Global and zonal total ozone variations estimated from ground-based and satellite measurements: 1964–2000

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[1] Six data sets of monthly average zonal total ozone were intercompared and then used to estimate latitudinal and global total ozone temporal variations and trends. The data sets were prepared by different groups and are based on TOMS, SBUV-SBUV/2, GOME, and ground-based measurements. Different approaches have been used to homogenize the records over the period 1979–2000. Systematic differences of up to 3% were found between different data sets for zonal and global total ozone area weighted average values. However, when these systematic differences were removed by deseasonalizing the data, the residuals agreed to within ±0.5% of the long-term mean ozone values. All data sets show changes in the rate of the total ozone decline in recent years. While global ozone was fairly constant during the 1990s, the average values of the 1990s are about 2–3% lower than those of the late 1970s. About 38% of the global ozone is located between 25°S and 25°N where the data show no decline. The strongest decline and the largest variability occur over the 35°N–60°N zone during the winter-spring season with the largest negative deviations occurring in 1993 and 1995. The decline in autumn is much smaller at these latitudes. Over the 35°S–60°S zone the ozone decline shows less seasonal dependence, and the largest deviations there were observed in 1985 and 1997. Sliding 11-year trends were calculated to estimate ozone changes over different time intervals. The first interval was from 1964 to 1974, and the last interval was from 1990 to 2000. The steepest year-round trends, of up to −5% per decade, occurred in the 11-year periods ending between 1992 and 1997 over the 35°–60°N zone and between 1985 and 1993 over the 35°–55°S zone. More recent 11-year trends have smaller declines. *INDEX TERMS:* 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 1610 Global Change: Atmosphere (0315, 0325); *KEYWORDS:* Ozone, Dobson, Brewer, TOMS, SBUV

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1. Introduction

[2] Concern for changes in the ozone layer due to human activity is an important subject for the scientific community, the general public and governments. This was expressed in the adoption of the Vienna Convention for Protection of the Ozone Layer (1985) and its Montreal Protocol (1987). Also in response to this concern, a series of international reports assessing different aspects of the scientific knowledge of ozone in the atmosphere have peen prepared [*WMO*, 1990a, 1990b, 1992, 1995, 1999]. These reports, as well as other studies [e.g., *Stolarski et al.*, 1992; *Reinsel et al.*, 1994; *Bojkov et al.*, 1995b; *Harris et al.*, 1997], have provided estimates of long-term variations and trends in atmospheric ozone. They have demonstrated a statistically significant year-round decline in the total amount of ozone in the atmosphere in the middle and polar latitudes of both hemispheres. Different aspects of the ozone trend problem have recently been reviewed by *Staehelin et al.* [2001] and the current theory of stratospheric ozone depletion is summarized by *Solomon* [1999]. Continuous changes in global ozone, further improvement in measurement techniques and improvement in the quality of past and present ozone data, make it appropriate to update the ozone trend results periodically.

[3] One of the major difficulties in assessing long-term global total ozone variations is data inhomogeneity. Changes in operational satellites, recalibration of ground-based instruments, or interruptions in observation records result in data sets, which may have systematic errors that change with time. These errors are usually significantly less than the ozone decline seen in recent years over middle and

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polar latitudes and therefore have had limited adverse effects on the trend estimates for these regions. However, variations of global ozone are about 2–3% [*WMO*, 1999] so a systematic error of 1%, which is typical even for the most reliable instruments, makes detection of real ozone changes on a global scale difficult. This problem has been addressed in recent years by comparing data from several sources and, if necessary, applying systematic corrections. Six data sets of zonal monthly mean total ozone values have been examined in this study. The data sets were produced by different teams of researchers using different approaches. The aim of this study is to find similarities and differences in these total ozone data sets and to update the estimates of global and zonal total ozone variations and trends.

[4] One of the major results of this study is that all six data sets demonstrate a similar picture of relative long-term changes in total ozone. However, there are substantial latitude-dependent systematic differences in absolute total ozone values between the different sets. Detailed information on the data sets is provided in section 2. The results of zonal and global ozone estimates from these six data sets and their differences are described in section 3. Total ozone trends over different time intervals are described in section 4 and concluding remarks are presented in section 5.

2. Data Sets

2.1. Ground-Based Data

[5] The ground-based data set is based on Dobson and Brewer spectrophotometer and filter ozonometer observations available from the World Ozone and UV Data Centre (WOUDC) (http://www.msc-smc.ec.gc.ca/woudc/). Large longitudinal inhomogeneities in the global ozone distribution and limited spatial coverage of the ground-based network make it impossible to estimate zonal and global total ozone values from station observations 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] show that this method can be used to estimate long-term variations of zonal values over 40°S–60°N with an uncertainty of 1% and with slightly higher uncertainty south of 40°S. In summary, the method measures ozone deviations from the "climatology" at the stations, then calculates the zonal means of the deviations, and finally the zonal mean ozone is determined by adding the zonal mean "climatology" to the zonal means of the deviations.

[6] Previous estimates of the zonal and global ozone variations are updated here and the period of the estimates has been extended to include data until the end of 2000. The ozone "climatology" has been recalculated using the new TOMS version 7 data. The overall quality of the ground-based data set available from the WOUDC has improved substantially since the time of the *Bojkov and Fioletov* [1995] publication. The data from a large number of stations have been reevaluated and resubmitted by the operating agencies. A review of the ground-based network performance was published by *Fioletov et al.* [1999]. Although as many stations as possible were used in this study, only stations with reliable data and without any major calibration problems in their records were included. Data from 44 stations with continuous records starting before 1983 and discussed by *WMO* [1999] were analyzed for the station trend estimates described in section 4. These stations, plus 70 additional stations, were utilized to estimate zonal and global ozone averages for the period 1964–2000.

