TOTAL OZONE MONITORING BY GROUNDBASED INSTRUMENTS AS PART OF GAW

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ABSTRACT

Total ozone measurements by ground based sun photometers (wavelength region: 305-340 nm) are part of the regular measuring program of Global Atmosphere Watch (GAW) of WMO. Such measurements can be performed by Dobson spectrophotometers and the more modern Brewer instruments. The most important motivation for such longterm series is the documentation of the effect of the release of manmade ozone depleting substances (ODS) such as chlorofuorocarbons on the ozone layer. Since the end of the 1970s the global ozone layer is also monitored from space. However, instruments operated from satellites have limited lifetimes and the construction of longterm series from different satellite instruments (merged total ozone series) is difficult and therefore reliable ground based measurements are still very important also to control the quality of merged satellite series.

Changes in the ozone layer in midlatitudes are comparably small (a decrease of a few percent per decade was documented for the 1980s when stratospheric concentration of ODS strongly increased). The basic challenge of the monitoring of the ozone layer is therefore the longterm stability of the calibration of the instruments. The network of total ozone measurements are based on primary instruments calibrated by the Langley plot method performed in the tropics or subtropics (the requirements include a clean atmosphere with minimal diurnal variation of the ozone layer) (the Brewer network also includes a triad of instruments operated at Toronto (Canada)). The station instruments are subsequently (re)calibrated by side by side comparisons with standard (or travelling) instruments. The basic design of the networks will be presented as well as their operation (going back to the 1970s) which allowed significant improvements of the data quality of ground based total ozone measurements of GAW. Particular attention will be given to the European network. However, also the limitations of the networks will be discussed as well as further improvements.

1. Introduction

Precise measurements of solar irradiance in the wavelength range 305-340 nm at the Earth’s surface allow determination of column ozone amount (total ozone). G.M.B. Dobson designed instrument(s) for precise total ozone measurement and the technique was fully developed by the International Geophysical Year (1958) and is still in use today (Dobson, 1957a, b; Komhyr, 1980). The Brewer spectrophotometer became commercially available in the 1980s (Kerr et al., 1980). This instrument is based on the same instrumental principle but it makes use of modern technology and it is fully automated (it also can be used to determine SO_2 column amount and UV-B measurements). Less precise total ozone measurements can be obtained by filter instruments developed in the former Soviet Union (Bojkov et al., 1994) whereas the SAOZ instrument allows precise column ozone determination based on absorption measurements in the visible (Pommerau et al., 1988).

At the beginning of the 1970s ozone destruction by anthropogenic emissions started to be discussed in science and public. Molina and Rowland (1974) showed that chlorofluorocarbons (CFCs) anthropogenically emitted at the Earth's surface can reach the upper stratosphere, where they can destroy stratospheric ozone after photolysis. This caused a change in paradigm of stratospheric ozone research: In the previous period stratospheric ozone measurements were performed for scientific purposes (e.g. to determine the climatology and to study the relation between meteorology and stratospheric ozone) and therefore the requirement in precision and accuracy were comparatively low because total ozone can change from one to another day up to 30% at mid-latitudes. Long-term changes in the ozone layer become a new topic in the debate of the anthropogenic destruction of the ozone layer particularly since the theory of Molina and Rowland (1974) was challenged by industry manufacturing ODS. However, it turned out that the network of earlier total ozone measurements did not fulfil the data quality requirements to be used for long-term trend analysis (note that the downward trend in total ozone caused by ODS at mid-latitudes never exceeded more than a few percent decrease per decade (see e.g. WMO, 1989); this implies that only a few data series going back in time prior to the 1970s can be used for long-term analysis after careful homogenization, see e.g. Figure 1).

