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Comparison of profile total ozone from SBUV(v8.6) with GOME-type and ground-based total ozone for 16-yr period (1996 to 2011)

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Abstract

This paper describes the comparison of the variability of total column ozone inferred from the three independent multi-year data records, namely, (i) SBUV(v8.6) profile total ozone, (ii) GTO(GOME-Type total ozone), and (iii) Ground-based total ozone data records covering the 16-yr overlap period (March 1996 through June 2011). Analyses are conducted based on area weighted zonal means for (0–30° S), (0–30° N), (50–30° S), and (30–60° N).

It has been found that on average, the differences in monthly zonal mean total ozone vary between −0.32 to 0.76 % and are well within 1 %.

For "GTO minus SBUV", the standard deviations and ranges (maximum minus minimum) of the differences regarding monthly zonal mean total ozone vary between 0.58 to 0.66 % and 2.83 to 3.82 % respectively, depending on the latitude band. The corresponding standard deviations and ranges regarding the differences in monthly zonal mean anomalies show values between 0.40 to 0.59 % and 2.19 to 3.53 %. The standard deviations and ranges of the differences "Ground-based minus SBUV" regarding both monthly zonal means and anomalies are larger by a factor of 1.4 to 2.9 in comparison to "GTO minus SBUV".

The Ground-based zonal means, while show no systematic differences, demonstrate larger scattering of monthly data compared to satellite-based records. The differences in the scattering are significantly reduced if seasonal zonal averages are analyzed.

The trends of the differences "GTO minus SBUV" and "Ground-based minus SBUV" are found to vary between −0.04 and 0.12 % yr^{-1} (−0.11 and 0.31 DU yr^{-1}). These negligibly small trends have provided strong evidence that there are no significant time dependent differences among these multi-year total ozone data records.

Analyses of the deviations from pre-1980 level indicate that for the overlap period of 1996 to 2010, all three data records show gradual recovery at (30–60° N) from −5 % in 1996 to −2 % in 2010. The corresponding recovery at (50–30° S) is not as obvious until after 2006.

1 Introduction

Concern for changes in the ozone layer due to human activity is an important subject for the scientific community, the general public and governments. Accurate long-term data records of total column ozone and vertical profiles of ozone are required for the scientific assessment of ozone depletion (WMO, 2011).

In response to the observed ozone loss, countries around the world adopted the Montreal Protocol and subsequent amendments calling for limitations on production and use of ozone-depleting substances (UNEP, 2006; UNFCCC, 1998). Beside the impact of ozone depleting substances, natural fluctuations such as the 11-yr solar cycle, the equatorial quasi-biennial oscillation of the lower stratospheric zonal wind (QBO), and volcanic eruptions also significantly affect the thickness of the ozone layer. Moreover, climate change due to increase in greenhouse gas concentration will influence stratospheric dynamics and chemistry and therefore the ozone layer. Many investigations have been conducted for monitoring and detection of global ozone trends and behaviour using a variety of ground-based and satellite instruments and their comparisons. Recent studies based on long-term ozone data records and model simulations have significantly improved our understanding in the roles of various dynamical and chemical processes governing the ozone variations (Yang, 2006; Stolarski, 2006). However, many detail characteristics of the expected ozone recovery such as the beginning of the recovery and the timing of the recovery are still unclear. One of the major difficulties in assessing the long-term global ozone variations is data inhomogeneity. Changes in operational satellites, revision of the retrieval algorithms, recalibration of ground-based instruments or interruptions in observation periods result in data sets which have systematic errors that change with time.

The purpose of this study is to conduct an investigation of the consistency in the variability of global and zonal total ozone inferred from three independent multi-year data records, namely, (1) the recently released SBUV (v8.6) profile total ozone data record, (2) the new European GOME-Type total ozone record (GTO), and (3) Ground-based total ozone data record based on Dobson and Brewer spectrometer and filter ozonometer observations available from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) (http://www.msc-smc-smc.ec.gc.ca/woudc/). The two satellite-based merged ozone data records (SBUV v8.6 and GTO) are the most recent versions released during 2012–2013. They represent the results of two independent attempts by US and European scientists to adopt an optimal technique to merge ozone measurements from a series of satellite instruments aiming to construct a homogeneous self-consistent, calibrated long-term data record.

The analyses are based on the 16-yr overlap period (March 1996 through June 2011). Our major goal is to quantitatively evaluate the long-term stability of the differences among these three multi-year data records regarding the variability of global and zonal total column ozone.

Discussions will be focused on the consistency regarding monthly zonal mean total ozone and the monthly zonal mean anomalies. The results obtained herein should be able to enhance our understanding of the accuracy of these multi-year data records and provide a guideline for assessing the ozone variability obtained from modelling studies.

Detailed information of the three data records is provided in Sect. 2. Results of comparisons based on 5-degree monthly zonal means between 60° S and 60° N are presented in Sect. 3.1. Further analysis using area weighted monthly zonal means for (0–30° S), (0–30° N), (50–30° S), and (30–60° N) are discussed in Sects. 3.2 and 3.3. Changes which will occur when switching to analysis using seasonal zonal means are reported in Sect. 3.4. Trends of the differences are discussed in Sect. 3.5. Investigation of total ozone deviations from pre-1980 levels are reported for (30–60° N) and (50–30° S) in Sect. 3.6. Concluding remarks from our study are summarized in Sect. 4.

2 Brief description of the three ozone data records

2.1 SBUV v8.6 profile total ozone data record

NASA and NOAA have been measuring ozone from space since 1970. The previously existing merged ozone data set provided by NASA combines the TOMS data (Nimbus 7 and Earth Probe) and SBUV-SBUV/2 data (Nimbus 7, NOAA 9, 11, 14, 16). Studies were made by Stolarski et al.(2006) to use the merged ozone data set to search for evidence of ozone recovery in response to the observed levelling off of chlorine compounds in the stratosphere. The philosophy for producing the merged data set is to take the individual data sets and combine them by making simple offset corrections in ozone based on overlap periods or comparisons with other data sets. The correction offset is determined as the average difference in the (50° S to 50° N) zone. No time dependence is applied to an individual data set. All the monthly zonal means for an instrument are adjusted by that fixed offset. There is no latitudinal dependence applied. All data sets available for each month are then averaged together to produce the final merged ozone time series.