[7] Several stations require specific mention. It was known that the data from Nairobi and Kagoshima contained some systematic errors that have been corrected as described by *WMO* [1999]. Data from Brisbane prior to 1985; Ahmedabad after 1995; and Bangkok prior to 1986 have not been used because of known instrument calibration problems [*Bojkov et al.*, 1988; *Bojkov and Fioletov*, 1996; *WMO*, 1999]. Macquarie Island is the only station between 46°S and 60°S, so it was necessary to use these data for the estimates. The Macquarie Island data prior to 1986 are believed to be unreliable and no calibration information is available. *Lehmann et al.* [1992] verified and revised the Macquarie Island Dobson total ozone record. However, TOMS overpass data were used to establish the base total ozone level for the station. A similar procedure was used when the 1980–1985 data were provisionally reevaluated. The Macquarie Island Dobson instrument has been well calibrated and well maintained since 1986. The latest 15 years of data demonstrate that there is a 2% bias between TOMS and Dobson total ozone values for that station. For this reason previously revised pre-1986 data were reduced by an additional 2% to match the current Dobson values.

[8] The longest records of continuous reliable measurements are available from stations that have been equipped with Dobson spectrophotometers since the 1960s or earlier. Some of the Dobson instruments were replaced by the automated Brewer spectrophotometers in the late 1980s and 1990s. Both instruments measure total ozone with the same uncertainty of about 1% for air mass values less than 3. No long-term systematic differences between the two types of the spectrophotometers have been reported, although an annual cycle of up to 2% difference between total ozone measured by the two instrument types has been observed [*Kerr et al.*, 1988; *Staehelin et al.*, 1998; *Köhler*, 1999]. Recent comparisons with satellite data also demonstrated a similar performance of Dobson and Brewer instruments [*Fioletov et al.*, 1999]. Dobson and Brewer instruments are calibrated using two independent calibration procedures. All Dobson instruments are calibrated, directly or indirectly, against the World Standard Dobson 83 at Boulder through a system of international and national intercomparisons [*Basher*, 1994]. All Brewers are calibrated against the traveling standard Brewer instrument and the traveling standard is calibrated against the Brewer triad at Toronto [*Kerr et al.*, 1997]. The Dobson and Brewer calibrations are independent and the fact that there is no systematic difference between the two types of instrument adds to confidence in the quality of the ground-based measurements. Filter ozonometers are widely used in the former USSR countries. This instrument is less accurate than the Dobson and the Brewer and the calibration is traceable to the Dobson reference. These observations are important for estimates of long-term ozone variations over vast regions

where data from several stations can be averaged to reduce the errors [*Bojkov et al.*, 1994].

[9] Some ground-based stations have a bias (usually negative) when compared with TOMS measurements and the cause is not always clear. In some cases the bias is likely to be due to local site conditions, such as high elevation above sea level, however there are some systematic features in the latitudinal distribution of the bias (Figure 1). The bias is about −2% to −3% at some equatorial stations and over southern midlatitudes, and it rises to about −5% over the Antarctic [*Fioletov et al.*, 1999; *Bodeker et al.*, 2001]. It is unlikely that the source of the bias is due to the ground-based data only. Recent intercomparisons show that at present Dobson instruments at main southern hemisphere sites agree with the World Standard Dobson to within 0.5% [*WMO*, 1998a, 2001]. The Dobson algorithm does not account for the temperature dependence of the ozone absorption cross sections. For southern midlatitudes the effect of this dependence is small, between 1 and 2% in the annual cycle [*Brinksma et al.*, 2000]. This effect is larger in the Antarctic. In the Antarctic stray light can also be a substantial additional source of the systematic error [*Olafson and Asbridge*, 1981; *McPeters and Labow*, 1996]. There is also a potential error for retrieved ozone values using the TOMS algorithm in the Antarctic because there is uncertainty as to whether a scene is snow covered or cloud covered. Estimates of total ozone from spectral UV irradiance measurements in the Antarctic demonstrate better agreement with the Dobson total ozone observations than with TOMS total ozone [*Bernhard et al.*, 2001].

[10] As described above, a TOMS-based ozone "climatology" was used to estimate the zonal and global total ozone variations from the ground-based network. However, there is some latitude-dependent systematic difference between ground-based and TOMS data. Although this difference itself does not affect estimates of long-term variations and trends, it is important for calculation of absolute values of zonal or global ozone. The TOMS-based ozone "climatology has been corrected based on a parameterization of the TOMS-Dobson difference as a function of latitude shown in Figure 1 as follows:

$$C = \begin{cases} 1.0, & \varphi \geq 22^\circ \\ 0.98 + 0.00004 \times \varphi^2, & -20^\circ \leq \varphi < 20^\circ \\ 1.008 + 0.0006 \times \varphi, & -59^\circ \leq \varphi < -20^\circ \\ 0.95, & \varphi < -59^\circ, \end{cases}$$

where φ is the latitude in degrees (positive for N, negative for S).

[11] The algorithm for calculation of zonal total ozone from ground-based data gives a continuous uninterrupted global record from the 1960s 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 limited.

[12] Detailed descriptions of the other data sets have already been published elsewhere. Therefore, only brief descriptions with references are given here. These six data sets have been prepared by different research groups using different techniques to weight, homogenize, and adjust various measurements made from the ground or satellite. As a result, the measurements from the same source may yield slightly different ozone values in different data sets. It should be also stressed that these data sets are not all entirely independent.

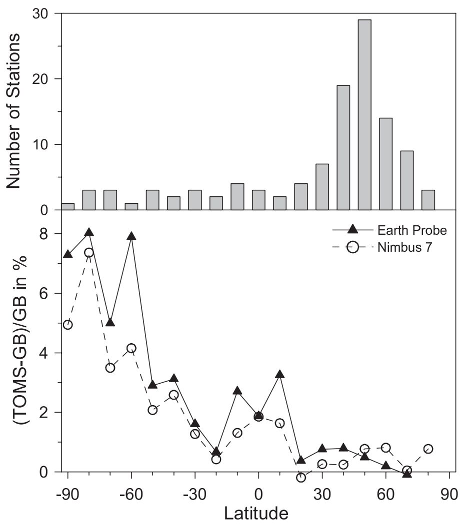

Figure 1. The mean difference in percent between Nimbus 7 (1979–1992) and Earth Probe (1996–2000) TOMS satellite data and ground-based measurements. The number of ground-based stations is shown on the top.