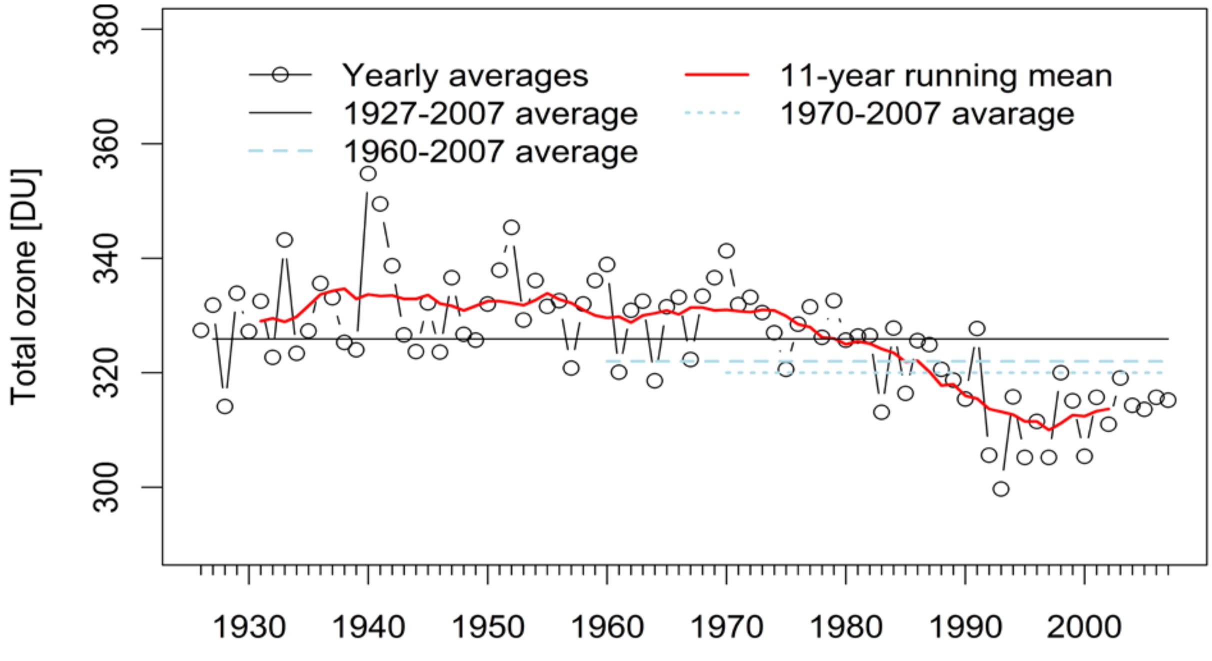

Figure 1: Total ozone series of Arosa (Switzerland) (homogenized series).

In order to fulfil the demand in data quality required for reliable long-term trend analysis a network was designed during the 1970s which runs under the auspices of the World Meteorological Organization (WMO) (e.g. Staehelin, 2008, Dlugokencky et al., 2010). It includes regular intercomparisons between station and standard instruments (see Section 3). The network was first named Global Ozone Monitoring System (GO3S) which was subsequently integrated in Global Atmosphere Watch (GAW). Since 1979 the global ozone shield is measured from space which allows (quasi) global and (quasi) continuous monitoring of the ozone layer. However, it become clear in the 1980s that it is very important to complement the global monitoring by satellite instruments with ground based measurements, because the long-term stability of ground based instruments can be more easily controlled than instruments operated onboard of satellites (e.g. Heath et al., 1988; WMO, 1989).

2. Total ozone measurements by Dobson and Brewer Instruments

Total ozone determination of Dobson and Brewer instruments is based on the following equation:

$$I(\lambda) = I_o(\lambda) \exp(-\alpha(\lambda) X \mu - \beta(\lambda) (p_s/p_o) m_R - \delta(\lambda) m_a) \tag{1}$$

Whereas: X is the total ozone amount (in Dobson units (DU) ; I is the solar irradiance at the wavelength λ measured at the Earth's surface, I_o (λ) is the intensity that would be measured outside the Earth's atmosphere; $\alpha(\lambda)$ is the monochromatic ozone absorption coefficient; p_s is the station pressure; p_o is the mean sea level pressure at 1013.25 hPa; μ is the relative slant path through ozone (air mass factor); $\beta(\lambda)$ is the Rayleigh scattering coefficient; m_R is the relative optical air mass corresponding to Rayleigh scattering (extinction); $\delta(\lambda)$ is the aerosol optical depth; and m_a is the relative optical air mass corresponding to aerosol scattering (extinction).

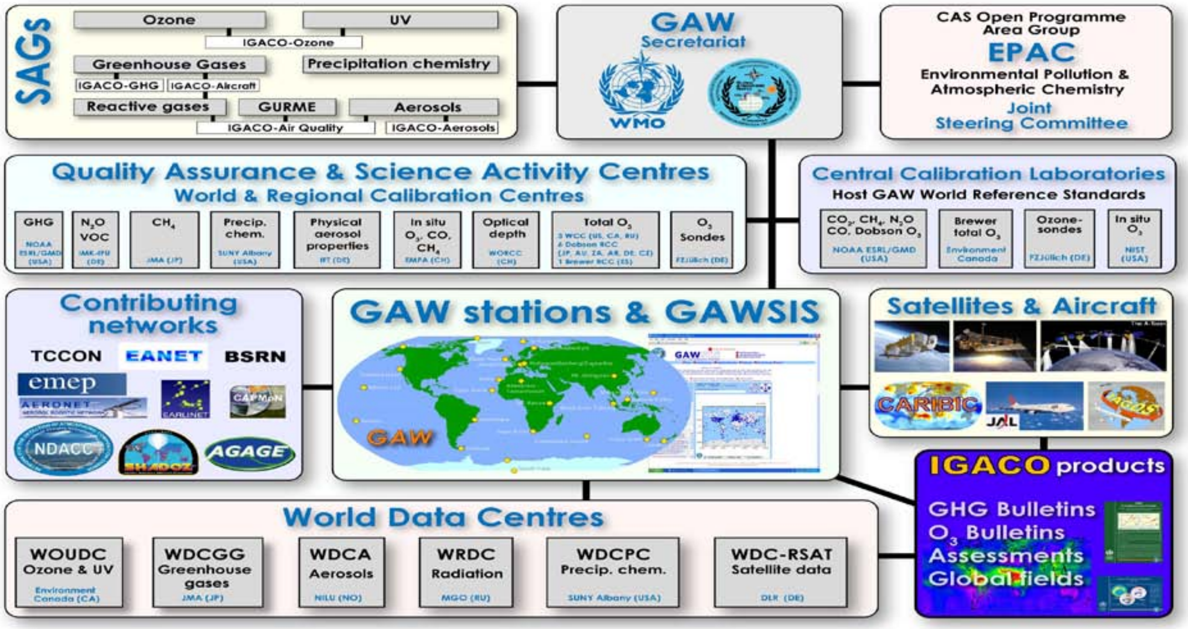

Figure 2: Concept of the Data Quality Assurance of the GAW (courtesy of Geir Braathen).

