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# Differences between ground Dobson, Brewer and satellite TOMS-8, GOME-WFDOAS total ozone observations at Hradec Kralove, Czech

**K. Vanicek**

Solar and Ozone Observatory, Czech Hydrometeorological Institute, Hvezdrana 456, 50008 Hradec Kralove, Czech Republic

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Correspondence to: K. Vanicek (vanicek@chmi.cz)

## Abstract

This paper presents key results achieved on analysis of relation between high-quality simultaneous Dobson, Brewer ground and TOMS-V8, GOME-WFDOAS satellite total ozone observations for Hradec Kralove, Czech Republic. Statistically significant seasonal differences with maxima up to 4% of monthly averages have been found between Dobson and Brewer measurements in winter/spring months. These differences can influence estimation of ozone trends if combined data series are used after replacement of the Dobson instrument by the Brewer spectrophotometer. The differences are mostly attributed to the influence of ozone effective temperature on ozone absorption coefficients and to total sulphur dioxide. Similar seasonal differences exist between Dobson, GOME and Brewer, TOMS data sets at Hradec Kralove while Dobson versus TOMS and Brewer versus GOME observations fit well with each other within the instrumental accuracy of spectrophotometers. The above findings are supposed to be relevant to other mid and high latitude stations and they have been confirmed by several independent analyses. The conclusions should be considered by data users because the differences between particular ground and satellite data sets can influence validation of satellite ozone observing systems and analyses of recovery of the ozone layer in mid and high latitudes, among others.

## 1 Introduction

Monitoring of atmospheric ozone by different ground instruments and space-born systems results in creation of diverse data sets that are used to investigate ozone changes caused both by natural atmospheric processes and man-made chemical emissions. Estimation of ozone trends and beginning of recovery of the ozone layer are the high-priory research tasks that require assessment of relation between long-term data records of the different origin.

Total column of ozone is a parameter that is frequently used to assess condition of the ozone layer. Roughly 125 ground stations regularly perform total ozone measurements in the network of the Global Atmosphere Watch Programme (GAW) and submit data into the World Ozone and UV Data Center, Toronto (WOUDC). The observations are predominantly taken with Dobson and Brewer ozone spectrophotometers at about 60 and 40 stations respectively Vanicek and Barrie (2004). Though the amount of both types of instruments is currently almost equivalent the capacity of the Brewer network is continuously increasing due to installation of Brewers at newly established stations and because of replacement of Dobsons by Brewers at existing stations. This raises a question whether the process of exchange of instruments can influence the long-term homogeneity of ground data records and their relation to satellite measurements.

The Solar and Ozone Observatory of the Czech Hydrometeorological Institute in Hradec Kralove, the Czech Republic (SOO-HK) is a GAW station (No. 096, 50.18° N, 15.83° E, 285 m a.s.l.) where total ozone measurements have been carried out since 1962. The SOO-HK is one of a few GAW stations where both Dobson and Brewer ozone spectrophotometers are operated simultaneously in complex modes for a long time. The observations thus make investigation of the above questions possible. Key results and some general conclusions that have been achieved at SOO-HK are presented in this paper. These can help scientists in understanding quality and proper application of total ozone data from WOUDC, e.g. for validation of satellite observations or for assessment of instrumental influences on estimation of ozone trends.

## 2 Measurements of total ozone with the Dobson and Brewer spectrophotometers in Hradec Kralove

### 2.1 Theory of measurements

The Dobson and Brewer ozone spectrophotometers measure total column ozone in the atmosphere by observations of Direct Sun (DS) spectral irradiances of solar radiation at selected wavelengths in the UV part of the spectrum with strong and weak



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absorption by ozone. Total ozone values *XDS* are derived by techniques of the differential optical absorption spectroscopy (DOAS) that are described in several reference papers, e.g. Dobson (1957), Komhyr (1980), Basher (1982), Kerr et al. (1981), Kerr (2002) and Evans et al. (2005). Calculation of total column ozone can be expressed by a general relation:

$$XDS = \left(Fo - F - \beta mp/po\right)/\alpha\mu \tag{1}$$

where *Fo* and *F* are linear combinations of logarithms of extraterrestrial and ground spectral irradiances measured by the instruments, $\alpha$ and $\beta$ are linear combinations of ozone absorption and Rayleigh molecular scattering coefficients at the same wavelengths, $\mu$ and $m$ are relative optical air masses of the ozone layer and the entire atmosphere, $p$ and $po$ are the observed and mean sea air pressures. The above linear combinations eliminate influences of the atmospheric aerosol on the observations.

