year. However, Figures 5, 8 and 9 indicate that there is considerable variability from one to another year, and therefore a data set covering only one single year is not sufficient for the construction of a suitable transfer function. The transfer function should be based on the following steps:

(1) Remove SO_2 column amount of Brewer measurements from the Dobson data (particularly important at polluted sites).

(2) Plot the differences of the quasi-simultaneous Dobson and Brewer measurements as a function of μ (comp. Figures 7 and 10). For these plots only the months with large variability in μ are suitable, e.g. measurements from April to August as used in the Canadian study (see Section 4.3).

Table 5: Minimal requirement of quasi-simultaneous direct sun measurements (μΔ ≤ 0.1, Δtime ≤ 20 min) to construct a transfer function between TO_3 measurements of a Dobson and a Brewer instrument by the statistical approach (see text). Periods of regular intercomparisons towards world (regional) reference instruments should be 2 years for Brewer spectrophotometers and 4 years for Dobson instruments.

- Measurements per day: 4-6 (quasi-simultaneous) measurements at different μ-values for many days in which direct sun measurements are feasible
- Seasonal variation: Measurements during every month
- Total length of the record: Measurements during three years

(3) Use equation (8) for the construction of the transfer function, which needs the proper adjustments of the required constants using equation (7).

6. SUMMARY AND CONCLUSIONS

High quality TO_3 measurements with excellent long-term stability have a very high priority within the GAW program of WMO. This has not been changed by the successful implementation of the Montreal Protocol and its amendments because

- the turnaround of the negative trends of the ozone shield needs to be demonstrated. The detection of the turnaround is expected to need more than a decade of continued high quality measurements [Wheatherhead et al., 2000];
- the several interactions between stratospheric ozone and climate needs further long-term observations;
- high quality TO_3 measurements from the ground are required to validate satellite observations including their long-term stability. This aspect becomes increasingly important because the world wide ozone monitoring by satellite observations is based more and more on composite satellite series.

Both types of instruments, the classical manually operated Dobson spectrophotometer with a technique that reached its final stage almost 50 years ago and the completely automated Brewer spectrophotometer, have shown their capabilities for reliable long-term TO_3 monitoring. We believe that the careful maintenance of the instruments including strict data quality control plays the most important role for successful ozone monitoring. The most valuable data for long-term trend analysis have been based in the past on Dobson measurements. Both types of instruments have their advantages and disadvantages. The Brewer instrument allows the simultaneous measurement of SO_2-column amount. This is important when the measurements are performed at polluted sites. The wavelengths used in the Brewer spectrophotometers have ozone absorption cross sections less dependent on temperature, which leads to a weaker seasonal dependence of TO_3 observations. On the other hand the formal calibration procedures and the documentation of the technical condition of the individual instruments and the data quality control of the Dobson network have reached a high level. Transparency is achieved because the results of the intercomparisons with the standard instruments are available to all interested scientists. We see a demand for improvements in the data quality control program of the Brewer network. At the present time, the calibration history of observations in the Brewer network are not known to the data users. A formal procedure of reporting on the results of the intercomparisons between the Brewer station instruments and the traveling standard instrument is strongly recommended.

The measurements of Dobson and Brewer spectrophotometers show characteristic seasonal differences, and are at least partially attributable to the different wavelengths chosen for the instruments. We recommend the simultaneous operation of the two types of instruments at the same stations providing redundancy of the measurements. In order to make best use of the redundancy we propose two approaches for comparison based on the results of previous studies. In

one approach, the temperature sensitivities of the wavelengths involved in TO_3 measurements of the two instruments are corrected based on ozone and temperature profile measurements of simultaneous ozonesonde measurements at the same station (see Section 5.1). For this purpose, the temperature coefficients of the involved wavelengths have to be treated individually with single profile information. The second approach for the comparison is based on a statistical treatment that makes use of the differences between the measurements as a function of the air mass leading to a statistical transfer function which inherently includes at least partially also a temperature correction (see Section 5.2). This approach requires a large number of quasi-simultaneous measurements. We hope that further studies of other stations will refine the proposed procedures. We do not recommend to change from a TO_3 series based on a Dobson to a Brewer instrument, partially because the simultaneous monitoring by the two types of instruments is important for data quality of the two independently operated networks of the ground based world wide TO_3 monitoring of WMO. However, if any conditions are forcing a change from a Dobson to a Brewer instrument, we strongly recommend the careful construction of a transfer function, which requires simultaneous measurements over a period of at least three years at the frequency shown in Table 5 and an evaluation according to Section 5. Otherwise the series might suffer from an induced change that never can be corrected in a way necessary for long-term trend analysis, since the TO_3 trends are small at mid-latitudes compared to the large natural variation. We finally recommend to coordinate and to publish in a joint effort (possibly coordinated by GAW/WMO) the investigation and further development of transfer functions of Dobson and Brewer measurements from collocated stations.