The newly released SBUV(v8.6) ozone profile data record incorporated the measurements from eight backscatter ultraviolet instruments (BUV on Nimbus 4, SBUV on Nimbus 7, and a series of SBUV/2 instruments on NOAA satellites). The coverage periods of each instrument used to create the merged ozone data set are shown in Table 1. Discussion of SBUV v8.6 algorithm is presented by Bhartia et al. (2013). An overview of the version 8.6 SBUV ozone data record is discussed by McPeters et al. (2013). Major improvement has been achieved by radiance adjustment made for each instrument to maintain a consistent calibration (DeLand et al., 2012). This new merged ozone data record covers the period from 1970 to 2011. Two other important changes in the processing of v8.6 are that the ozone cross sections of Brion, Daumont and Malicet have been used and that a cloud climatology derived from the Aura/OMI (Ozone Monitoring Instrument) cloud-height retrievals has been used.

2.2 GTO ozone data record

The European satellite-borne sensors GOME/ERS-2 (1995–2011), SCIAMACHY/ENVISAT (2002–2012), and GOME-2/METOP-A (2007–present) provide global total ozone measurements for the last 17 yr. A summary of the instrument properties and viewing geometries is given in Table 2.

The GTO merged ozone data record combines those measurements and a continuous and homogeneous monthly mean time series is generated (Loyola et al., 2009; Loyola and Coldewey-Egbers, 2012). The first GTO version was created using products obtained with the GOME Data Processor (GDP) version 4.x algorithm (Van Roozendael et al., 2006; Lerot et al., 2009; Loyola et al., 2011), which is based on the Differential Optical Absorption Spectroscopy approach. Geophysical validation shows that GDP 4.x total ozone has an accuracy at the percentage level compared with ground-based instruments (Loyola et al., 2011; Koukouli et al., 2012). The resulting GTO data record was used for the WMO ozone assessment report 2010 and for ozone studies (Dameris et al., 2012).

In this study we use the most recent version of the GTO data record that has been developed within the framework of the European Space Agency's Climate Change Initiative (ESA-CCI). It incorporates the ozone data products retrieved using the newly developed GOME Direct Fitting algorithm GODFIT (Lerot et al., 2010, 2013; Van Roozendael et al., 2012) and covers the period from March 1996 to June 2011.

The GTO merging approach accounts for differences among the individual instruments, which mainly depend on latitude, season, and time. Due to excellent long-term stability, the GOME measurements are used as a transfer standard, whereas SCIAMACHY and GOME-2 data are adjusted accordingly in periods of instrument overlap (Loyola et al., 2009). The adjustments comprise two parts: a basic latitudinal correction for each month of the year averaged over all years, and a time-dependent offset for each individual month accounting for the slight drift found in SCIAMACHY and GOME-2

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data with respect to GOME. Finally, monthly mean GOME, adjusted SCIAMACHY and GOME-2 data are merged.

2.3 Ground-based ozone data record

The World Ozone and Ultraviolet Radiation Data Centre (WOUDC) in Toronto began collecting and publishing ozone data in 1961 and remains the main source of ground-based ozone data for researchers. Global distributions of ground-based stations used in this study are depicted in Fig. 1. Large longitudinal inhomogeneity and limited spatial coverage make it impossible to estimate zonal and global total ozone values from station values directly. However, if an ozone "climatology" (i.e. long-term mean for each point of the globe for each day of the year) estimated from satellite data is used with ground-based measurements of ozone deviations from that "climatology" at the stations, then long-term zonal and global ozone variations can be estimated using ground-based data (Bojkov and Fioletov, 1995). In summary, the method measures ozone deviations from the "climatology" at the stations, then calculates the zonal deviations, and finally the zonal mean ozone is determined by adding the zonal mean "climatology" to the zonal means of the deviations. The results give a continuous uninterrupted global total ozone data record that is fairly independent from other data sources.

However, the absence of data over vast regions (e.g. oceans) and sensitivity to individual instrument errors is an important factor, particularly in the tropical region and the southern hemisphere where the number of stations is very limited. Comparisons of global and zonal ozone variations from ground-based and satellite measurements for the period 1964–2000 were presented by Fioletov et al. (2002). The Ground-based multi-year total ozone record used in this study is the recently updated one extending through November 2012.

3 Results and discussions

Even though the most recently released SBUV (v8.6) ozone profile and Ground-based total ozone data records cover 43-yr period (1970–2012) and 49-yr period (1964–2012) respectively, our studies will be focused on the 16-yr period (March 1996 to June 2011) for which these two data records overlap with GTO (GOME-Type total ozone data record). For high latitude regions, the number of ground stations is very limited to represent the characteristics of the latitudinal zones. It is also known that the sampling for satellite measurements is drastically reduced in the high latitude regions in both hemispheres. For example, as shown in Fig. 2, among the 184 months (from March 1996 to June 2011) selected for this study, there are more than 20 % of the months with missing data poleward of 60° S and 65° N in SBUV (v8.6) data records. Thus, our analyses and comparisons will only be based on the twenty four 5-degree monthly zonal mean time series (covering 60° S to 60° N) from these three multi-year data records.

3.1 5-degree monthly zonal means between 60° S and 60° N

Figure 3a–c show the monthly zonal mean total column ozone as a function of latitude and time given by SBUV (v8.6), GTO and Ground-based data records respectively. Black regions in Fig. 3a represent missing data in SBUV (v8.6). Variations for the twenty four 5-degree latitudinal zones between 60° S and 60° N are depicted along the vertical direction and the month-to-month variations are illustrated horizontally. The features revealed in these figures clearly indicate that the three data records exhibit almost identical patterns of temporal and latitudinal variations for the entire 16-yr period.

The differences (in %) between each pair of data records are further illustrated in Fig. 4a–c. Black regions in Fig. 4a and b represent missing data in SBUV (v8.6). It is interesting and encouraging to find out that these results have led to the conclusion that the agreement between the two satellite-based ozone data records is significantly better than the agreement between each satellite data record and the Ground-based record. Statistical parameters for the percentage differences revealed in these figures are listed in Table 3a–c.