Total ozone observations from scattered Zenith Sky radiation (ZS) are carried out with instruments if DS measurements can not be performed due to bad weather condition. In that case total ozone *XZS* is determined by means of zenith polynomials $f(\mu, F)$:

$$XZS = f(\mu, F) \tag{2}$$

The polynomials are empirical functions derived from quasi-simultaneous observations of *XDS*, and *ZS* readings of $F$ taken at $\mu$. The $f(\mu, F)$ can be developed separately for Zenith Blue (ZB) and for Zenith Cloudy (ZC) skies, respectively. Investigations show that zenith measurements can produce reliable values of total ozone. But Asbridge (1998), De Backer (1998) and Vanicek et al. (2003) have shown that the polynomials have to be developed for a particular instrument and location individually as they depend significantly on external and internal scattering of the light

The Dobson spectrophotometer measures spectral irradiances at three wavelength pairs marked *A*, *C*, *D* that are selected by fixed slits. Total ozone values *XAD* and *XCD* can be calculated for combinations of double pairs AD and CD. Because of the best precision of the instrument for the *AD* measurements the *XAD* observations are recommended as the reference once – see Komhyr (1980), Basher (1982). The Brewer instrument scans the UV spectrum by a rotating slit mask for five wavelengths that can be precisely defined by lamp tests. Only one representative total ozone value *X* is calculated from the relations Eqs. (1) or (2).

It is important to point out as for the next parts of this paper that:

- Values of the *F* come from measurements and they reflect actual composition of atmosphere

- Parameters *Fo* depend on technical condition of the instrument and they are called the "extraterrestrial constants" (ETCs). Their values represent key calibration constants of spectrophotometers.

- The linear combination *F* for the Brewer spectrophotometer makes measurement of total column sulphur dioxide possible and thus this fraction can be separated from total ozone.

- Since January 1992 the Bass-Paur differential ozone absorption coefficients $\alpha$ have been used for calculation of total ozone at all GAW stations, as recommended by the International Ozone Commission and WMO, Meggie et al. (1991) and Hudson et al. (1991).

- All Dobson spectrophotometers use the values of $\alpha$ determined for the slit function of the World Primary Dobson Spectrophotometer D083 (WPSS) and effective ozone temperature $TOeff$=–46.3°C, Komhyr et al. (1993).

- For processing of the Brewer observations the coefficients $\alpha$ are defined for wavelengths actually measured by a spectrophotometer. Therefore, the Brewer total ozone values do not contain total $SO_2$ fraction and they are *TOeff* independent as shown in Kerr (2002).

- As for Dobson total ozone measurements only observations taken on the reference wavelength pair AD are presented in this paper.

### 2.2 Measurements in Hradec Kralove, calibration stability of instruments

Regular measurements of total ozone have been performed with the Dobson D074 and the Brewer B098 ozone spectrophotometers at SOO-HK since 1962 and 1994 respectively. The Dobson observations are taken every day if weather condition allows (no rain or heavy clouds) on A, C, D wavelength pairs in 1-min intervals. Though DS observations are preferred since 1967 zenith ZB and ZC measurements have been carried out, as well. The Brewer observations are performed daily under any weather condition in pre-defined schedules that include both DS and ZS measurements. Thus a big number of quasi-simultaneous DS and ZS total ozone values are available to develop zenith polynomials for both instruments and the location. Generally, about 1300 Dobson and 10 000 measurements are taken per year. Roughly 30–40% of them are DS observations.

The D074 and B098 spectrophotometers are maintained in the calibration scales defined by the world standards – the World Primary Dobson Spectrophotometer D083 (WPDS) Komhyr et al. (1989) and the Brewer Reference Triad (BRT) Kerr et al. (1998), by means of regular intercomparison towards travelling references and by lamp tests. A detailed analysis of calibration records has confirmed in Vanicek (2003) that precision of the D074 instrument was 1–2% for the period 1962–1979 and 1% from 1980 onwards for DS-AD measurements and the range of $\mu$ below 3.2. The B098 spectrophotometer keeps permanently its calibration stability with 1% accuracy for $\mu$ less than 3.4.

### 2.3 Evaluation of data sets

A complex re-evaluation of total ozone data series from SOO-HK was performed by reprocessing of 52 162 Dobson and 63 540 Brewer observations from original raw readings of the periods 1962–2003 and 1994–2003 respectively. Re-defined monthly values of calibration constants, the Bass-Paur absorption coefficients and zenith polynomials updated for D074 and B098 instruments were applied in the re-calculation. The new total ozone data were checked for their quality and about 5% of unreliable measurements were cancelled. The methodology was defined with the aim to results achieved at other GAW stations, e.g. Degorska and Rajewska-Wiech (1991), De Muer and De Backer (1992), Koehler (1995), Staehelin et al. (1998), Josefsson, (2000). Results of the evaluation presented in Vanicek et al. (2003) show that operational accuracy of individual Dobson observations was about 1% for DS, 2% for ZB and 3% for ZC respectively while for the Brewer instrument the accuracy was 1% for DS and 3–5% for ZS measurements. Long–term offsets between DS and zenith total ozone values were less than 1% for both D074 and B098 observations and all months of the year, as documented in Fig. 1.