In Dobson instruments the difference in intensity of the radiation of two wavelengths is measurement using an optical wedge (allowing to decrease the signal of the wavelength with larger intensity until a zero signal is measured). Measurements are performed at two wavelength pairs in order to minimize the effects of aerosols. The world standard measurements are based on AD wavelength pairs (wavelengths: A-pair: 305.5 and 325.4 nm; D-pair: 317.6 and 339.8 nm) (for more details see: Komhyr, 1980; Evans, 2008). In Brewer instruments the absolute intensity are measured at 5 wavelengths (4 are used for column ozone determination: 310.0, 313.5, 316.8, 320.0 nm) and the ozone determination is based on a linear combination of the measurements at the different wavelength using weighting coefficients (for more details see Kerr et al., 1981). (The Brewer instrument also allows for SO_2 column determination; note that high SO_2 concentration in the planetary boundary layer is a significant interference for total ozone measurements of Dobson instruments, De Muer and De Backer, 1992) However note, that both types of instruments need calibration since the intensity of the solar radiation outside the atmosphere (I_o) is required to determine total ozone amount.

Most precise column ozone measurements can be obtained by direct sun observations. Zenith sky observations (e.g. Asbridge et al., 1996; De Backer, 1998) are particularly important at sites where cloudiness prevents representative sampling.

3. Data quality Assurance of column ozone measurements as part of GAW

Dobson and Brewer instruments are part of the Data Quality Assurance program of GAW (see Figure 2). The rules and terminology of GAW is described in the “Strategic Plan of GAW” (WMO, 2008). All measurements performed as part of GAW are published (free of charge) within the respective World Data Centre (see Fig. 2). Total ozone measurements are available at the World Ozone and Ultraviolet Data Centre (WOUDC) operated by Environment Canada (http://www.msc-smc.ec.gc.ca/woudc/, managed by Ed Hare).

For total ozone measurements the data quality program of GAW includes the following elements:

a. Absolute Calibration using the Langely plot method

For calibration of sun photometers of the type of Dobson and Brewer instruments the extraterrestrial constants need to be known (i.e. intensity of the radiation outside the atmosphere at the required wavelengths). For this purpose the Langley plot method is applied, i.e. the measured irradiance is plotted against the μ-value in order to extrapolate to $\mu=0$; this concept requires constant total ozone amount at clean sites for at least one half day, which is difficult to ensure for extratropical sites, because changes in synoptic meteorological condition can lead to changes in column ozone amount (e.g. Dobson and Normand, 1962). This problem is much less severe in remote (clean) sites in the tropics (or subtropics), and it is therefore more adequate to perform absolute calibration at such sites.

The **operational calibration scale of the Dobson network** is tied to the World Primary Dobson instrument, which is maintained by a group of the Earth System Research Laboratory (ESRL) of NOAA at Boulder (head of the group: Robert Evans) and regularly calibrated by the Langley plot method at the Mauna Loa observatory at Hawaii. The results of these calibrations are shown in Fig. 3, indicating that the instrument was very stable with fluctuations that did not exceed more than ± 0.5 % during more than 30 years.

The **Brewer operational calibration scale** is defined by a triad of Brewer instruments operated and maintained by Environment Canada (EC) and operated in Toronto (responsible scientists: Tom McElroy and Volodya Savastiouk). Individual instruments of the triad undergo regular absolute calibration by the Langley plot method at the Mauna Loa Observatory at Hawaii. The long-term stability of the calibration scale of the Brewer triad is well documented (Fioletov et al., 2005). The deviations of the monthly mean total ozone measurements of the single instruments are approximately ±0.5 % since 1994, while deviations of individual instruments of the triad tended to be sometimes larger in the period between 1984 and 1994 (maximally ± 1.5 %).

At the European regional Brewer calibration center at Izaña (Tenerife) a triad of Brewer spectrophotometers is operated and these instruments are regularly calibrated by the Langley plot method, which can be done at the subtropical station in Izaña; these measurements introduces an element of redundancy in the calibration scale of the Brewer network.

The Brewer user workshops which take place every two years provides an opportunity for knowledge exchange and training for scientists working with Brewer instruments.