After a more detailed investigation of the three data records, it has been found that the monthly zonal mean at (60–55° S) from Ground-based record has an obvious outlier appearing at one particular month, namely, November 2009. Thus, we have intentionally exclude that particular data point in deriving the statistical parameters listed in Table 3b and c. The entries with asterisk listed in the first row in Table 3b and c would increase to 27.58 and 28.27 % respectively without excluding this data point.

Major findings from the results of Table 3a–c can be summarized as follows:

1. For both “GTO versus SBUV” and “satellite-based record versus Ground-based record”, the standard deviations and the ranges (maximum minus minimum, representing peak-to-peak variations) of the differences are similar for (0–30° S), (0–30° N), and (30–60° N) and are much smaller than those at (30–60° S).
2. The standard deviations of the differences between the two satellite-based records vary between 0.70 to 0.98 %. The corresponding standard deviations for satellite-based record versus Ground-based record are significantly larger, ranging between 1.37 to 2.13 %.
3. The ranges of the differences “GTO minus SBUV” vary between 3.96 and 9.87 %. The corresponding ranges of the differences for (Ground-based record versus Satellite-based record) are larger by a factor of 2 to 3.

3.2 Area weighted monthly zonal means for broader latitudinal zones

In order to examine the characteristics of the differences between pairs of data records for several wider latitudinal zones, we have computed the area weighted monthly zonal mean time series for (i) 0–30° S, (ii) 0–30° N, (iii) 50–30° S, and (iv) 30–60° N. Cosines of the mean latitudes correspond to each 5-degree zones are used for the weighting factors. For the southern hemisphere, area weighted means are limited to equator-ward of 50° S due to a large number of months (namely, 26 months) with missing data in (55–60° S) in SBUV (v8.6) data record. The monthly zonal mean time series for these four broad latitudinal zones are plotted in Fig. 5a–c, and d respectively. The corresponding differences, with respect to SBUV, are illustrated in Fig. 6a–d. The statistical parameters corresponding to these differences are summarized in Table 4.

The entries of mean differences in Table 4 have led to the conclusion that on average, the differences of monthly zonal mean total ozone between the two satellite records and between satellite record and Ground-based record vary between −0.32 to 0.76 % and are well within 1 %. The long-term stability of the differences during the 16-yr period is revealed by the standard deviations and ranges listed in Table 4. The standard deviations for "GTO minus SBUV" are found to lie between 0.58 and 0.66 % while "Ground-based minus SBUV" exhibits less stability with standard variations varying between 0.91 and 1.23 %. The ranges of the differences for "GTO minus SBUV" vary between 2.83 and 3.82 %. It is also noticed that the corresponding ranges of the differences for "Ground-based minus SBUV" are larger by a factor of 1.4 to 2.4, varying between 5.14 and 6.92 %.

3.3 Monthly zonal mean anomaly

The consistency among the data records in terms of interannual variations in total ozone could be examined through investigation of the monthly zonal mean anomaly. For the purpose of our current study, monthly zonal mean anomaly for each month is calculated by simply subtracting the averaged over the entire 16-yr period (for the same calendar month) from each monthly zonal mean total ozone. The times series of monthly zonal mean anomaly for the four broad latitudinal zones are plotted in Fig. 7a–d. The corresponding differences, with respect to SBUV, are illustrated in Fig. 8a–d. The statistical parameters corresponding to these differences are listed in Table 5. The standard deviations of the differences for "GTO minus SBUV" vary between 0.40 and 0.59 %, and the corresponding values for "Ground-based minus SBUV" are larger by a factor of 1.8 to 2.6. The anomalies inferred from GTO and SBUV show very good agreement, with ranges of the differences varying between 2.19 and 3.53 %. The corresponding ranges for “Ground-based minus SBUV” exhibit larger scattering with values ranging between 4.35 and 6.29 %.

3.4 Seasonal zonal mean and anomaly

It is generally acknowledged that the poor spatial sampling and the relatively infrequent measurements could be the major factors causing the differences between ground-based and satellite monthly zonal mean total ozone data. To further explore evidence supporting such an argument, we have conducted additional analysis for the comparisons of “GTO versus SBUV” and “Ground-based versus SBUV” using the seasonal zonal means instead of the monthly zonal means. Results of the differences in seasonal zonal means and in seasonal zonal mean anomalies are summarized in Tables 6 and 7 respectively. The entries with brackets in these tables denote the reduction of each parameter compared to the corresponding values in Tables 4 and 5, which are based on monthly zonal means. The results in Tables 6 and 7 clearly indicate that the reduction in both the standard deviations and the ranges of the differences for “Ground-based minus SBUV”, when switching from monthly zonal means to seasonal zonal means are found to significantly exceed the corresponding reduction for “GTO minus SBUV”.

These results have led to the conclusion that Ground-based zonal means, while show no systematic differences, demonstrate larger scattering of monthly data compared to satellite-based records. The differences in the scattering are significantly reduced if seasonal zonal averages are analyzed.

3.5 Trend of the differences

Another approach to examine the consistency in the variability of total ozone exhibited by the multi-year data records is to investigate whether there is any time dependency in their differences. In this regard, we have computed the linear trends using the differences of monthly zonal means for "GTO minus SBUV" and "Ground-based minus SBUV" represented by the red curve and black curve depicted in Fig. 6a–d. The trends of the differences for the four latitudinal zones are listed in Table 8a in terms of percent per year. The corresponding trends in DU per year are also listed in Table 8b. These results have provided strong evidence that both the differences "GTO minus SBUV" and "Ground-based minus SBUV" show no significant trends for the 16-yr period (1996–2011) under investigation.

Quantitatively speaking, the trends are found to vary between -0.04 and $0.12\,\%\,\mathrm{yr}^{-1}$ (or) -0.11 and $0.31\,\mathrm{DU}\,\mathrm{yr}^{-1}$. The slightly larger trends for the differences of "Ground-based minus SBUV" at (0–30° N) is mainly driven by the high bias of Ground-based data points in early 2010 as indicated by the black curve in Fig. 6b. Future updating of the Ground-based data record might achieve further improvement in this aspect.