### 2.4 Accuracy of estimation of monthly means of total ozone

Monthly averages of total ozone *Xm* reported to WOUDC are calculated at stations from daily means *Xd* and thus they depend on numbers of days with observations in a particular month. If the number of days in a month is too low, e.g. because of bad weather condition or due to interruption of observations, then the value of *Xm* becomes statistically less representative. To assess accuracy of estimation of true monthly means by calculation of *Xm* from incomplete monthly sets of *Xd* value the Monte Carlo technique was applied on the re-evaluated forty-year data set from SOO-HK measured by D074.

In the experiment sets of moths with high number of observation-days ($n$>20) were selected for each month of the year and the period 1962–2003. Then in each month-set numbers $n$ of days were decreased by a consequent random extraction of values *Xdi* in a series from $n$ to $n-i$, $i$=1...$n$−1 and new monthly averages *Xmi* were calculated. Then *Xmi* and *Xm* values were compared and their differences used to assess the accuracy of estimation of the monthly means in dependence on the $i$. Results of the experiment are given in Table 1 as numbers of *i* that are needed to reach 1 to 5 percent accuracy of estimation of monthly means at the 95% confidence level in particular months of the year. It is evident from the table that a strong annual dependence of the numbers of days i exists being the highest in winter and the lowest in summer. Generally, if a monthly mean of total ozone is to be estimated with better than 3 percent accuracy then at least 10 days in summer months and up to 20 days in winter months are needed. It has to be pointed out that Table 1 is based on total ozone data observed in Hradec Kralove and therefore, it is relevant to the northern mid-latitudes where high ozone variations appear in the winter and spring months. For other regions the numbers can be different according to seasonal ozone variability.

## 3 Differences between Dobson and Brewer total ozone observations

### 3.1 General aspects

The Brewer spectrophotometer was introduced as an advanced and compatible successor of the Dobson spectrophotometer in the early nineties. In the beginning comparative observations analyzed by Kerr et al. (1988) did not show significant biases between both spectrophotometers. But later operators from some mid and high latitude stations, where collocated instruments are operated, have found seasonal deviations that substantially exceed precision of the well calibrated instruments. The complex analysis given in Staehelin et al. (2003) identified following possible reasons of the differences that should be further investigated.

- The Dobson instruments are mostly calibrated at group intercomparisons that are taken in climate conditions of summer stratosphere when *TOeff* is close to –46.3°C. In the winter season or at stations located in higher latitudes the spectrophotometers are operated under colder stratospheres and thus the Dobson observations can become *TOeff* dependent.



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– The Brewers are predominantly calibrated by travelling standards at home stations and because of the technology of observations their data should not be *TOeff* dependent.

– Unlike the Brewers, which measure at wavelengths with exactly attributed ozone absorption coefficients, the Dobsons are believed to measure at the effective wavelengths of the WPSS instrument and its values of $\alpha$ are commonly used for processing of measurements. If this assumption is not properly guaranteed (e.g. by incorrect adjustment of slits) then the above $\alpha$ values do not reflect the actual wavelengths and the observations can be more *TOeff* dependent.

– The Dobson total ozone columns contain also a fraction of total sulphur dioxide while in Brewer measurements the $SO_2$ is separated. At Dobson stations that are affected by strong local/regional emissions the $SO_2$ can influence accuracy of total ozone observations if its column is higher than about 3 DU (1% precision of the instrument).

– Indispensable differences in total ozone can appear for low solar elevations and high total ozone because of somewhat different algorithms used for calculation of $\mu$ in Dobson and Brewer operational software. This concerns roughly the range of $\mu>4$.

### 3.2 Relation between Dobson and Brewer observations in Hradec Kralove

Identification of instrumental and methodological sources of differences between Dobson XD and Brewer XB observations and assessment of their impacts on estimation of trends of total ozone were the main goals of investigation. Attention was focused mainly on the high quality Direct Sun observations. As the amount of measurements taken with the manually operated D074 and the automated B098 are substantially different, the individual quasi-simultaneous DS observations instead of averaged (e.g. monthly) total ozone values of the period 1994–2004 were compared. About 6.900 pairs of



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measurements taken in 10-min intervals at $\mu$<3.5 (SZA<74°) were selected from the re-evaluated data sets. Their differences $DIF=100(XD-XB)/XD$ in percents: were analyzed after application of corrections as follows.

### 3.2.1 Original data

Differences between the original Dobson *XDorig* and Brewer *XBorig* data are viewed in Fig. 2. They confirm the seasonal course with maxima in summer and minima in winter months that differ up to 3–4 percents. A sudden shift in differences is evident in June/July 1997 when both D074 and B098 instruments were re-calibrated towards the world traveling standards (D065, NOAA and B017, IOS) at the same time but at different places. Though the latest papers by Evans et al. (2004) and Fioletov et al. (2004) confirm stability of the world calibration scales and their transfer into the network, an analysis of results of calibration campaigns in Vanicek (2003) indicates that the offset is probably caused by the transfer of the Dobson calibration scale. Though the shift is less than 1% that is still in limits of the accuracy of calibration procedures, its appearance at other stations of the global network should be taken into account by data users.