2.2. TOMS Zonal Averages

[13] The TOMS zonal average data set is produced by NASA Goddard Space Flight Center (http://toms.gsfc.nasa.gov/) and is based on daily high-resolution near-global (except for the polar night areas) measurements by Nimbus 7 (1978–1993), Meteor 3 (1993–1994), and Earth Probe (1996–2000) satellites. This data set is independent from all other data sources and all data have been processed with the same version 7 algorithm [*McPeters et al.*, 1996]. The data set has periodic gaps in 1993 and 1994 due to the Meteor 3 orbit, and there were no data in 1995 and the first half of 1996. No adjustments have been made to merge the data from the different satellites and therefore some systematic error from one instrument to another could be present. In particular, the Earth Probe TOMS values are 0.5% higher than the others due to small wavelength errors. The quality of the Earth Probe TOMS data for 2000 is affected by changes in the optical properties of the scanning mirror, and therefore these data should be interpreted with caution.

2.3. TOMS Overpass Data Set

[14] The overpass data set is also produced by the TOMS team (http://toms.gsfc.nasa.gov/). This data set is based on TOMS measurements taken at the same set of sites as the ground-based data set using the same algorithms applied to calculate zonal and global ozone. This data set was primarily used to estimate errors in the ground-based data set

related to poor spatial coverage of the ground-based network. No adjustments or corrections have been made.

2.4. SBUV-SBUV/2 Zonal Averages

[15] The SBUV-SBUV/2 data set is prepared by NOAA and NASA and is based on Solar Backscattered Ultraviolet (SBUV) Nimbus 7 (1978–1985), SBUV/2 NOAA 9 (1985–1988, 1994–1995), SBUV/2 NOAA 11 (1989–1993, 1998–2000), and SBUV/2 NOAA 14 (1996–1998) data [*Planet et al.*, 2001]. All data have been processed using the same version 6 algorithm [*Bhartia et al.*, 1996] with some corrections applied to align the data from different satellites. It is a continuous data set with no major gaps. There is a systematic error in SBUV/2 retrieved ozone values at solar zenith angles more than 80° and such measurements have not been included here. The combination of the 80° solar zenith angle cutoff and the orbital drift of NOAA 9 and NOAA 11 result in increased data loss poleward of 45°S during 1988, 1992, 1993, and 1998. This undersampling is one potential source of differences with the other data sets discussed here.

2.5. Merged Satellite Data Set

[16] The merged satellite data set is prepared by NASA and combines the TOMS data (Nimbus 7 and Earth Probe) and SBUV-SBUV/2 data (Nimbus 7, NOAA 9, 11, and 14) and is available at (http://code916.gsfc.nasa.gov/Data_services/merged/. The data from different instruments were adjusted using the instrument overlap periods when the data from two or more instruments were available. This is a continuous data set with no gaps and effects of instrument changes have been minimized. Different algorithms for TOMS and SBUV-SBUV/2 and different spatial resolution of the two instruments may introduce instrument-specific systematic errors in parts of the data set.

2.6. NIWA Assimilated Data Set

[17] This assimilated data set, prepared by National Institute of Water and Atmospheric Research (NIWA), New Zealand, is based on TOMS (Nimbus 7, Meteor 3, Earth Probe and Adeos) version 7 and Global Ozone Monitoring Experiment (GOME) data adjusted to ground-based observations [*Bodeker et al.*, 2001]. A smoothed function of the TOMS-ground-based differences with latitude and season was used for the adjustment. The gap in the TOMS data record between December 1994 and July 1996 was partially filled by adjusted GOME measurements. It is a nearly continuous data set with the only gap from December 1994 to June 1995. Adjustment to the ground-based network smoothes transitions from one instrument to another and gives the advantage of global satellite coverage of TOMS with the long-term calibration stability of the ground-based network. However, some ground-based stations have site- or instrument-specific bias against TOMS. Use of the records of such stations may potentially affect the adjustment of the satellite data.

3. Zonal and Global Total Ozone Variations

[18] All six data sets were converted into monthly averages over 5° latitude zones, and were then deseasonalized. To remove the seasonal cycle, monthly averages for each month of the year for the period 1979–1987 were calculated and then subtracted from the data. The 1979–1987 period was chosen as a "baseline" to reduce the influence of seasonal ozone trends on the annual cycle estimate. For the "ozone hole" period (August–November at 60°–90°S) the seasonal cycle was estimated from the 1964–1980 ground-based data to avoid large positive departures in the pre-"ozone hole" years. While most of this study focuses on deseasonalized data, the annual cycle estimates themselves provide information about offsets between the different instruments.

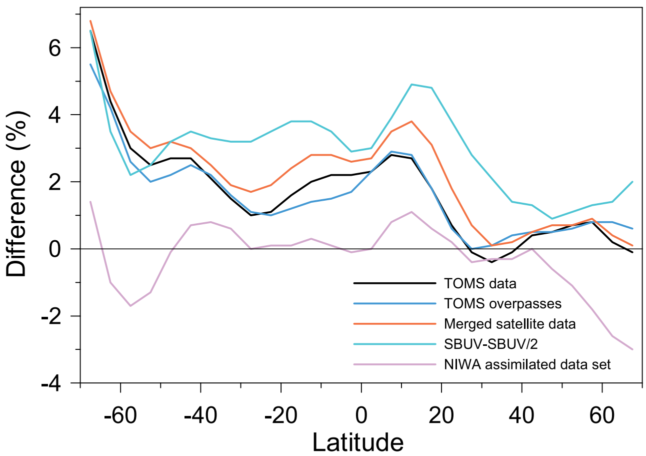

Figure 2. The difference between total ozone zonal means estimated from five data sets and ground-based data as a function of latitude for the period 1978–1987. Monthly mean values calculated from ground-based data have been subtracted from the monthly means of each of the five remaining data sets and the results are expressed in percent of the ground-based monthly means. The annual average of monthly mean differences is shown.