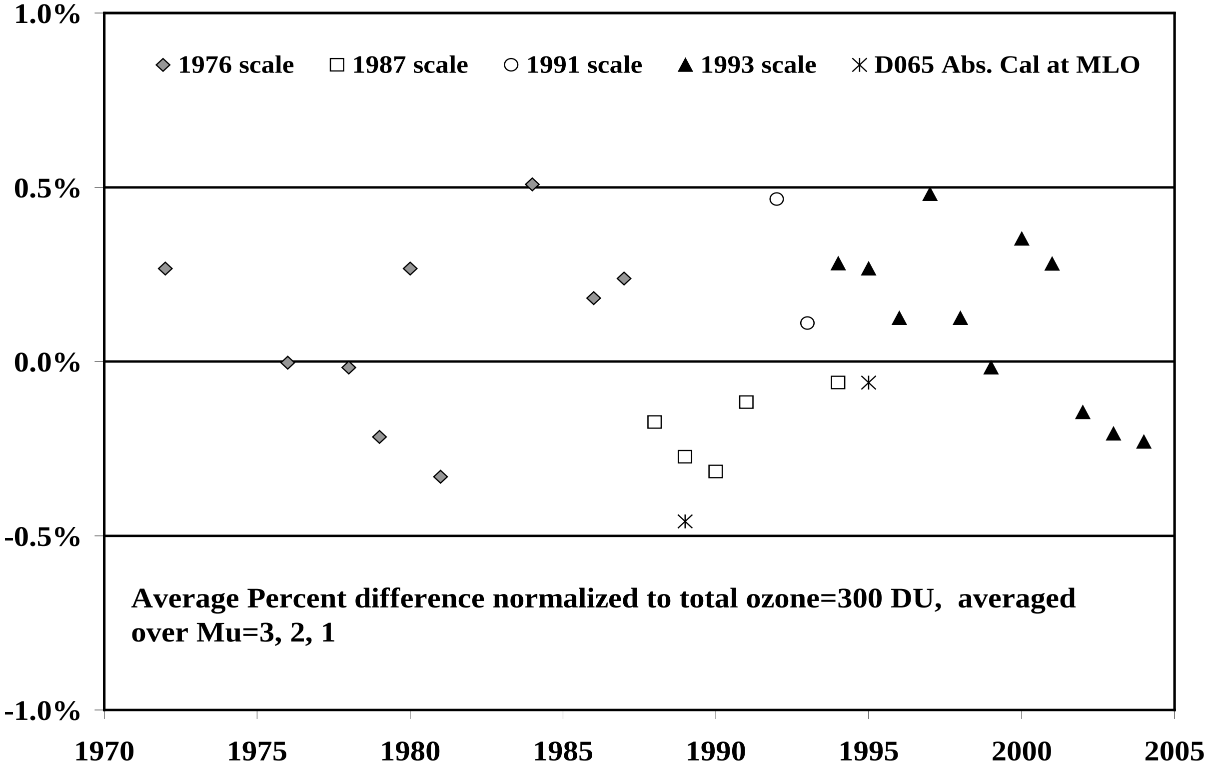

Figure 3: Stability of calibration of World primary Dobson instrument (D083): Percent difference in calculated total ozone based on corrections to D083 A and D tables derived from Langley plot method calibrations at Mauna Loa Observatory, Hawaii (MLO) (from Evans et al., 2004 and Komhyr et al., 1989).

b. Calibration of the networks

The calibration scale of the world primary instruments needs to be transferred to the station instruments; this is done by side by side calibration with standard instruments.

The ***calibration of the Dobson network*** (see Figure 4) is based on regional standard instruments which are first calibrated by comparison with the World primary Dobson instrument and subsequently used to calibrate the station instruments by side by side comparison in so called Dobson intercomparisons (however, note that not all regional Dobson centers shown in Fig. 4 are currently fully operational). During Dobson intercomparisons some instrumental technical problems can be fixed and the operators of the manually operated Dobson instruments can be trained. Each operational Dobson should particiapte in regular Dobson intercomparisons every four years.

The ***calibration of the Brewer instruments*** is organized in a different way. Intercomparisons of Brewer instruments with standard instruments should take place every two years. The transfer of the calibration scale is normally not the duty of regional calibration centres (only the European regional Brewer calibration presently exists) and different institutions are involved in the calibration of the Brewer station instruments: The instruments of the Canadian network are calibrated by Environment Canada and for European instruments the European Brewer calibration center offers this service. IOS (International Ozone Service) is a private company that can be engaged for calibration of Brewer station instruments. However, because IOS is a private company the institution of the station needs to finance this service, which can be difficult particularly for developing countries. WMO can be asked for support but the resources are limited. The company Kipp and Zonen (the company that manufactories Brewer instrument) also offers Brewer calibration.