### 3.2.2 Corrections for *TOeff*

In the first step the original data were corrected for ozone effective temperature by means of correction factors $t_D$=0.13% and $t_B$=0.07% per 1°K for the Dobson and the Brewer respectively defined in Kerr et al. (1988). But finally the updated Brewer factor $t_B$=0.005% per 1°K was specified by Kerr (2002). The values of *TOeff* were calculated from convoluted vertical temperature and ozone profiles measured by ozone sondes at the GAW observatories in Praha, Czech and Hohenpeissenberg, Germany (100 and 450 km apart from Hradec Kralove). The corrections for *TOeff* have decreased seasonal amplitudes of differences remarkably – see Fig. 2.

#### 3.2.3 Corrections for total $SO_2$

A certain improvement of the relation between both data series in Fig. 2 has been reached by correction of the Dobson observations for total $SO_2$ measured by the Brewer instrument.

#### 3.2.4 Corrections for $\mu$

As some residuals of seasonal oscillation of differences *DIF* still persisted after all above corrections their possible influence of $\mu$ was also investigated. But no $\mu$-dependency of *DIF*s has been found for D074 and B098 by linear approximations of differences for the periods 1994–1997 and 1997–2004 – see Fig. 3. Therefore, no $\mu$-corrections have been applied to the *XDorig* and *XBorig* values. The curves are drawn for both periods separately to avoid an influence of the calibration shift in June/July 1997. Nevertheless, a significant impact of $\mu$ can appear for other spectrophotometers that have strong stray light effect.

The Dobson *XDcor* and Brewer *XBcor* total ozone values that were corrected by the relations:

$$XBcor = XBorig - 0.005\,(-46.3 - TOeff) \tag{3a}$$

$$XDcor = XDorig - SO2 + 0.13\,(-46.3 - TOeff) \tag{3b}$$

have reduced the seasonal differences *DIF*s to about 1% limits that correspond to operational precision of the spectrophotometers. As for the measurements from Hradec Kralove the relations (3a) and (3b) can be used for creation of coherent Dobson and Brewer data series. This methodology confirms conclusions stated in Staehelin et al. (2003) and it can be recommended at least for partial corrections of total ozone data saved in WOUDC. Calculation of the *TOeff* values for stations where ozone profiles are not available can be solved by regressions between *TOeff* and the most correlated temperature of standard pressure levels measured by the nearest aerological stations(s) or by temperature profiles taken from assimilated climate data bases



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(e.g. ERA-40, NCEP/NCAR Re-analyses). It should be noted that application of the Eqs. (3a) and (3b) for high latitude stations have to include also effects of temperature and ozone vertical profiles on calculation of $\mu$ as these can lead to substantial systematic errors in calculation of total ozone, see Evans et al. (2005).

### 3.3 Influence of corrections on estimation of long-term trends of total ozone

Re-evaluation and correction of total ozone observations described in Sects. 2.3 and 3.2 resulted in creation of three different data sets from SOO-HK of the period 1962–2004:

X1 . . . the re-evaluated Dobson data deposited in WOUDC (1962–2004)

X2 . . . the X1 data prior 1993 combined with Brewer data since 1994 (1962–1994–2004)

X3 . . . the X2 data corrected by relations (3a) and (3b) of the periods (1967–1994–2004)

The X3 series starts in 1967 because vertical ozone sonde profiles were not available for calculation of *TOeff* values prior 1967. The X1, X2 and X3 data series were used for estimation of decadal trends by means of a simple linear regression model. The trends are viewed in Fig. 4 in percents per decade for particular months, winter (DJFM), summer (MJJA) and year of the period 1967–2004. More sophisticated trend models (e.g. "Hockey Stick") were not applied as the analysis was focused on impacts of corrections and combination of data sets, not on accurate trend estimations.

Figure 4 shows that annual course of trends of all data series X1, X2, X3 are very similar and typical for NH mid latitudes (the highest depletion of the ozone layer in winter and early spring, almost no change in autumn). Differences between trends (X1–X2 and X2–X3) that reflect effects of combination and correction of the X1 are also viewed in the graph. They indicate more than 0.5% offsets per decade in the



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winter/spring months that can exceed 1% instrumental accuracy of observations during considered 3–4 decades (1967–2004) and thus significantly influence estimation of long-term changes. Trends of summer and in yearly averages seem to be not significantly affected.