[19] Figure 2 shows the 1978–1987 annual mean percentage differences between the zonal averages estimated from five data sets and the ground-based data as a function of latitude. All data sets agree to within ±1% of the ground-based data at 40°–50°N, that is, in the region where most of the stations are located. As mentioned above, the ground-based data set has some latitude-dependent differences with TOMS zonal means as shown in Figure 2. The TOMS overpass data set shows the same differences from the ground-based data as the TOMS zonal mean data set. The SBUV-SBUV/2 data set is about 3% higher than the ground-based data set in the tropics and the southern hemisphere. The NIWA assimilated data set in 1978–1987 is based on TOMS zonal averages adjusted to fit the ground-based data. The curve of the difference between the NIWA and ground-based data sets therefore is near zero. The merged satellite data set is a combination of TOMS and SBUV-SBUV/2 data and its difference from the ground-based data set lies between the TOMS and SBUV-SBUV/2 curves in Figure 2. For the entire 60°S–60°N zone the area weighted differences between the other data sets and ground-based zonal averages are the following: 1.5% higher for the TOMS zonal mean and TOMS overpasses data set, 2.1% higher for the merged satellite data set, 0% for the NIWA assimilated data set, and 3% higher for the SBUV-SBUV/2 data set.

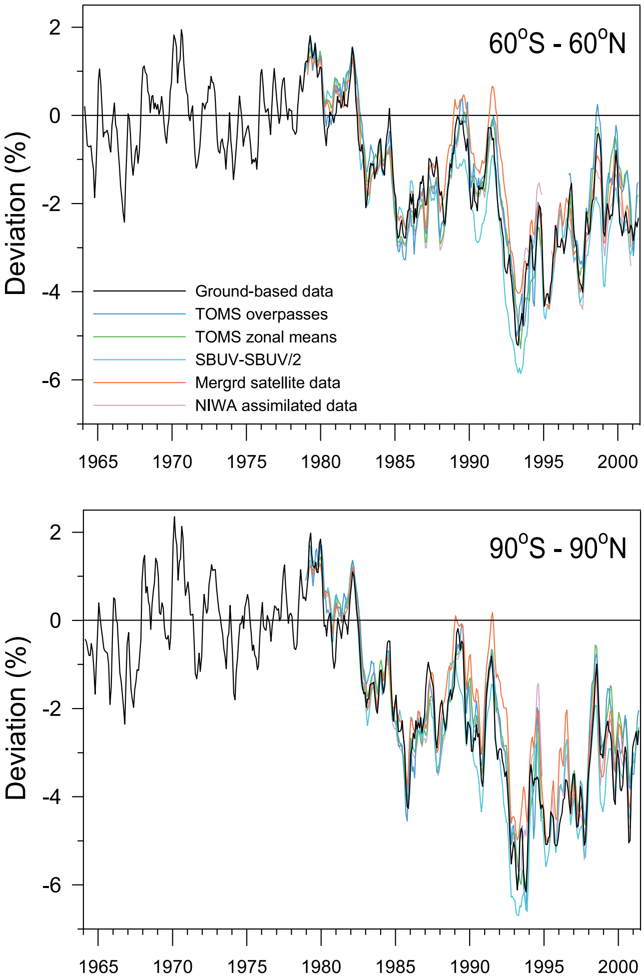

Figure 3. Area weighted deseasonalized total ozone variations in percent for the 60°S–60°N zone and for the globe estimated from the six data sets. The data are smoothed by 3 month running means. The zero line indicates the pre-1980 level.

[20] The 1979–1987 monthly zonal means for each record were then subtracted from the respective data sets to obtain deviations from the annual cycle and to remove the data set-specific biases. Area weighted ozone deviations were then calculated and expressed as anomalies relative to the 1964–1980 total ozone averages calculated from the ground-based data. The results are presented as ozone deviations from the pre-1980 level expressed in percent.

[21] Figure 3 (top) shows area weighted total ozone deviations for the 60°S–60°N zone. The time series were smoothed by 3-month running averages to reduce the "noise" in the ground-based data series. Figure 3 (top) shows that there are ±2% natural ozone short-term fluctuations, a periodic component with maxima at about 1970, 1980, 1990, and 2000 related to the solar cycle, and a large, about −5%, ozone anomaly in 1993. Ozone values in 1998 and 1999 approached pre-1980 levels, however the values for 2000 again demonstrated substantial negative deviations.

[22] The 60°S–60°N zone does not completely represent global ozone. This region does not include Antarctica where severe ozone loss, the "ozone hole," occurs during the austral spring [*Farman et al.*, 1985; *Stolarski et al.*, 1986] and the northern polar region where strong negative ozone anomalies have been seen recently [e.g., *Newman et al.*, 1997; *Fioletov et al.*, 1997b]. All of these data sets, however, cannot provide total global coverage because of the lack of data during the polar night and assumptions have to be made about total ozone values over the areas with no data. Rare Dobson and Brewer moon observations made at Arctic and Antarctic stations and total ozone estimated from ozonesonde flights over the Canadian Arctic were used to estimate ozone values over the polar night areas for the ground-based data set. It was also assumed, for all data sets, that ozone deviations over regions with no data are the same as the deviations in the surrounding 5° zones. The same assumption was also made to fill the gaps in the SBUV-SBUV/2 data set over middle latitudes in the 1990s that were caused by the precessing satellite orbit. Area weighted total ozone deviations for the entire globe are shown in Figure 3 (bottom). Figure 3 shows that ozone in the late 1990s was about 2% lower than in the 1970s for the 60°S–60°N zone and about 3% lower for the globe. Otherwise, ozone variations for the 60°S–60°N zone and estimated for the entire globe are alike and this study will focus on the 60°S–60°N zone.

[23] Figure 3 demonstrates that all six data sets show similar ozone variations, although the range of deviations for the different sets is as high as 2%. To illustrate the differences, the individual data records were compared with the average of all six data sets. The average of all six estimates of the 60°S–60°N total ozone deviations (Figure 3, top) was calculated for each month and then subtracted from the six data sets. The differences are shown in Figure 4.