3.6 Deviations from pre-1980 level

Even though the investigation of the ozone trend is beyond the scope of our discussion, it is still interesting to examine the deviations of total column ozone from pre-1980 levels inferred from the three multi-year data records. Since a substantial part of ozone variability is related to QBO and the 11-yr solar cycle (Bowman, 1989; Hamilton, 1989; Bojkov and Fioletov, 1996), removing these natural components from the data records will make it easier to examine the long-term changes. Our analysis to achieve this purpose was conducted as follows:

i. A regression model fit was performed using the ground-based monthly zonal mean total ozone time series covering 1964–2011. The model includes the annual cycle, EESC (Effective equivalent stratospheric chlorine)-related trend, solar cycle-related component (using solar flux at 10.7 cm), QBO-related component (using the normalized equatorial wind at 30 and 50 hPa), and volcanic component (using stratospheric optical depth at 550 nm, only for the year following El-Chichon and Pinatubo eruptions).

ii. The QBO-, and solar cycle-related variations obtained from step (i) were subtracted from all three data records.

The annual deviations from pre-1980 levels are computed and depicted in Fig. 9a and b for (30–60° N) and (50–30° S) respectively. Pre-1980 averaged monthly zonal means based on ground-based data record are used as our baseline.

It is noticed from these results that for both of these two latitudinal bands, the three data records show very good agreement regarding the year-to-year changes in the deviations from pre-1980 level. The agreement in the deviations inferred from the three data records is better than 1 %.

From 1980 to 1993, both ground-based record and SBUV reveal gradual decrease from pre-1980 level, reaching −7 and −5 % at (30–60° N) and (50–30° S) respectively. For the overlap period of 1996 to 2010, all three data records indicate gradual recovery in the northern hemisphere from a deviations of −5 % in 1996 to −2 % in 2010. The recovery in the Southern Hemisphere is not as obvious until after 2006.

4 Concluding remarks

We have presented the comparisons of the variability of zonal mean total column ozone inferred from three recently released independent multi-year data records. The analyses are based on the 16-yr overlap period (March 1996 through June 2011). The results of our investigation have led to the conclusion that despite the differences in the satellite sensors and retrieval methods, SBUV (v8.6) merged profile total ozone and GTO (v2) merged total ozone data records show very good agreement in terms of monthly zonal mean total ozone and monthly zonal mean anomalies. The ground based zonal means, while show no systematic differences, demonstrate larger scattering of monthly data compared to satellite-based records. The differences in the scattering are significantly reduced if seasonal zonal averages are analyzed.

The major findings based on the characteristics in the four latitudinal zones (0–30° S), (0–30° N), (50–30° S), and (30–60° N) can be summarized as follows:

1. It has been found that on average, the differences in monthly zonal mean total ozone vary between −0.32 to 0.76 % and are well within 1 %.
2. The standard deviations of the differences in monthly zonal mean total ozone for (GTO minus SBUV) vary between 0.58 and 0.66 %. The corresponding differences for (Ground-based minus SBUV) are larger by a factor of 1.4 to 1.9.
3. The ranges of the differences “GTO minus SBUV” vary between 2.83 and 3.82 % while the corresponding ranges for "Ground-based minus SBUV" are larger by a factor of 1.4 to 2.4 with values ranging between 5.14 and 6.92 %.
4. The standard deviations of differences “GTO minus SBUV” in monthly zonal mean anomalies vary between 0.40 and 0.59 %. The corresponding standard deviations for “Ground-based minus SBUV” are larger by a factor of 1.8 to 2.6.
5. The ranges of the differences in monthly zonal mean anomalies for “GTO minus SBUV” vary between 2.19 and 3.53 % while the corresponding ranges for “Ground-based minus SBUV” are larger by a factor of 1.5 to 2.9 with values ranging between 4.35 and 6.29 %.

Both the differences “GTO minus SBUV” and “ground-based minus SBUV” show no significant trends for the 16-yr period indicating the absence of time dependent differences among the three data records.

Analyses of the deviations from pre-1980 level indicate that for the overlap period of 1996 to 2010, all three data records show gradual recovery at (30–60° N) from −5 % in 1996 to −2 % in 2010. The corresponding recovery at (50–30° S) is not as obvious until after 2006.

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Table 1. Period of coverage by each instruments used in constructing the SBUV Merged Profile Total Ozone Data Record.

Satellite instrument	Period covered	Remarks
Nimbus 4 BUV	May 1970–Apr 1976	(All data)
Nimbus 7 SBUV	Nov 1978–May 1990	(All data)
NOAA 11 SBUV/2	Jan 1989–Mar 1995	(Enter terminator orbit; ECT[*] 6 p.m.)
NOAA 11 SBUV/2	Oct 1997–Mar 2001	(8 a.m. ECT[*]; end of record)
NOAA 14 SBUV/2	Mar 1995–Apr 2000	(4 p.m. ECT[*]; nearing terminator)
NOAA 14 SBUV/2	Jul 2004–Sep 2006	(8 a.m. ECT[*]; end of record)
NOAA 16 SBUV/2	Oct 2000–Jun 2007	(4 p.m. ECT[*]; nearing terminator)
NOAA 16 SBUV/2	Dec 2011–Dec 2011	(8 a.m. ECT[*])
NOAA 17 SBUV/2	Aug 2002–Sep 2011	(8 a.m. ECT[*]; nearing terminator)
NOAA 18 SBUV/2	Jul 2005–Dec 2011	

[*] ECT: Equator Crossing Time.

Table 2. Characteristics of the three European Satellite Instruments.

Parameter	GOME	SCIAMACHY	GOME-2
Data availability	Jul 1995–Jun 2011*	Aug 2002–Mar 2012	Jan 2007–today
Spectral coverage	240–790 nm	240–2380 nm	240–790 nm
Spectral resolution	0.2–0.4 nm	0.2–1.5 nm	0.2–0.4 nm
Ground pixel size	320 × 40 km^2	60 × 30 km^2	40 × 80 km^2
Swath width	960 km	960 km	1920 km
Equatorial crossing	10:30 LT	10:00 LT	09:30 LT
Global coverage	3 days	6 days	almost daily

* No global coverage since June 2003.

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Table 3. Summary of the differences in monthly zonal mean total ozone.