Though the above conclusions show influence of technical condition of spectrophotometers operated in Hradec Kralove and ozone climatology at the place they generally confirm that sophisticated trend analyses for identification of ozone recovery should be carried out by means of coherent Dobson/Brewer data sets. This conclusion will become more important in coming years when the major number of Dobson spectrophotometers will be re-placed by Brewers in the global network and thus combined data sets will be more frequently used.

## 4 Differences between ground and satellite total ozone observations

### 4.1 TOMS Version 8 and GOME WF-DOAS total ozone data sets

In the considered period 1994–2004 operational total ozone observations were performed by the TOMS (Total Ozone Mapping Spectrometer) and the GOME (Global Ozone Monitoring Experiment) instruments on board the Earth Probe (NASA) and ERS-2 (ESA) satellites, respectively. Though both systems use the backscatter ultraviolet (BUV) techniques they differ in methods of total ozone calculations. The TOMS makes measurements at six UV wavelengths. Its retrieval algorithm that is described by McPeters et al. (1998) uses the standard DOAS approach with a-priory ozone profile climatology and the best fitting of ozone cross-sections to normalized radiances. The TOMS Version 8 is the latest data set that has been evaluated and released in 2004 by Labow et al. (2004). The GOME performs high-resolution scans of the nadir spectral radiances. A new WF-DOAS (Weighting Function DOAS) algorithm that has been developed and tested by the team of the University Bremen, see Coldewey-Egbers et al. (2005) and Weber et al. (2005) is one of technologies currently used for pro-



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cessing of GOME observations. This sophisticated technique fits the vertically integrated ozone weighting function to the sun-normalized radiances instead of fitting the ozone absorption coefficients. Therefore, unlike the TOMS observations the GOME total ozone values should not be *TOeff*-dependent.

In this paper the EP-TOMS Version 8 and GOME-WFDOAS data series from July 1996 to June 2003 (period when both data sets overlapped each other) were used for comparison towards the ground observations from SOO-HK. The TOMS data were taken from the files distributed by NASA in 2004. The GOME observations gridded for the location of Hradec Karlove were provided by M. Weber, University Bremen under the CANDIDOZ project.

### 4.2 Comparison of satellite and Dobson observations at Hradec Kralove

To avoid errors due to averaging over a day the Dobson DS total ozone measurements selected from the re-evaluated data set X1 were compared with the simultaneous (10-min to overpass time) satellite observations. Smoothed curves of differences presented in Fig. 5 show that the TOMS observations correspond to Dobson measurements within 1-percent limit of the Dobson's precision almost in the whole period of July 1996 – December 2001 and without seasonal features. But in January 2002 a sudden and persistent 3–4% offset has appeared. It confirms that also for Hradec Kralove the effect of technical degradation of the EP-TOMS instrument has not been eliminated in the Version 8 data set as it was supposed in Labow et al. (2004).

As for the GOME observations, their differences versus Dobson data have clear seasonal shape with maxima in summer and minima in winter. The winter peaks exceed the 1% range (Dobson values are lower) and they show similar features in time and magnitude like the differences between Brewer and Dobson observations discussed in the Sect. 3.2. This is evident also from averaged annual course of differences viewed in Fig. 7. Generally, prior January 2002 the Dobson measurements agree better with TOMS than with GOME observations.

### 4.3 Comparison of satellite and Brewer observations at Hradec Kralove

Smoothed differences between Brewer and TOMS and GOME overpass data are given in Figs. 6 and 7. The graphs show that GOME and Brewer agree within the 1% limits in the whole considered period. The TOMS measurements drop below –1% in the winter months of the comparable magnitude like Dobson-Brewer differences in Fig. 2. Persistent offsets about 3–4% of TOMS measurements appear again after 2001. Conclusions can be made that Brewer observations fit with GOME data within the instrumental precision of the B098 while the TOMS differences are seasonally dependent. As the offsets exceed the limits of accuracy also on days without the snow cover when errors due to high ground albedo can not contribute, the deviations are likely originated by seasonality of stratospheric climatology, e.g. by impacts of *TOeff* on the TOMS observations.

## 5 Conclusions

High quality homogenized Dobson and Brewer total ozone observations from Hradec Kralove were analyzed. It has been shown that both Direct Sun and Zenith observations can be used for estimation of ozone trends if both types of measurements are properly performed and processed with well developed zenith polynomials. If monthly averages are used for statistical studies then number of observation-days plays an important role as concerns accuracy of estimation of monthly means of total ozone.

Seasonal difference between simultaneous Dobson and Brewer observations have been found at Hradec Kralove. When the Dobson measurements were corrected by the relation (3a) for ozone effective temperature and for total sulphur dioxide then the differences mostly do not exceed 1-percent limits of instrumental accuracy of spectrophotometers. These results are in agreement with outputs published by some other stations with collocated Dobson and Brewer instruments.