[24] There is always some uncertainty in the calibration of an instrument (or an ensemble of instruments) and combining data from different sources cannot remove these uncertainties completely. For example, the merged satellite and the SBUV-SBUV/2 data sets show about 1.5% differences in late 1993 in Figure 3 even though both are based on data from the same instrument (NOAA-11 SBUV/2). This is because the same data can be adjusted differently depending on comparison criteria. If there is a discrepancy

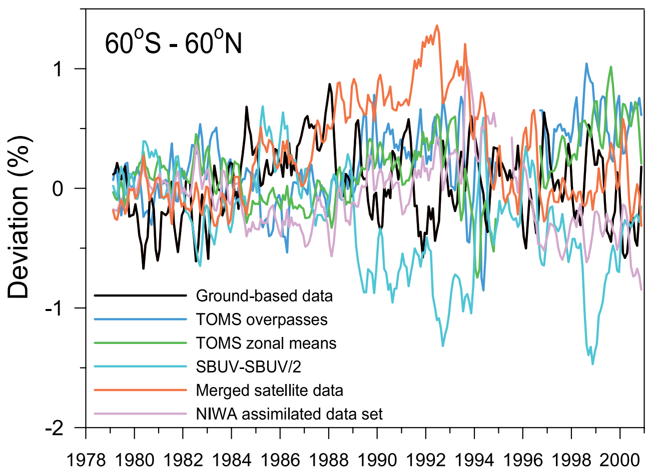

Figure 4. Difference between the six estimates shown in Figure 3 (top) from their average. The average of the six estimates was calculated for each month and then subtracted from all six data sets. The data are smoothed by 3 month running means.

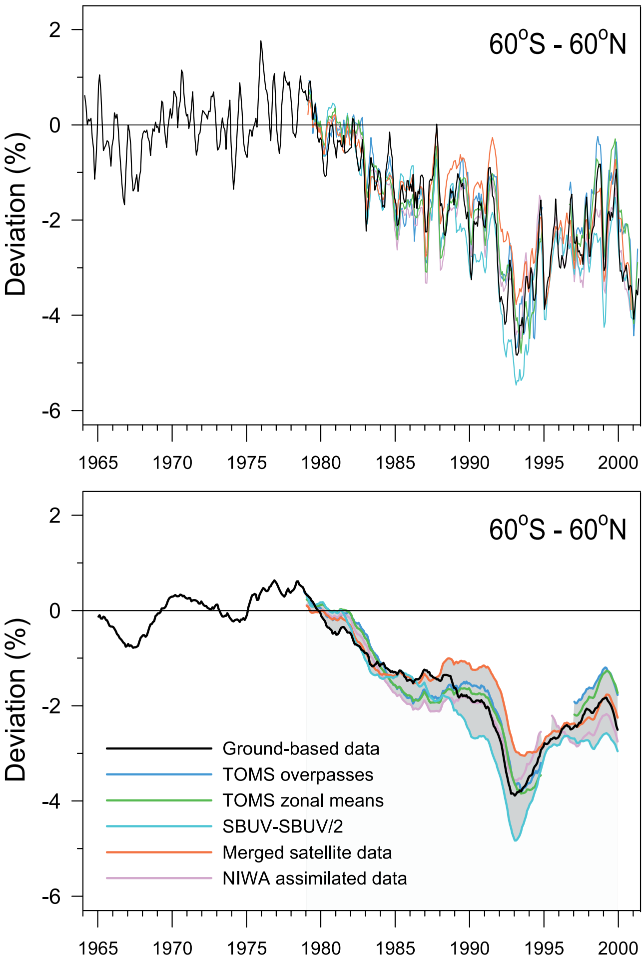

Figure 5. (Top) Area weighted total ozone values adjusted for the seasonal, solar, and QBO effects in percent of the pre-1980 monthly means for 60°S–60°N for the six data sets. Solar and QBO effects have been estimated using ground-based data only and then subtracted from all six data sets. The data are smoothed by 3 month running means. (Bottom) The same data smoothed by 25 month running means to illustrate low-frequency variations. The shaded area indicates the spread of the different data sets.

between instruments, it is not always possible to determine which instrument gives the correct absolute values. There is also a possibility that measurements made between 1979 and 1987 have been influenced by a time dependent systematic error. As mentioned previously, these measurements are used as a baseline in this study and the deviations from that baseline are plotted in Figure 3.

[25] It is well known that a substantial part of the ozone variability is related to the QBO and the 11-year solar cycle [e.g., *Bowman*, 1989; *Hamilton*, 1989; *Chandra and Stolarski*, 1991; *Zerefos et al.*, 1992; *Yang and Tung*, 1994; *Randel and Cobb*, 1994; *Chandra and McPeters*, 1994, *Bojkov and Fioletov*, 1996]. Removing these natural components from the data sets make it easier to see long-term changes. Statistical models are a common tool for isolating these components. A statistical model that fits total ozone data by the annual cycle, a seasonal linear trend, a solar cycle-related component (using solar flux at 10.7 cm), and QBO-related component (using the normalized equatorial wind at two levels, 30 and 50 hPa) was used to isolate the natural component in the ozone variations. The model is described in detail in the *WMO* [1998b] report as Fioletov's model. The parameters of the model were estimated for the 60°S–60°N zone using the ground-based data set. Then the QBO-, and solar cycle-related variations were subtracted from all six data sets. The same approach was used for all other latitudinal zones discussed further: QBO and solar cycle-related variations were determined from the ground-based data set only and then the results were subtracted from all other sets. It is important to subtract the same estimate of the natural component from all data sets. A drift of an individual instrument over certain periods may mimic, for example, the solar cycle, as happened with the TOMS data (see *WMO* [1999], Figure 4-1). Comparisons of different sets would show better agreement if data sets independently corrected for QBO and solar cycle than if they are all adjusted by a common correction. The ground-based data set was chosen because it is the longest record.

[26] Figure 5 (top) demonstrates ozone deviations for the 60°S–60°N zone with the solar cycle and QBO removed. Short-term fluctuations have an amplitude of about 1%, which is smaller than the long-term ozone deviations seen in the late 1980s and 1990s. Ozone deviations have always been negative since 1983. To make long-term changes more prominent, the short-term fluctuations can be removed by smoothing the time series, as is commonly done when the data are compared to model estimates [e.g., *Solomon et al.*, 1996]. Figure 5 (bottom) shows the ozone variations with seasonal, QBO, and solar cycle-related components removed and smoothed by 25-month running means. It is quite apparent that ozone levels have been fairly stable up to the late 1970s and declined almost linearly in the 1980s and early 1990s with a deep minimum in 1993 likely related to the Mount Pinatubo eruption effects. Then it bounced back to the late 1980s level in 1998–1999 and then started to decline in 2000.