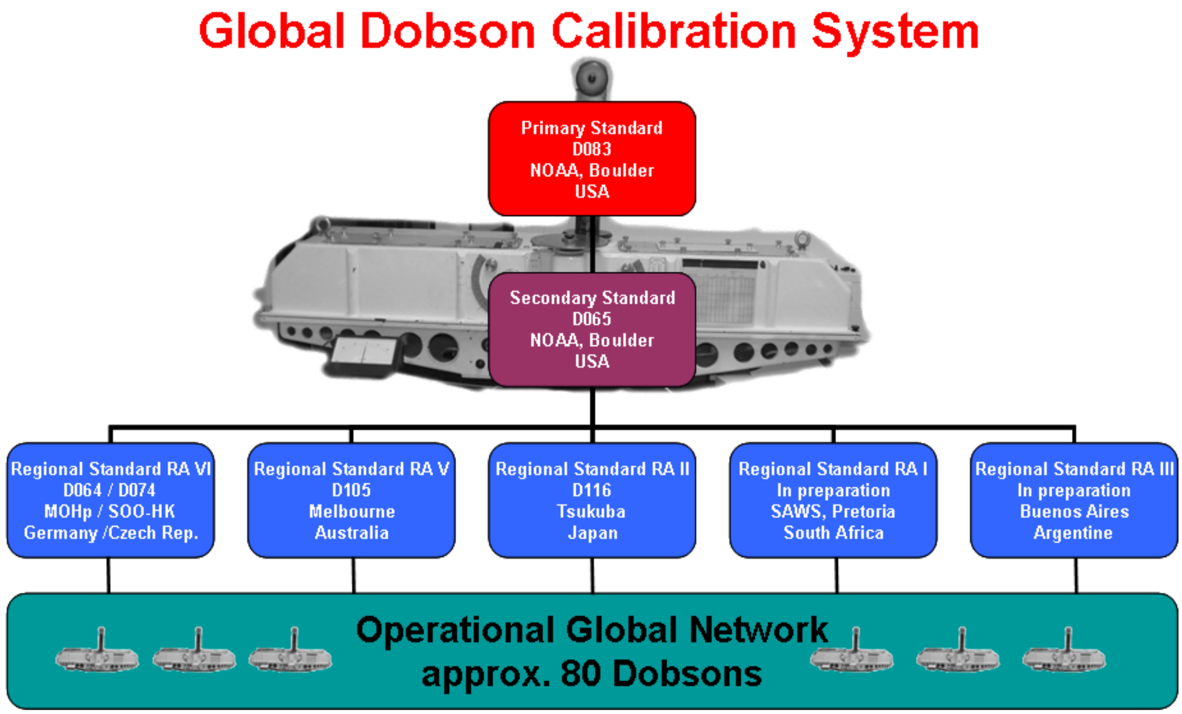

Figure 4: Concept of the global Dobson calibration system.

4. Experience with the GAW network of total ozone measurements

At the beginning of Dobson intercomparisons the readings of the Dobson instruments are always compared with standard instruments (prior to calibration). In the 1970s when this procedure was introduced, initial intercomparisons of individual instruments often showed large differences with the standard instruments (up to ±10%, see Fig. 5). Some problems of these early comparisons were described by Basher (1995). Since the middle of the 1980s the procedures used in the intercomparisons have been refined and now yield better agreement of the (initial comparisons) of station instruments and the standard instruments (see Fig. 5). (Note that potential instrumental shifts in calibration of station instruments can be linearly corrected using the information of the calibration of the instruments of two subsequent intercomparisons in connection with the results from the regular standard lamp tests.)