Statistical experiments with combined data sets allowed the author to state that if



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the Dobson data series from Hradec Kralove is replaced (continued) by the Brewer one then estimation of decadal changes of total ozone can be significantly affected in winter and spring moths. This conclusion rises up a requirement for homogenization of all total ozone data sets at stations where Dobsons have been or will be replaced by Brewers if long-term changes of the ozone layer are to be well defined.

Similar seasonal differences have appeared also between ground and satellite total ozone data sets derived from TOMS-8 and GOME-WFDOAS observations for Hradec Kralove. The differences are evident for Dobson versus GOME and Brewer versus TOMS simultaneous observations. On the contrary, good fits exist for Dobson versus TOMS and Brewer towards GOME data. It seems to be caused by similar sensitivity of TOMS observations to ozone effective temperature like of Dobsons while the Brewer and GOME-WFDOAS observations are TOeff independent. The above seasonal offsets between different satellite data sets due to algorithms used for their processing should be taken into account and long-term homogeneity of observations further investigated by data users if recovery of the ozone layer is to be clearly identified by space missions, as well.

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**Table 1.** Numbers of days in particular months of the year needed to reach 1 to 5 percent accuracy of estimation of monthly means of total ozone on the 95% confidence level, Hradec Kralove, the D074 data set.

| | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Accuracy | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1% | 29 | 26 | 29 | 27 | 25 | 24 | 24 | 23 | 24 | 26 | 27 | 29 |
| 2% | 24 | 22 | 24 | 20 | 16 | 15 | 14 | 13 | 16 | 17 | 21 | 24 |
| 3% | 19 | 17 | 18 | 14 | 10 | 9 | 9 | 8 | 10 | 11 | 15 | 18 |
| 5% | 11 | 10 | 10 | 7 | 5 | 4 | 4 | 3 | 5 | 5 | 8 | 11 |



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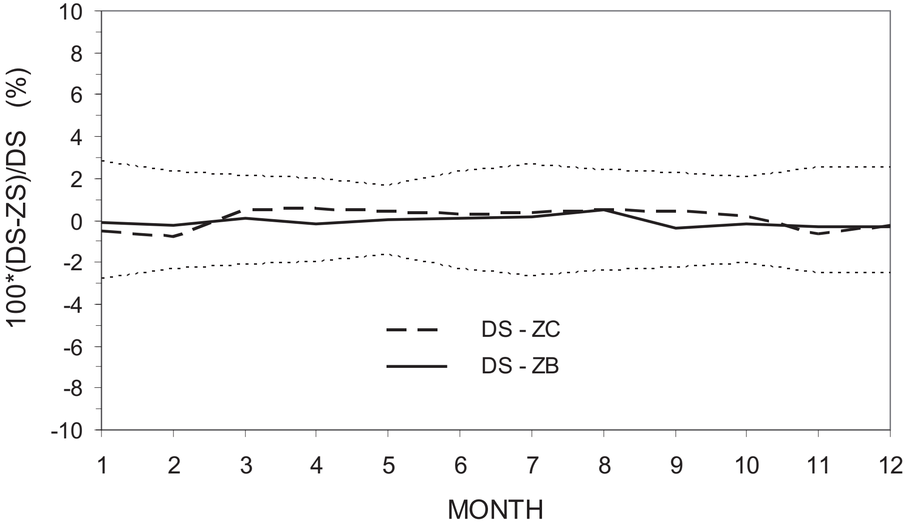


**Fig. 1.** Monthly average relative differences and their 1-STD limits between simultaneous Dobson and Brewer DS, ZB and ZC total ozone observations, Hradec Kralove, updated seasonal zenith polynomials.



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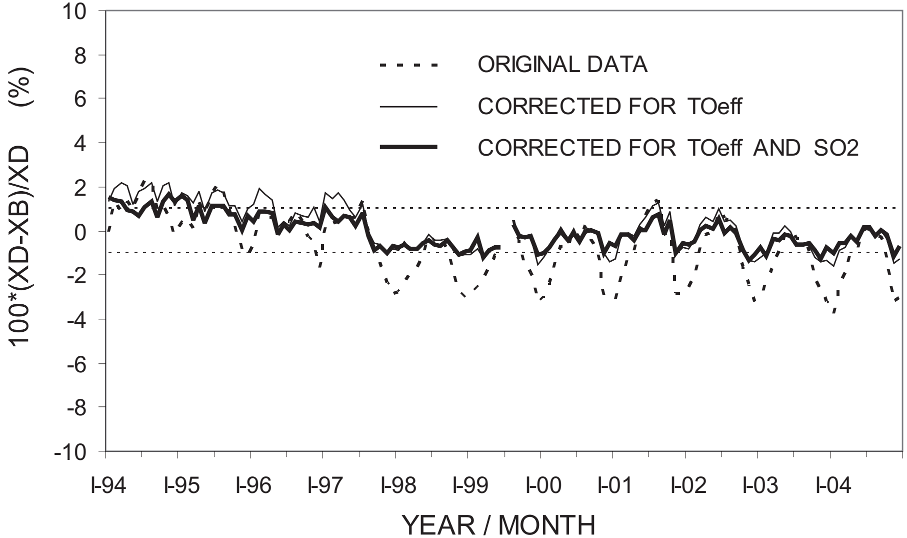


**Fig. 2.** Relative differences between simultaneous (10-min) Dobson XD and Brewer XB Direct Sun total ozone observations, Hradec Kralove, 1994–2004, original and corrected data, monthly smoothed curves.