Latitudinal zones	Differences in percent		
	Mean	Standard deviations	Range (Max–Min)
(a) GTO minus SBUV			
(30–60° S)	0.55	0.98	9.87
(0–30° S)	0.74	0.75	5.65
(0–30° N)	0.43	0.70	3.96
(30–60° N)	0.18	0.78	6.47
(b) Ground-based minus SBUV			
(30–60° S)	−0.61	2.07	19.17[*]
(0–30° S)	0.56	1.37	11.32
(0–30° N)	0.10	1.67	12.71
(30–60° N)	0.67	1.56	12.04
(c) GTO minus Ground-based			
(30–60° S)	1.21	2.13	19.89[*]
(0–30° S)	0.19	1.39	12.72
(0–30° N)	0.33	1.62	12.42
(30–60° N)	0.11	1.66	12.18

[*] One outlier data point from Ground-based record (November 2009; 60–55° S) was excluded.

Table 4. Summary of the Differences in monthly zonal mean total ozone [four broad latitudinal zones].

Latitudinal zone	GTO minus SBUV (in %)			Ground-based minus SBUV (in %)		
	Mean	Standard deviation	Range (Max–Min)	Mean	Standard deviation	Range (Max–Min)
(0–30° S)	0.76	0.63	3.63	0.56	0.91	5.14
(0–30° N)	0.43	0.58	2.83	0.10	1.12	6.92
(50—30° S)	0.67	0.66	3.82	−0.32	1.23	5.75
(30–60° N)	0.20	0.63	3.35	0.09	0.98	6.31

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Table 5. Summary of the Differences in monthly zonal mean anomaly [four broad latitudinal zones].

Latitudinal zone	GTO minus SBUV (in %)		Ground-based minus SBUV (in %)	
	Standard deviation	Range (Max–Min)	Standard deviation	Range (Max–Min)
(0–30° S)	0.45	2.89	0.79	4.35
(0–30° N)	0.40	2.19	1.06	6.29
(50–30° S)	0.59	3.53	1.16	7.74
(30–60° N)	0.47	3.19	0.87	5.79

Table 6. Summary of the Differences in seasonal zonal mean total ozone [four broad latitudinal zones].

Latitudinal zone	GTO minus SBUV (in %)			Ground-based minus SBUV (in %)		
	Mean	Standard deviation	Range (Max–Min)	Mean	Standard deviation	Range (Max–Min)
(0–30° S)	0.76	0.55 (0.08)	2.72 (0.91)	0.56	0.73 (0.18)	3.82 (1.32)
(0–30° N)	0.43	0.48 (0.10)	1.99 (0.84)	0.10	0.97 (0.15)	4.60 (2.33)
(50–30° S)	0.67	0.49 (0.17)	2.74 (1.08)	−0.33	0.89 (0.34)	4.51 (1.25)
(30–60° N)	0.20	0.54 (0.09)	2.21 (1.14)	0.10	0.79 (0.19)	3.66 (2.65)

The entries in brackets represent the reduction compared to analysis based on monthly zonal means.

Table 7. Summary of the Differences in seasonal zonal mean anomaly [four broad latitudinal zones].

Latitudinal zone	GTO minus SBUV (in %)		Ground-based minus SBUV (in %)	
	Standard deviation	Range (Max–Min)	Standard deviation	Range (Max–Min)
(0–30° S)	0.38 (0.07)	1.76 (1.13)	0.62 (0.17)	3.09 (1.26)
(0–30° N)	0.34 (0.06)	1.57 (0.62)	0.92 (0.14)	4.11 (2.18)
(50–30° S)	0.51 (0.08)	2.74 (0.79)	0.89 (0.27)	4.51 (1.23)
(30–60° N)	0.38 (0.09)	2.08 (1.11)	0.71 (0.16)	3.70 (2.09)

The entries in brackets represent the reduction compared to analysis based on monthly zonal mean anomalies.

Table 8. (a) Trend of the Differences (in % per year) for Monthly Zonal Mean Total Ozone. (b) Trend of the Differences (in DU per year) for Monthly Zonal Mean Total Ozone.

Latitudinal zone	GTO minus SBUV	Ground-based minus SBUV
	(a)	
(0–30° S)	0.05 % yr^{-1}	−0.04 % yr^{-1}
(0–30° N)	0.05 % yr^{-1}	0.12 % yr^{-1}
(50–30° S)	0.07 % yr^{-1}	0.04 % yr^{-1}
(30–60° N)	0.04 % yr^{-1}	−0.02 % yr^{-1}
	(b)	
(0–30° S)	0.14 DU yr^{-1}	−0.11 DU yr^{-1}
(0–30° N)	0.14 DU yr^{-1}	0.31 DU yr^{-1}
(50–30° S)	0.22 DU yr^{-1}	0.12 DU yr^{-1}
(30–60° N)	0.14 DU yr^{-1}	−0.07 DU yr^{-1}

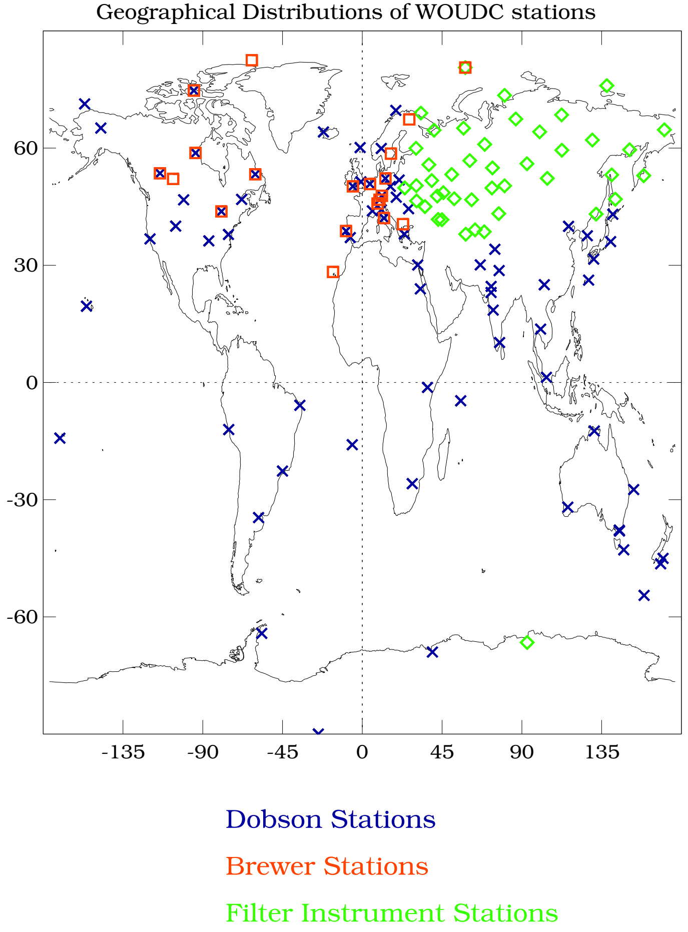


Fig. 1. Geographical distributions of WOUDC ground stations.