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25. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at May 1984. November 1984 (TD No. 13)

26. Sulphur and Nitrogen in Precipitation: An Attempt to Use BAPMoN and Other Data to Show Regional and Global Distribution by Dr. C.C. Wallén. April 1986 (TD No. 103)

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63. Report of the Informal Session of the Executive Council Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Sofia, Bulgaria, 26 and 28 October 1989

64. Report of the consultation to consider desirable locations and observational practices for BAPMoN stations of global importance, Bermuda Research Station, 27-30 November 1989

65. Report of the Meeting on the Assessment of the Meteorological Aspects of the Fourth Phase of EMEP, Sofia, Bulgaria, 27 and 31 October 1989

66. Summary Report on the Status of the WMO Global Atmosphere Watch Stations as at 31 December 1990 (TD No. 419)

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70. Report of the Second Session of EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Santiago, Chile, 9-15 January 1991 (TD No. 633)

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72. Integrated Background Monitoring of Environmental Pollution in Mid-Latitude Eurasia by Yu.A. Izrael and F.Ya. Rovinsky, USSR (TD No. 434)

73. Report of the Experts Meeting on Global Aerosol Data System (GADS), Hampton, Virginia, 11 to 12 September 1990 (TD No. 438)

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80. Report of the WMO Meeting of Experts on the Quality Assurance Plan for the GAW, Garmisch-Partenkirchen, Germany, 26-30 March 1992 (TD No. 513)

81. Report of the Second Meeting of Experts to Assess the Response to and Atmospheric Effects of the Kuwait Oil Fires, Geneva, Switzerland, 25-29 May 1992 (TD No. 512)

82. Global Atmospheric Background Monitoring for Selected Environmental Parameters BAPMoN Data for 1991, Volume I: Atmospheric Aerosol Optical Depth (TD No. 518)

83. Report on the Global Precipitation Chemistry Programme of BAPMoN (TD No. 526)

84. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at GAW-BAPMoN sites for the year 1991 (TD No. 543)

85. Chemical Analysis of Precipitation for GAW: Laboratory Analytical Methods and Sample Collection Standards by Dr Jaroslav Santroch (TD No. 550)

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87. Report of the Third Session of EC Panel/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Geneva, 8-11 March 1993 (TD No. 555)

88. Report of the Seventh WMO Meeting of Experts on Carbon Dioxide Concentration and Isotopic Measurement Techniques, Rome, Italy, 7 - 10 September 1993, (edited by Graeme I. Pearman and James T. Peterson) (TD No. 669)

89. 4th International Conference on CO_2 (Carqueiranne, France, 13-17 September 1993) (TD No. 61)

90. Global Atmospheric Background Monitoring for Selected Environmental Parameters GAW Data for 1992, Volume I: Atmospheric Aerosol Optical Depth (TD No. 562)

91. Extended Abstracts of Papers Presented at the WMO Region VI Conference on the Measurement and Modelling of Atmospheric Composition Changes Including Pollution Transport, Sofia, 4 to 8 October 1993 (TD No. 563)

92. Report of the Second WMO Meeting of Experts on the Quality Assurance/Science Activity Centres of the Global Atmosphere Watch, Garmisch-Partenkirchen, 7-11 December 1992 (TD No. 580)

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94. Report on the Measurements of Atmospheric Turbidity in BAPMoN (TD No. 603)

95. Report of the WMO Meeting of Experts on UV-B Measurements, Data Quality and Standardization of UV Indices, Les Diablerets, Switzerland, 25-28 July 1994 (TD No. 625)