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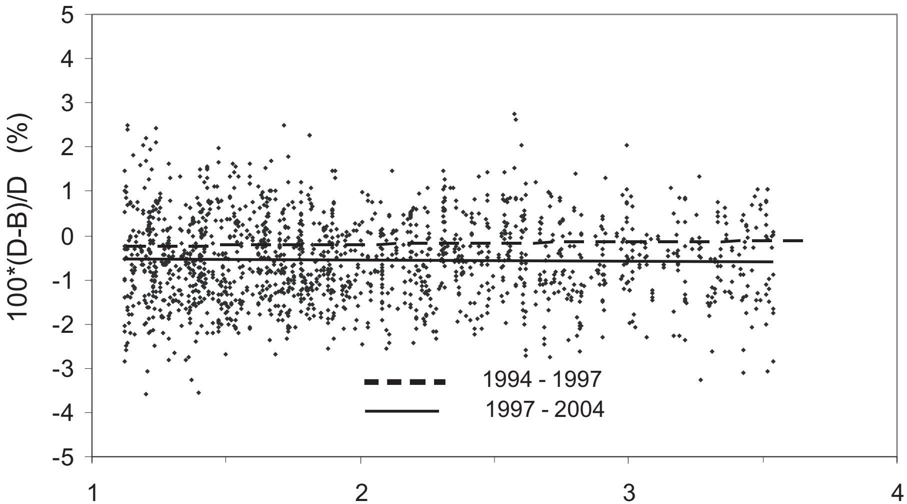


**Fig. 3.** Linear approximations of relative differences between simultaneous Dobson and Brewer Direct Sun total ozone observations – corrected data sorted by relative optical air masses of the ozone layer, Hradec Kralove, 1994–2004.



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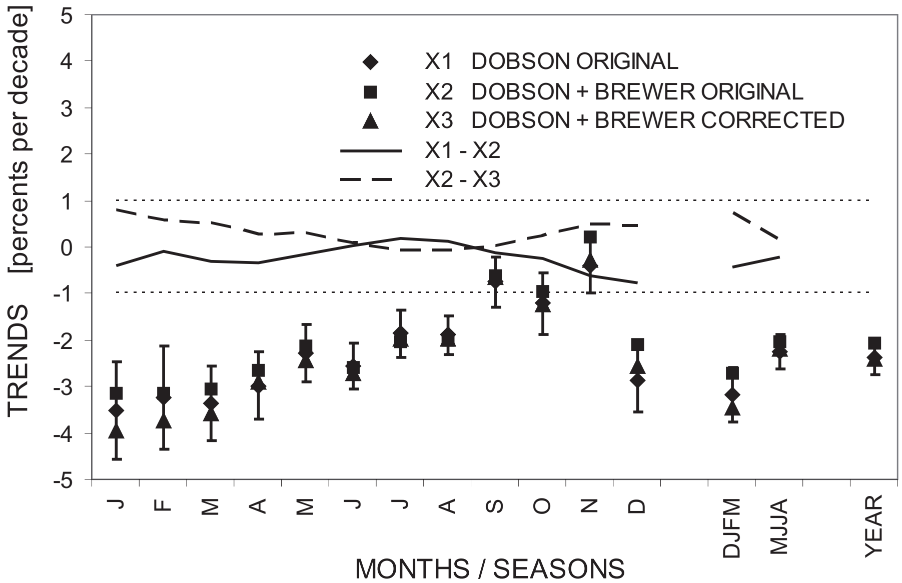


**Fig. 4.** Monthly and seasonal trends of the re-evaluated X1, combined X2 and corrected-combined X3 and differences between trends X1–X2, X2–X3 of Dobson and Brewer total ozone data series, Hradec Kralove, 1967–2004.