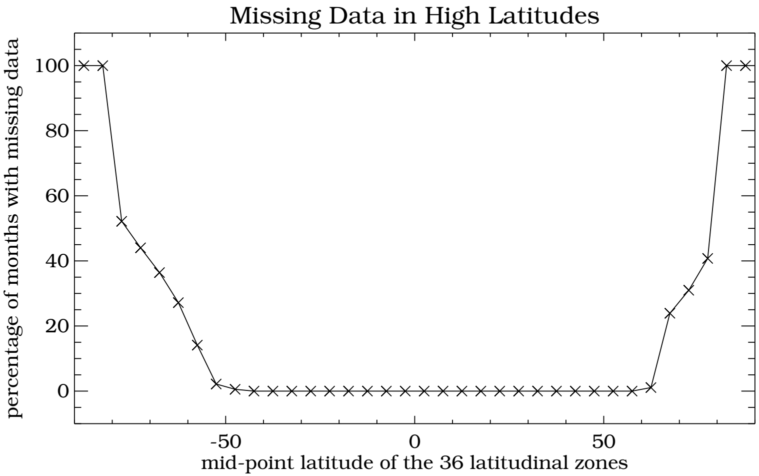


Fig. 2. Missing data in high latitudes (for SBUV v8.6).

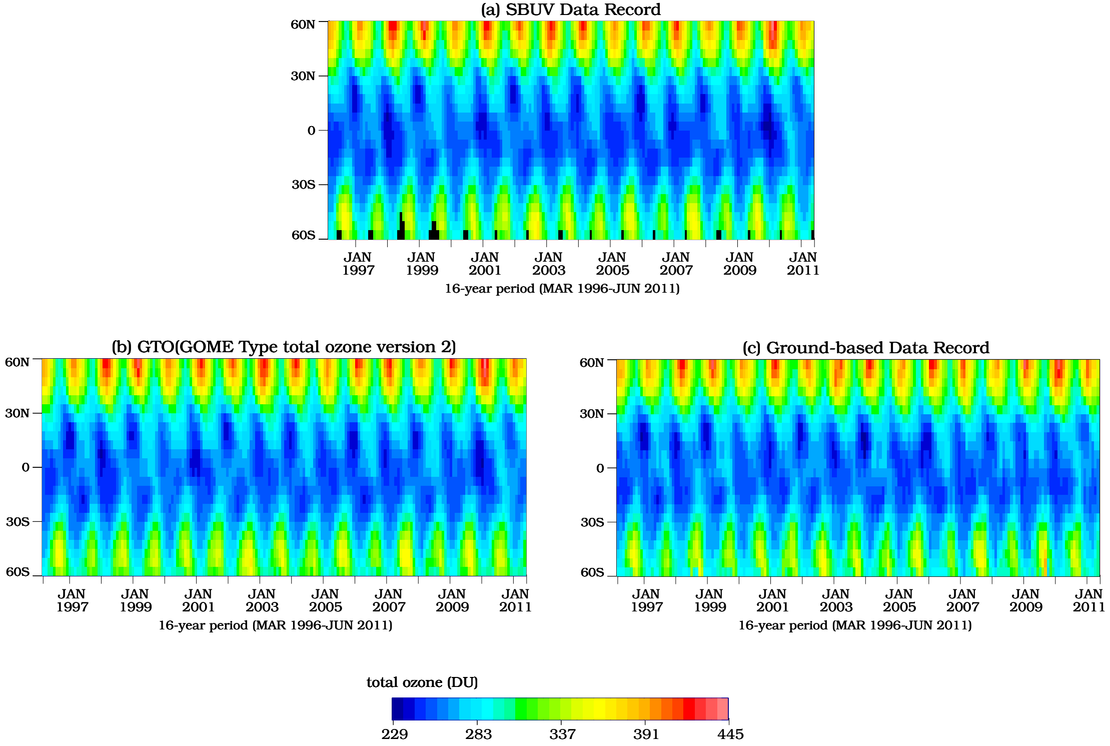
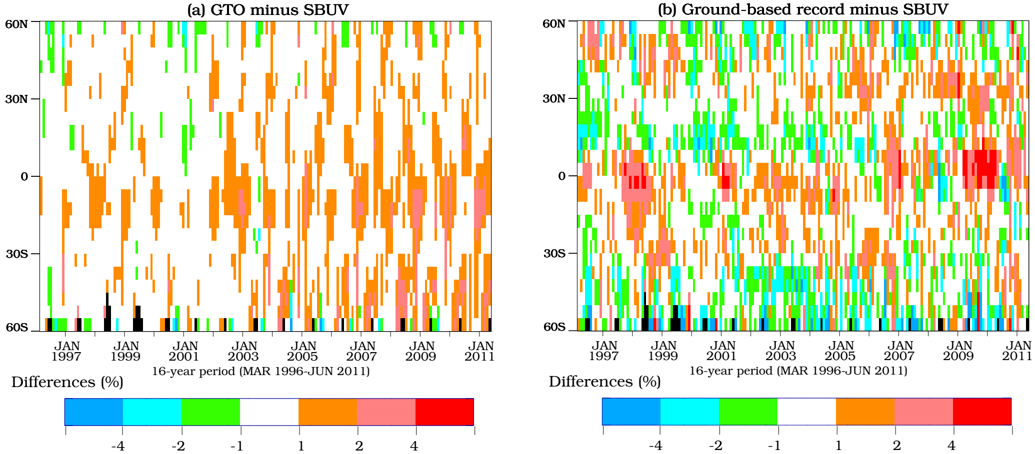
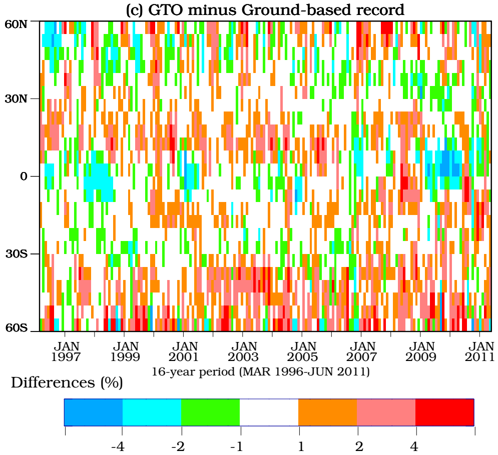