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97. Quality Assurance Project Plan (QAPjP) for Continuous Ground Based Ozone Measurements (TD No. 634)

98. Report of the WMO Meeting of Experts on Global Carbon Monoxide Measurements, Boulder, USA, 7-11 February 1994 (TD No. 645)

99. Status of the WMO Global Atmosphere Watch Programme as at 31 December 1993 (TD No. 636)

100. Report of the Workshop on UV-B for the Americas, Buenos Aires, Argentina, 22-26 August 1994

101. Report of the WMO Workshop on the Measurement of Atmospheric Optical Depth and Turbidity, Silver Spring, USA, 6-10 December 1993, (edited by Bruce Hicks) (TD No. 659)

102. Report of the Workshop on Precipitation Chemistry Laboratory Techniques, Hradec Kralove, Czech Republic, 17-21 October 1994 (TD No. 658)

103. Report of the Meeting of Experts on the WMO World Data Centres, Toronto, Canada, 17-18 February 1995, (prepared by Edward Hare) (TD No. 679)

104. Report of the Fourth WMO Meeting of Experts on the Quality Assurance/Science Activity Centres (QA/SACs) of the Global Atmosphere Watch, jointly held with the First Meeting of the Coordinating Committees of IGAC-GLONET and IGAC-ACE, Garmisch-Partenkirchen, Germany, 13 to 17 March 1995 (TD No. 689)

105. Report of the Fourth Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry (Garmisch, Germany, 6-11 March 1995) (TD No. 718)

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107. Extended Abstracts of Papers Presented at the WMO-IGAC Conference on the Measurement and Assessment of Atmospheric Composition Change (Beijing, China, 9-14 October 1995) (TD No. 710)

108. Report of the Tenth WMO International Comparison of Dobson Spectrophotometers (Arosa, Switzerland, 24 July - 4 August 1995)

109. Report of an Expert Consultation on 85Kr and 222Rn: Measurements, Effects and Applications (Freiburg, Germany, 28-31 March 1995) (TD No. 733)

110. Report of the WMO-NOAA Expert Meeting on GAW Data Acquisition and Archiving (Asheville, NC, USA, 4-8 November 1995) (TD No. 755)

111. Report of the WMO-BMBF Workshop on VOC Establishment of a "World Calibration/Instrument Intercomparison Facility for VOC" to Serve the WMO Global Atmosphere Watch (GAW) Programme (Garmisch-Partenkirchen, Germany, 17-21 December 1995) (TD No. 756)

112. Report of the WMO/STUK Intercomparison of Erythemally-Weighted Solar UV Radiometers, Spring/Summer 1995, Helsinki, Finland (TD No. 781)

113. The Strategic Plan of the Global Atmosphere Watch (GAW) (TD No. 802)

114. Report of the Fifth WMO Meeting of Experts on the Quality Assurance/Science Activity Centres (QA/SACs) of the Global Atmosphere Watch, jointly held with the Second Meeting of the Coordinating Committees of IGAC-GLONET and IGAC-ACE^{Ed}, Garmisch-Partenkirchen, Germany, 15-19 July 1996 (TD No. 787)

115. Report of the Meeting of Experts on Atmospheric Urban Pollution and the Role of NMSs (Geneva, 7-11 October 1996) (TD No. 801)

116. Expert Meeting on Chemistry of Aerosols, Clouds and Atmospheric Precipitation in the Former USSR (Sankt Peterburg, Russian Federation, 13-15 November 1995)

117. Report and Proceedings of the Workshop on the Assessment of EMEP Activities Concerning Heavy Metals and Persistent Organic Pollutants and their Further Development (Moscow, Russian Federation, 24-26 September 1996) (Volumes I and II) (TD No. 806)

118. Report of the International Workshops on Ozone Observation in Asia and the Pacific Region (IWOAP, IWOAP-II), (IWOAP, 27 February-26 March 1996 and IWOAP-II, 20 August-18 September 1996) (TD No. 827)

119. Report on BoM/NOAA/WMO International Comparison of the Dobson Spectrophotometers (Perth Airport, Perth, Australia, 3-14 February 1997), (prepared by Robert Evans and James Easson) (TD No. 828)