[27] The shaded area in Figure 5 (bottom) indicates the spread between the highest and the lowest departure values among the 6 data sets. It reflects the uncertainty of the estimate of recent global ozone if we assume that all data sets agreed during the 1979–1987 baseline period. The area is about 1% wide, which agrees well with present estimates of long-term stability of existing ozone observing systems.

[28] From Figure 5 it appears the decline slows down and even levels off in the late 1990s. To be more certain about the ozone tendencies in the 1990s it is appropriate to analyze ozone variations in the latitudinal zones where the major decline occurs.

[29] About 38% of the global ozone is located between 25°S and 25°N and analysis of these data shows little decline with long-term variations dominated by the solar cycle (Figure 6, top). When the solar cycle is removed and residuals are smoothed by a 25-month running mean, all data sets show variations staying within a range of ±1% with no trend (Figure 6, bottom). The period between 1992 and 1994 shows 1–2% reduction in total ozone over these latitudes likely due to the Mount Pinatubo eruption in June 1991 [e.g., *Chandra*, 1993].

[30] Outside the 25°S–25°N zone the strongest ozone decline occurs poleward of 35°S and 35°N, while the 25°–

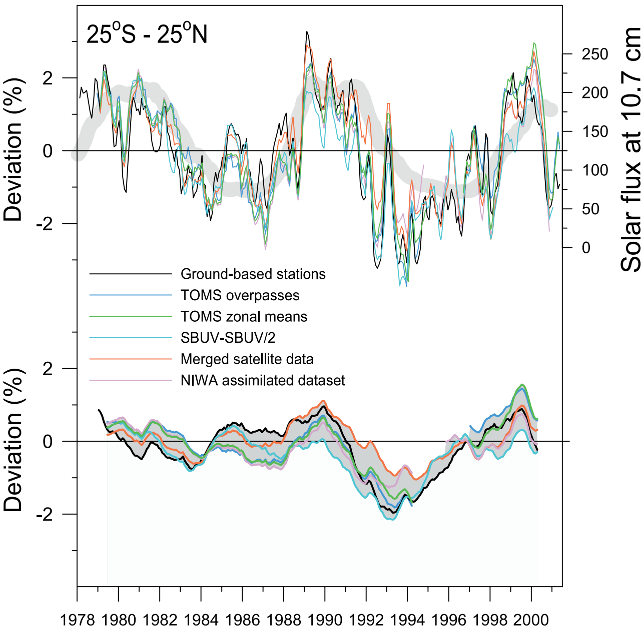

Figure 6. (Top) Area weighted deviation values adjusted for the seasonal effects for 25°S–25°N estimated from the six data sets. The data are smoothed by 3 month running means. The smoothed solar flux at 10.7 cm is also shown. (Bottom) The same data but adjusted for the seasonal, solar, and QBO effects and smoothed by 25 month running means. Solar and QBO effects have been estimated using ground-based data only and then subtracted from all six data sets. The shaded area indicates the spread of the different data sets.

35° zones are transitional areas from a zero trend over the tropics to a significant decline over midlatitudes. Both the annual cycle and ozone vertical distribution of ozone behave differently at middle latitudes than at tropical regions, and the border between these two regions is located at about 35° (south and north). It is appropriate therefore to analyze ozone variations over the 35°–60°S and 35°–60°N latitudinal zones. Figure 7 shows deseasonalized ozone values integrated over the 35°–60°S and 35°–60°N latitude zones.

[31] Figure 7 demonstrates that the ozone level in the late 1990s is several percent lower than in the late 1970s and the decline over the two midlatitudes zones is evident from the plot. However, the ozone fluctuations over northern midlatitudes are rather different from those over southern midlatitudes. The largest deviations occurred in 1992–1995 over the northern zone, and the 1985 anomaly is the most distinct feature of the 35°–60°S record. Figure 7 also shows that the ozone level was fairly stable over both zones up to the late 1970s.

[32] The QBO- and solar cycle-related components were estimated using the ground-based data set and removed from the time series of ozone values over the 35°–60°S and 35°–60°N zones for all 6 data sets. The residuals smoothed by a 25-month running mean are shown in Figure 8. The seasonal dependence of temporal variations of total ozone over northern and southern midlatitudes is shown in Figure 9.

[33] Figures 7, 8, and 9 demonstrate significant differences in total ozone variations between northern and southern midlatitudes. Over northern midlatitudes ozone declined nearly linearly between 1979 and the late 1980s-early 1990s, then was extremely low in the winter and spring of 1993 and 1995, and then leveled off in the late 1990s. Figure 9 shows that the largest negative anomalies occurred in the northern midlatitudes during the winter and spring and the long-term decline is also stronger in these seasons. The anomalies are not as strong in summer and hardly noticeable in fall, although a negative trend can be also seen in these seasons. Low values in 1993 have been widely discussed [*Gleason et al.*, 1993; *Bojkov et al.*, 1993; *Kerr et al.*, 1993; *Komhyr et al.*, 1994] and are mostly due to the effects (dynamical and/or chemical) of the eruption in the Philippines of Mount Pinatubo in June 1991 [*Brasseur and Granier* 1992; *Labitzke and McCormick*, 1992; *Solomon et al.*, 1996]. Low ozone values were also seen in the winter and spring of 1995, particularly over Siberia, when the Mount Pinatubo volcanic aerosol cloud had practically disappeared [*Bojkov et al.*, 1995a]. Ozone values were relatively high in 1998 and 1999 reaching the pre-1980 level in 1998. However, low values in 2000 suggest that these higher anomalies were more likely an illustration of ozone variability rather than evidence suggesting the reversal of the long-term trend.