Fig. 3. Monthly zonal mean total column ozone (5-degree zones) **(a)** SBUV, **(b)** GTO (GOME Type total ozone), **(c)** ground-based data record.



(a) GTO minus SBUV

(b) Ground-based record minus SBUV



(c) GTO minus Ground-based record

Fig. 4. Differences in monthly zonal means (5-degree zones) **(a)** GTO minus SBUV, **(b)** ground-based minus SBUV, **(c)** GTO minus Ground-based.

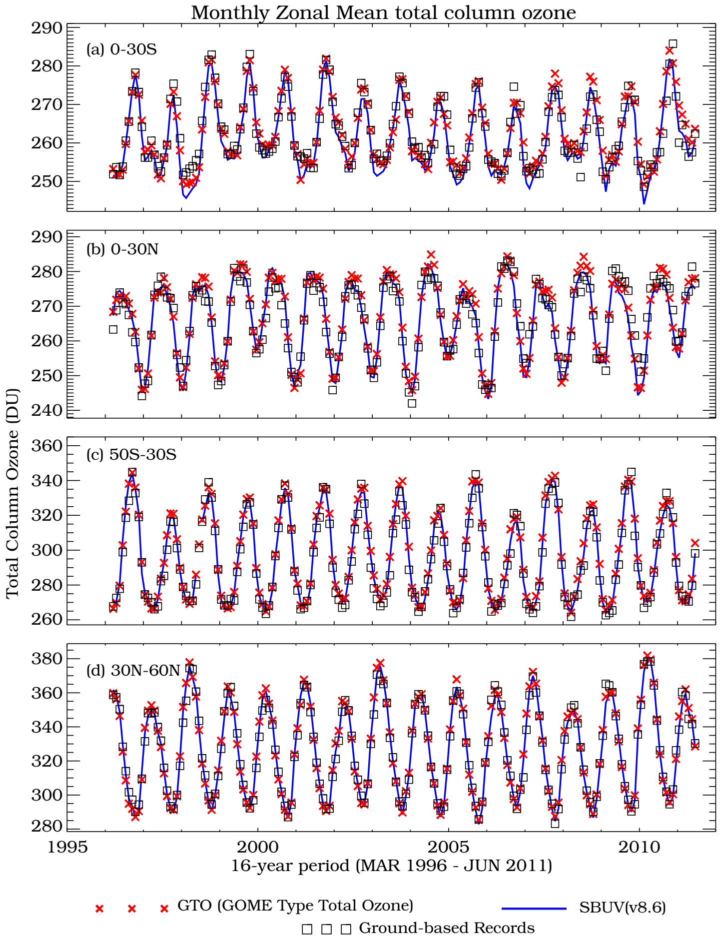


Fig. 5. Monthly zonal mean total ozone [area weighted zonal means for broader latitudinal zones].

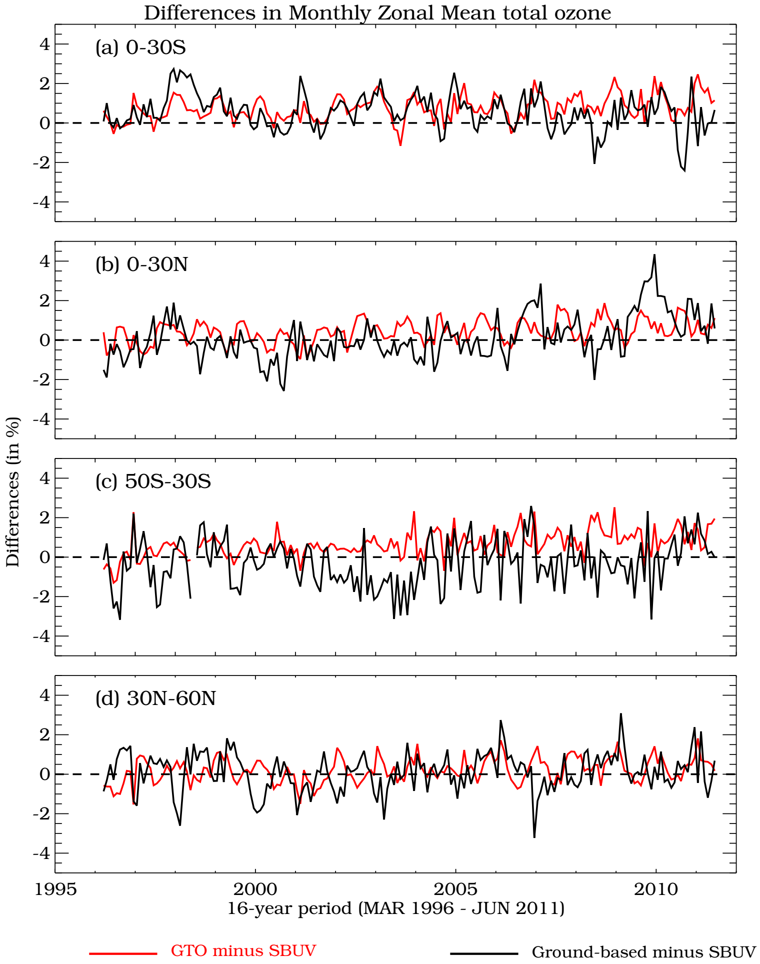


Fig. 6. Differences in monthly zonal mean total ozone.