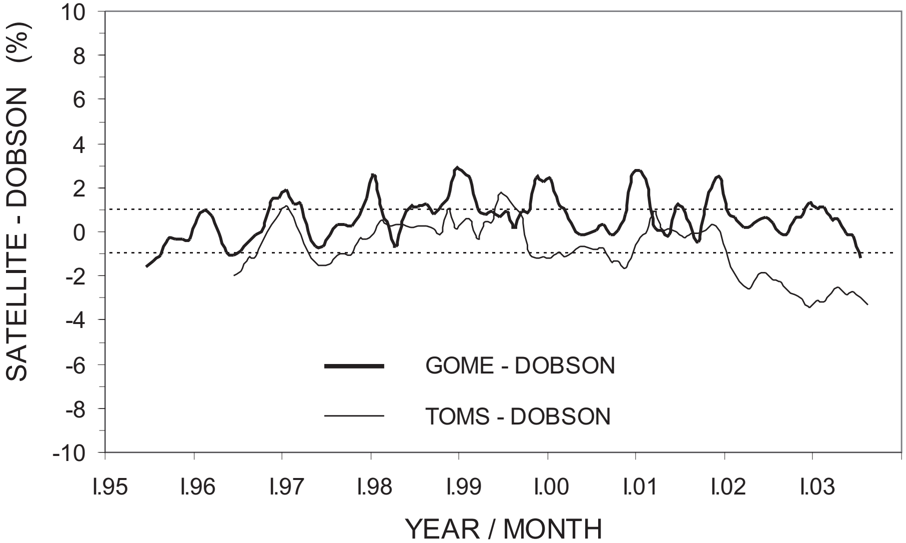


**Fig. 5.** Relative differences between simultaneous satellite and Dobson DS total ozone observations and 1-percent precision limits of the Dobson spectrophotometer, Hradec Kralove, July 1995–June 2003.



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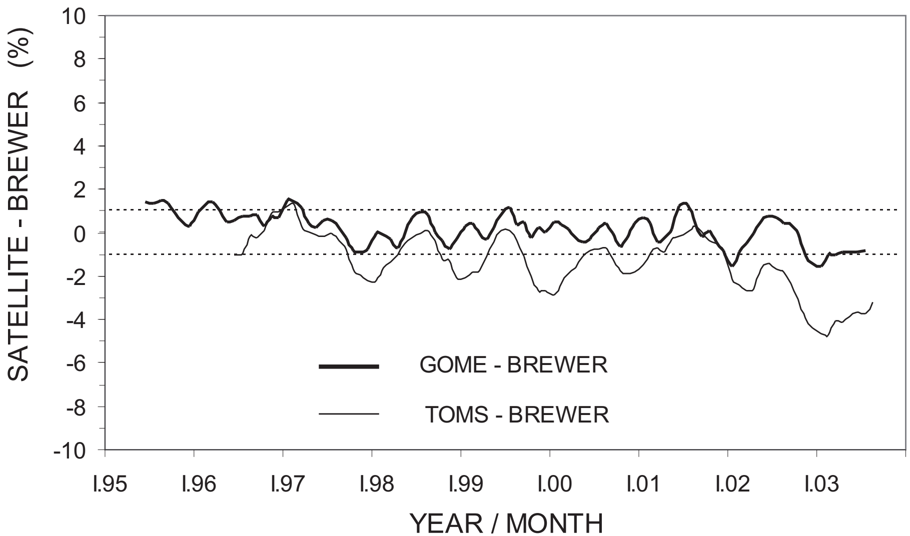


**Fig. 6.** Relative differences between simultaneous satellite and Brewer DS total ozone observations and 1-percent precision limits, Hradec Kralove, July 1995–June 2003.

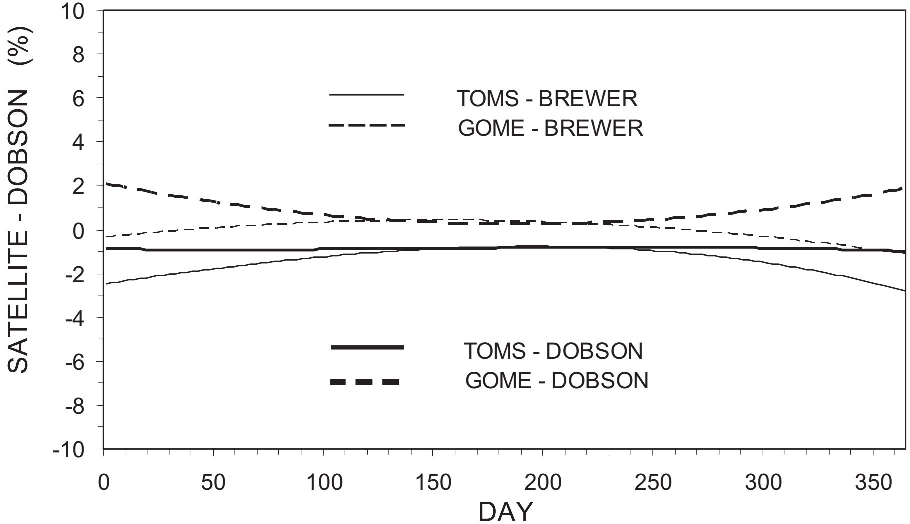


**Fig. 7.** Smoothed annual course of relative differences between simultaneous satellite and ground DS total ozone observations, Hradec Kralove, July 1996–June 2003.



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