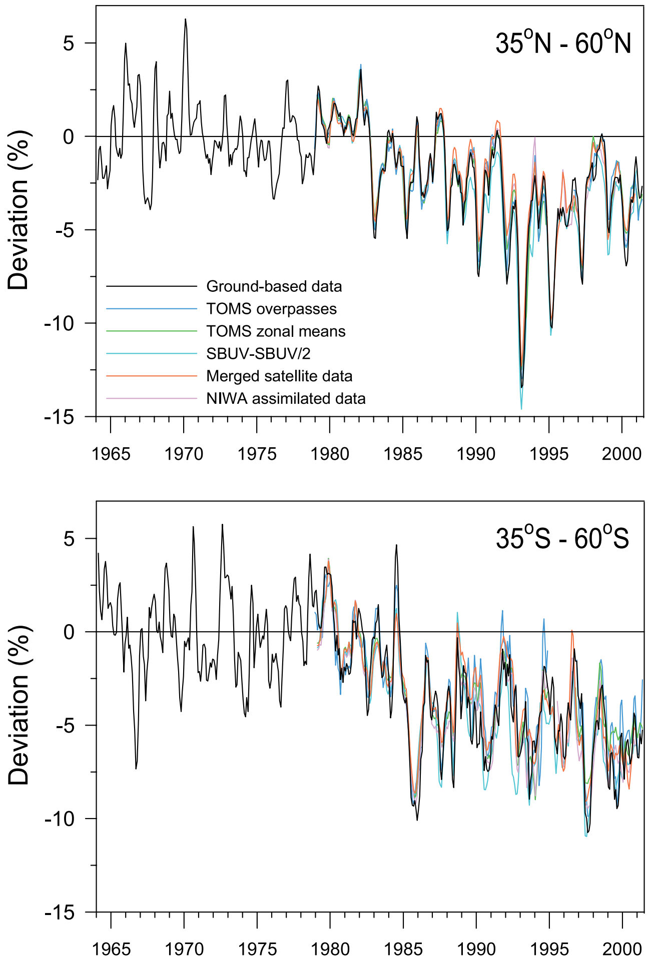

Figure 7. Area weighted total ozone deviations from the 1979–1987 monthly means in percent of the means for the 35°N–60°N and 35°S–60°S zones estimated from the six data sets. The data are smoothed by 3 month running means.

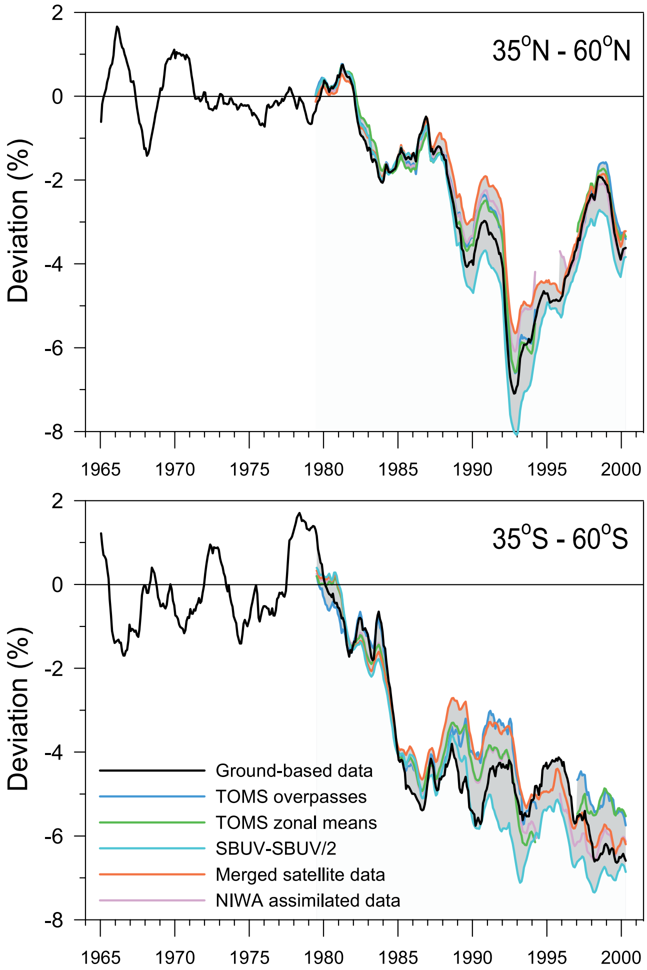

Figure 8. Total ozone deviations from the pre-1980 level in percent for the 35°–60°S and 35°–60°N zones estimated from the six data sets with seasonal, QBO, and solar cycle-related components removed. The data are smoothed by 25 month running means. The shaded area indicates the spread of the different data sets.

[34] In contrast, ozone over southern midlatitudes has behaved quite differently. There was a sharp decline between 1979 and 1988 with the most dramatic changes occurring between 1984 and 1985. The cause of these changes is presently unknown, although the fact that the changes between 1984 and 1985 are smaller when the natural components of ozone variations are removed suggests a strong dynamical influence. Record large deviations were also seen in 1997 [*Brinksma et al.*, 1998; *Connor et al.*, 1999]. The rate of decline becomes lower after 1988. No clear seasonal dependence can be seen in the ozone decline over southern midlatitudes as noted earlier by *WMO* [1995, 1999]. The southern midlatitudes record also does not show the significant reductions in 1992–1993 that occurred over the northern region.

4. Total Ozone Trends

[35] The trends in total ozone presented in previous publications [*WMO*, 1992; *Stolarski et al.*, 1992, *WMO*, 1995; *Bojkov et al.*, 1995b; *Harris et al.*, 1997; *WMO*, 1999], have been updated using monthly mean values from ground-based stations data through December 2000. Trends have been estimated using the statistical model mentioned above that fits ozone data with monthly linear trends, QBO- and solar cycle-related components and contains an auto-correlated noise term [*WMO*, 1998b]. The total ozone trends are plotted as a function of latitude in Figure 10. Figure 10 also shows average trends over wide latitudinal zones calculated in the same manner as by *WMO* [1999]. The trend estimates are scattered due to longitudinal differences of the ozone changes, gaps in records from some stations and small instrument calibration errors. However, all seasonal and year-round trends are negative outside the 30°S–30°N zone and all year-round trends there are statistically significant (95% confidence level). A seasonal dependence of the trend is seen over northern midlatitudes where the strongest decline of −3.9% per decade occurred in March–May and the weakest (−1.1% per decade) occurred in September–November. The average seasonal trends over southern midlatitudes show little dependence on the time of the year and were between −1.7% and −2.8% per decade.