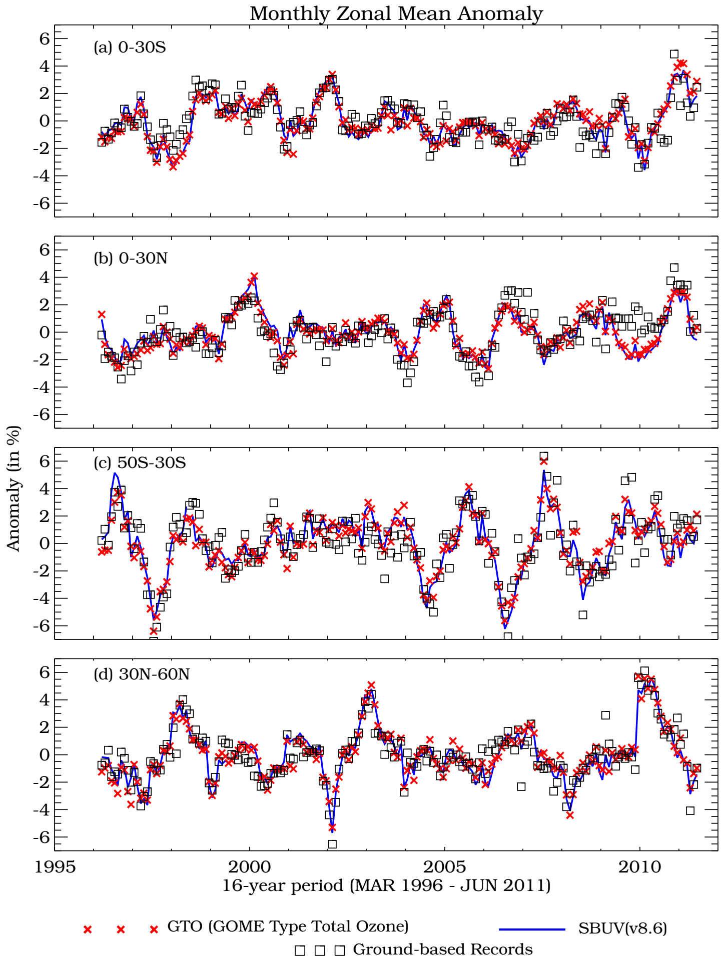


Fig. 7. Monthly zonal mean anomaly.

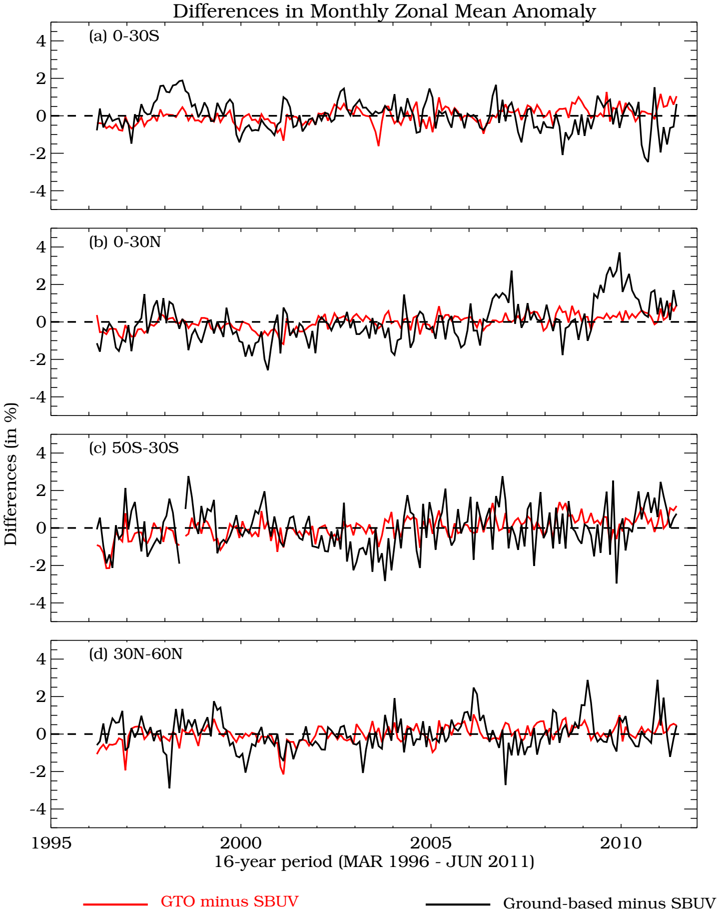


Fig. 8. Differences in monthly zonal mean anomly.

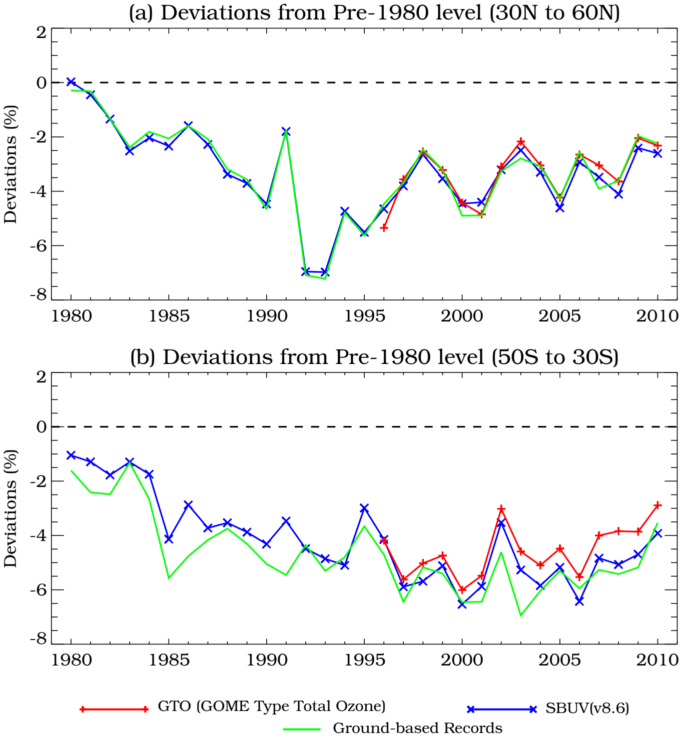


Fig. 9. Deviations from pre-1980 levels.