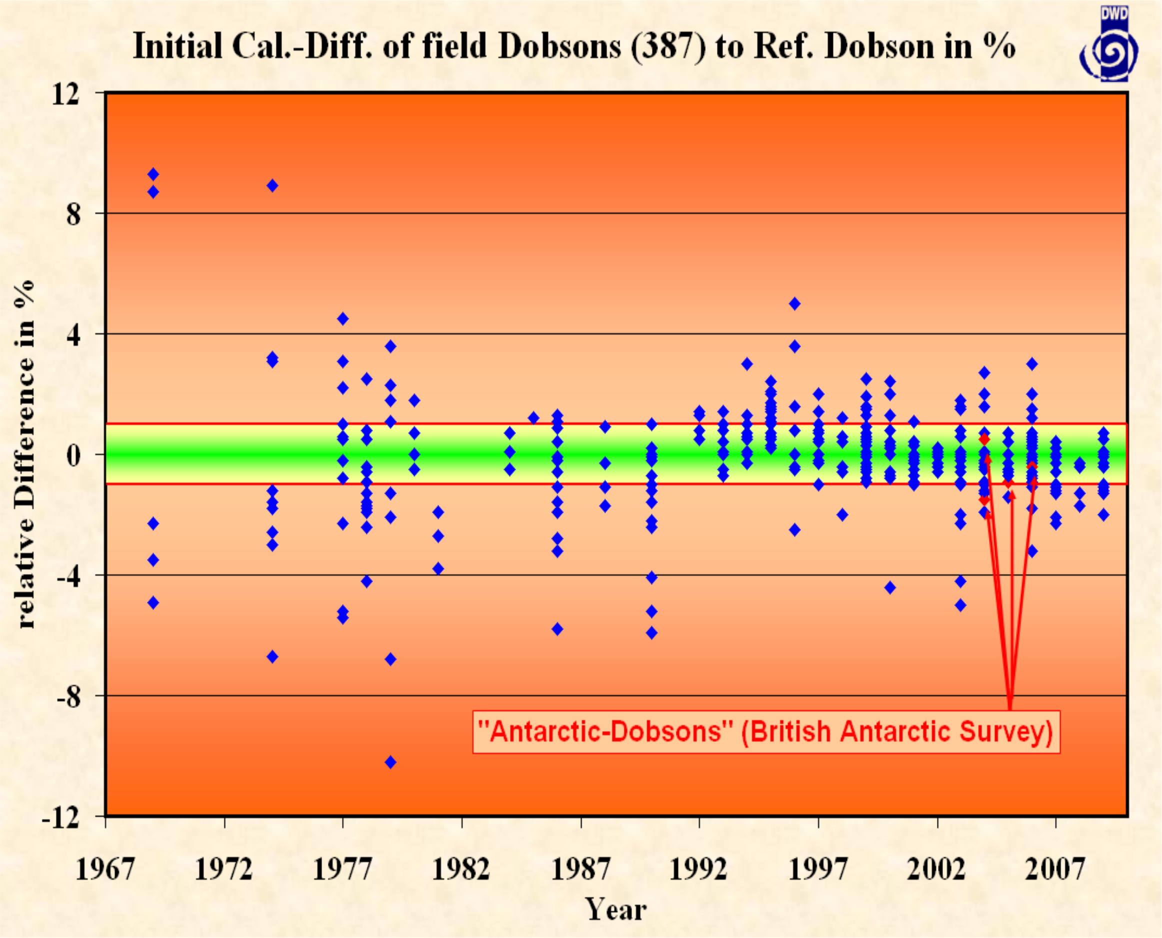

Figure 5: Relative differences between the Dobson instruments and compared station instruments during the initial calibrations of the intercomparisons since 1969 (from Köhler et al., 2004).

The results of Fig. 5 provide evidence that the intercomparisons improved the overall data quality of the Dobson network considerably, providing reliable total ozone measurements which are useful for long-term monitoring of the world ozone shield and useful for comparison with ozone satellite measurements. However, note that the transfer of extraterrestrial constants from one to another instrument can be only guaranteed with a precision of ±1% (for total ozone values corresponding to 300 DU). Since two transfers are involved in the calibration of the station instruments (from World primary Dobson instrument to the regional standard (or travelling standard) instrument and subsequently to the station instruments) the difference of individual station instruments can be larger than ±1% vs. the World Primary Dobson instrument. As an example, the intercomparison of Arosa in 1995 yielded a shift vs. the Arosa station instrument against the standard instrument of 1.95% (for AD observations at 300DU) compared to the intercomparison of 1990. However, in the next intercomparison (1999) the relative shift against the reference of 1990s was determined to be only 0.90% (see Scarnato et al., 2010). This implies that the calibration procedure is very suitable to maintain longterm calibration stability of the entire network within approximately ± 1% but occasional fluctuations of single station records can be larger.

High data quality total ozone measurements are essential for comparison with total ozone satellite observations (also compare Section 6). However, overpass satellite measurements can also used to get information about the quality of individual ground-based total ozone records; this method can be applied to identify technical problems of some stations which often show up as marked differences against the satellite data, often during some periods. Fioletov et al. (2008) used particular statistical metrics to identify “suspicious” or “outsider” of total ozone ground-based sites (for particular periods). Figure 6 illustrates that the majority of the stations have high data quality (since 1979, according the used statistical analysis). However, despite the large efforts of GAW a substantial fraction of the stations still doesn’t fulfil the requirements to be used e.g. for reliable long-term trend analysis. One main reason for such insufficient data quality of some records is probably the lack of correction of the data by applying the results obtained by intercomparisons. A workshop is planned by SAG-ozone to provide guidance to homogenize valuable historical total ozone records of some station.