120. WMO-UMAP Workshop on Broad-Band UV Radiometers (Garmisch-Partenkirchen, Gemany, 22 to 23 April 1996) (TD No. 894)

121. Report of the Eighth WMO Meeting of Experts on Carbon Dioxide Concentration and Isotopic Measurement Techniques (prepared by Thomas Conway) (Boulder, CO, 6-11 July 1995) (TD No. 821)

122 Report of Passive Samplers for Atmospheric Chemistry Measurements and their Role in GAW (prepared by Greg Carmichael) (TD No. 829)

123 Report of WMO Meeting of Experts on GAW Regional Network in RA VI, Budapest, Hungary, 5 to 9 May 1997

124 Fifth Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, (Geneva, Switzerland, 7-10 April 1997) (TD No. 898)

125. Instruments to Measure Solar Ultraviolet Radiation, Part 1: Spectral Instruments (lead author G. Seckmeyer) (TD No. 1066)

126. Guidelines for Site Quality Control of UV Monitoring (lead author A.R. Webb) (TD No. 884)

127. Report of the WMO-WHO Meeting of Experts on Standardization of UV Indices and their Dissemination to the Public (Les Diablerets, Switzerland, 21-25 July 1997) (TD No. 921)

128. The Fourth Biennial WMO Consultation on Brewer Ozone and UV Spectrophotometer Operation, Calibration and Data Reporting, (Rome, Italy, 22-25 September 1996) (TD No. 918)

129. Guidelines for Atmospheric Trace Gas Data Management (Ken Masarie and Pieter Tans), 1998 (TD No. 907)

130. Jülich Ozone Sonde Intercomparison Experiment (JOSIE, 5 February to 8 March 1996), (H.G.J. Smit and D. Kley) (TD No. 926)

131. WMO Workshop on Regional Transboundary Smoke and Haze in Southeast Asia (Singapore, 2 to 5 June 1998) (Gregory R. Carmichael). Two volumes

132. Report of the Ninth WMO Meeting of Experts on Carbon Dioxide Concentration and Related Tracer Measurement Techniques (Edited by Roger Francey), (Aspendale, Vic., Australia)

133. Workshop on Advanced Statistical Methods and their Application to Air Quality Data Sets (Helsinki, 14-18 September 1998) (TD No.956)

134. Guide on Sampling and Analysis Techniques for Chemical Constituents and Physical Properties in Air and Precipitation as Applied at Stations of the Global Atmosphere Watch. Carbon Dioxide

135. Sixth Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry (Zurich, Switzerland, 8-11 March 1999) (WMO TD No.1002)

136. WMO/EMEP/UNEP Workshop on Modelling of Atmospheric Transport and Deposition of Persistent Organic Pollutants and Heavy Metals (Geneva, Switzerland, 16-19 November 1999) (Volumes I and II) (TD No. 1008)

137. Report and Proceedings of the WMO RA II/RA V GAW Workshop on Urban Environment (Beijing, China, 1-4 November 1999) (WMO-TD. 1014) (Prepared by Greg Carmichael)

138. Reports on WMO International Comparisons of Dobson Spectrophotometers, Parts I – Arosa, Switzerland, 19-31 July 1999, Part II – Buenos Aires, Argentina (29 Nov. – 12 Dec. 1999 and Part III – Pretoria, South Africa (18 March – 10 April 2000).

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140. WMO/CEOS Report on a Strategy for Integrating Satellite and Ground-based Observations of Ozone (WMO TD No. 1046).

141. Report of the LAP/COST/WMO Intercomparison of Erythemal Radiometers (Thessaloniki, Greece, 13-23 September 1999) (WMO TD No. 1051).

142. Strategy for the Implementation of the Global Atmosphere Watch Programme (2001-2007), A Contribution to the Implementation of the Long-Term Plan (WMO TD No.1077).

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144. Report of the Seventh Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry and the GAW 2001 Workshop (Geneva, Switzerland, 2 to 5 April 2001).

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146. Quality Assurance in monitoring solar ultraviolet radiation: the state of the art.

147. Workshop on GAW in RA VI (Europe), Riga, Latvia, 27-30 May 2002.

148. Report of the Eleventh WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracer Measurement Techniques (Tokyo, Japan, 25-28 September 2001) (WMO TD No 1138).