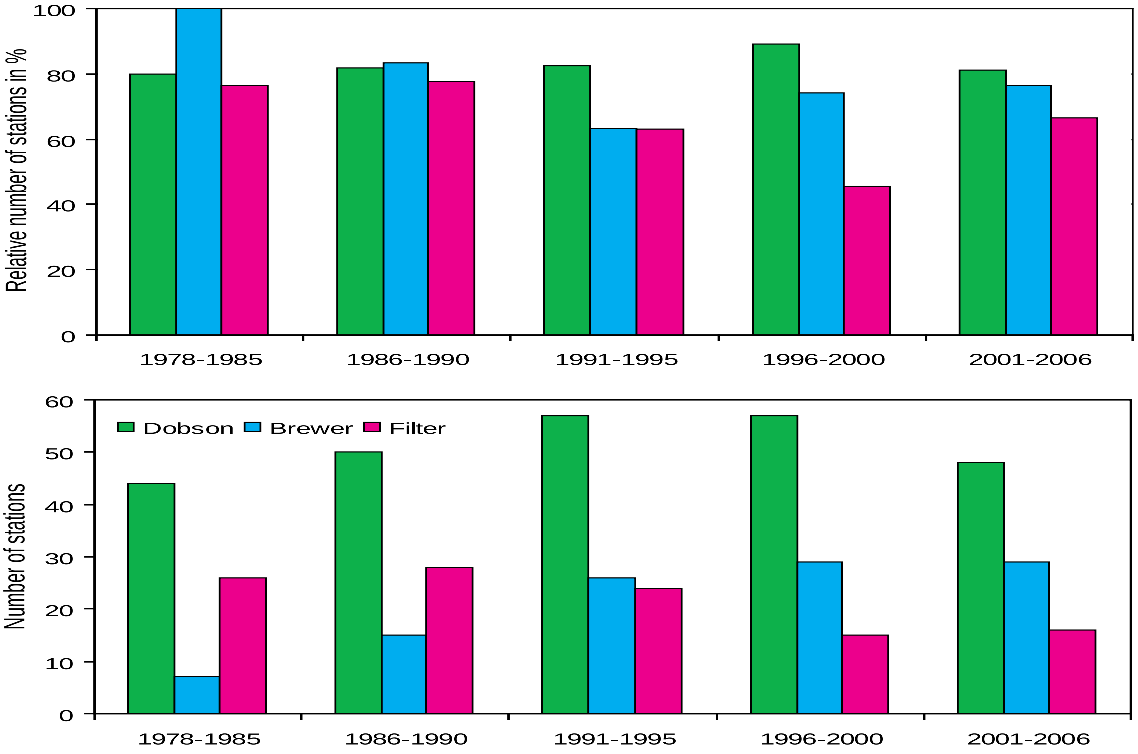

Figure 6: Absolute and relative (in percent from the total number) number of sites with ‘‘no issues’’ (see text) in the record in 5 bins for Dobson, Brewer, and filter instrument sites located between 60°S and 60°N (from Fioletov et al., 2008).

5. Conclusions and Outlook

The ground-based monitoring networks for Dobson and Brewer spectrophotometers of GAW were able to provide high data quality total ozone measurements suitable for long-term trend analysis (e.g. WMO, 2007) and validation of satellite instruments (e.g. Labov et al., 2004).

Due to its excellent instrumental design the Dobson instrument is still used as standard instrument in the GAW network. The instrumental precision of individual total ozone observations of Dobson instruments (AD-wavelength pairs) (as deduced from quasi simultaneous measurements of two instruments) was determined to be in the order of ±0.5 %, whereas the same value of the modern Brewer instrument is ±

0.15 % (Scarnato et al., 2010). The Dobson network reached high maturity whereas the Brewer network still can profit from improvements.

The redundancy of two independent networks was certainly useful to strengthen the reliability of long-term of the ground based monitoring of the ozone layer. (Note that the Dobson network provides significant additional information concerning total ozone in the time prior to the systematic measurements of satellite instruments.)

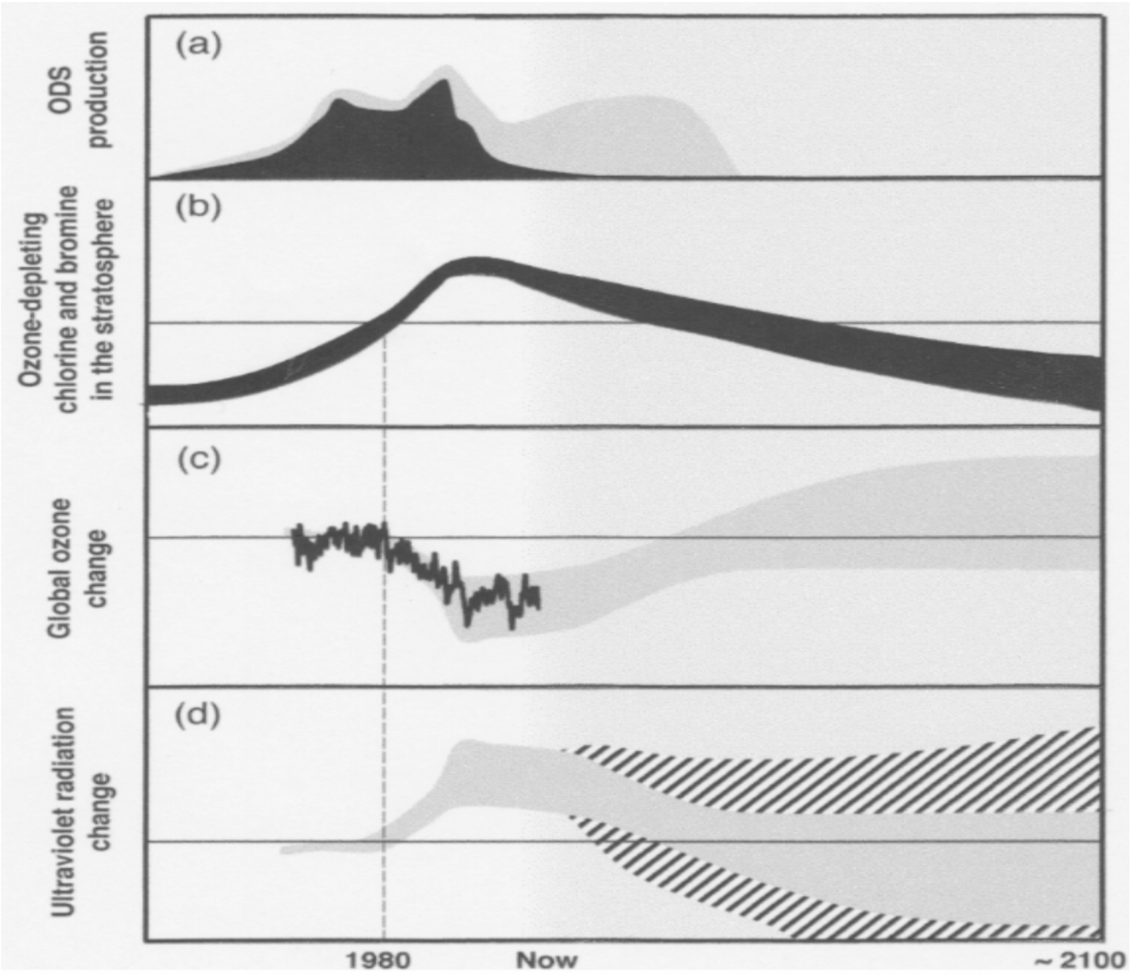

Figure 7: Overview of the stratospheric ozone history (WMO, 2007)

Because of the larger manpower demand it is expected, that the Dobson instruments might be more and more replaced by the completely automated Brewer instrument in future. However, note that the two instruments show systematic differences in seasonal variation (e.g. Kerr et al., 1988; Scarnato et al., 2009) and therefore a sudden replacement of Dobson by Brewer instruments leads to breaks in the time series implying that such series are no longer valuable for long-term trend analyses (e.g. Staehelin et al., 2003). It is therefore recommended to operate the two types of instruments simultaneously which allows to strengthen the reliability of the measurements of a ground-based site (at Arosa, Switzerland two Dobson and three Brewer instruments are presently in operation allowing to obtain valuable information on longterm stability of these types of total ozone instruments (e.g. Scarnato et al., 2010). If the replacement of Dobson by Brewer instrument cannot be avoided it is highly recommended to run the two type of instruments in parallel for at least three years allowing to construct reliable transfer functions.

A transfer of replaced Dobsons to developing countries, where manpower is not a financial issue, is then recommended to fill gaps in the global network.

Reliable and precise total ozone measurements are feasible in tropics and mid-latitudes whereas the accuracy of total ozone measurements by Dobson and Brewer instruments is strongly restricted in polar latitudes during winter since accurate total ozone measurements at low solar elevation are challenging. The same is also true for satellite instruments based on absorption in the ultraviolet. This problem needs further study.

The global coverage of ground-based total ozone instruments is still incomplete and it is desirable to extend the reliable ground-based monitoring (e.g. in Africa and South America).

The accuracy of the retrievals of ground-based as well as satellite instruments depends on ozone absorption cross sections. For instruments making use of ozone absorption in the Huggins band (300-340 nm) ozone absorption cross sections of Bass and Paur (1985) are currently used as standard values. However the more recent laboratory measurements of a French group (DBM: Daumont, Brion, Malicet, Malicet et al., 1995) have better accuracy and therefore the shift from Bass and Paur (1985) to DBM cross sections are presently evaluated. Indeed, the use of the same absorption cross sections in ground-based and in satellite instruments is desirable in order to limit the uncertainties in the comparisons between the two types of instruments.

At the present time it is still controversial whether it is possible to document by measurements the beneficial effect of the Montreal Protocol for the protection of the ozone layer (WMO, 2007). Particularly in light of the political relevance it is therefore crucial to continue the high data quality ozone monitoring for the next decades.

Satellite records are also very suitable for longterm stratospheric ozone monitoring and to document the recovery of the ozone shield. However, satellite instruments have limited lifetimes and therefore composite satellite series (merged satellite series) are becoming more and more important in future. The construction of such series from space instruments is often a very difficult task since the overlapping periods of satellite instruments are usually short and the correction of small offsets between individual satellite instruments is often impossible with adequate precision. In order to check the required precision of merged satellite total ozone series ground-based total ozone measurements with high data quality are therefore becoming even more important for the future.

Figure 7 summarizes the history of stratospheric ozone depletion. The production (and the related emissions) of ODS started after World War II and peaked in the late 1980 before they started to decrease because of the Montreal Protocol (panel a). The effect of chemical ozone depletion peaked for mid-latitudes in the middle of the 1990s and is presently slowly decreasing (panel b). Panel c indicates that available total ozone measurements of 60°S to 60°N seem to grossly reflect the temporal evolution expected from the manmade release of ODS and therefore one might ask whether high quality column ozone measurements will still have the same high priority in the future (after documentation of the recovery) as in the last decades. Indeed, it is not expected that new ODS emissions will basically reverse the expected slow recovery of the ozone shield. Panel c indicates (grey area) the prediction of numerical simulations indicating that a large part of state of the art numerical models expect, that the thickness of the ozone layer in mid-latitudes might become considerably larger than prior to the period when ODS started to deplete stratospheric ozone. This so called “super recovery” in extratrotpics might be caused by enhancements of the Brewer Dobson circulation which is expected as consequence of climate change (due to greenhouse warming) on stratospheric circulation. This effect might cause higher ozone concentrations in the tropopause region in the extratropics where ozone acts as a strong greenhouse gas. This implies that after the successful recovery of the ozone layer from the damage of ODS a new problem concerning change in climate might emerge. This new problem requires continuation of high quality measurements of total ozone also in the future.

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