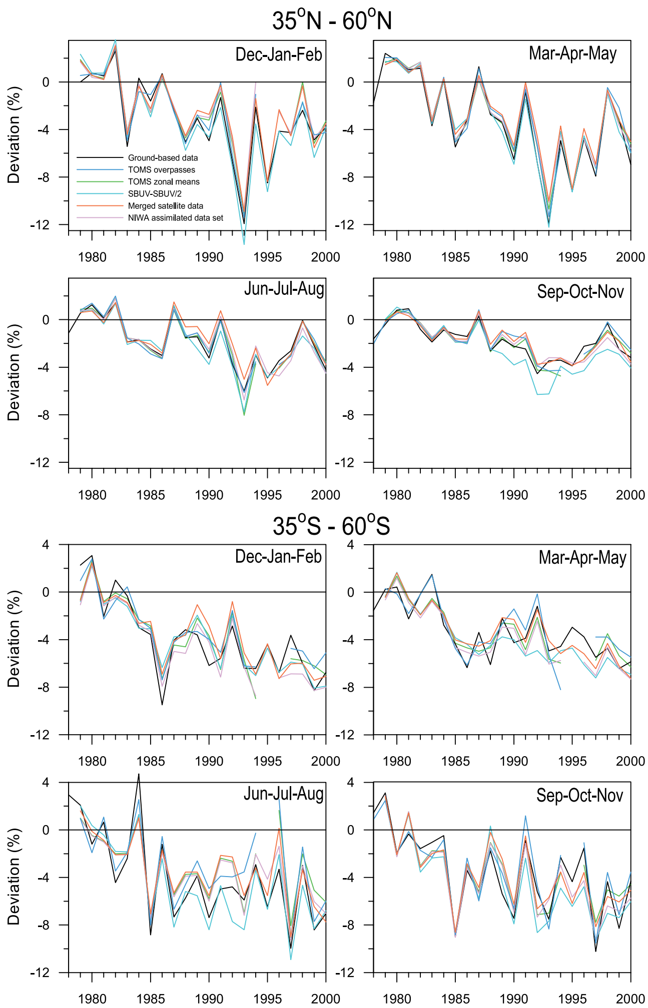

Figure 9. Seasonal area weighted total ozone deviations from the pre-1980 level in percent for the 35°N–60°N and 35°S–60°S zones estimated from the six data sets.

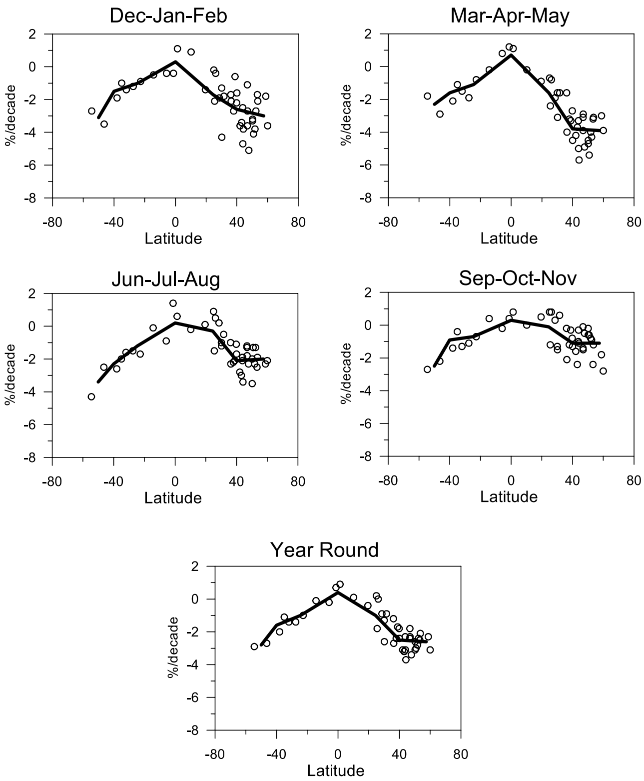

Figure 10. Ground-based total ozone trends by season and year-round over the period 1/1979–12/2000 for 44 individual stations (open circles) and for zonal averages (thick line).

[36] Seasonal and year-round trends have also been calculated using the other data sets described in this study. Figure 11 shows trend estimates from the merged satellite data set along with their 95% confidence levels. The ground-based station zonal-average trends from Figure 10 are also shown by the thick gray line with triangles at the middle of each zone. In general the agreement between the trends from satellite and ground-based data is very good: they both show latitudinal dependence of the trend with nearly zero values over the equator and substantial decline outside the 35°S–35°N zone.

[37] Annual trend estimates over midlatitudes from some previous publications and the trends calculated from the six data sets of this study are summarized in Table 1. The latitudinal zones and the trend calculation methods have differed from one study to another, but in general, Table 1 reflects the evolution of the total ozone trend estimates over midlatitudes. The first estimates of the global total ozone changes were done by *WMO* [1990a] using TOMS data. The TOMS algorithm at that time yielded time series with a long-term drift in ozone values that was comparable with the trend itself [*Fleig et al.*, 1986] and Dobson network observations were used to calibrate the satellite data. Dobson data had their own problems at that time [*Bojkov et al.*, 1988]. To correct them, records of many stations were provisionally reevaluated, that is, corrected for major errors based on instrument intercomparison results. The TOMS trends reported by *WMO* [1990a] over midlatitudes had large error bars due to the very short time span of the data. The reported accumulated ozone loss of about −5% over the southern midlatitudes and about −1.2 to −2.7% for the northern midlatitudes is in agreement with the results shown in Figure 8. Dobson data were also used for the trend estimates by *WMO* [1990a] and their analysis demonstrated a statistically significant winter-spring trend from −2.3% to −6.2% over northern midlatitudes for the entire 1970–1986 period.

[38] A new version 6 of the TOMS algorithm had become available by 1991 [*Herman et al.*, 1991; *Stolarski et al.*, 1991]. The long-term downward trend with respect to the ground-based network has been largely removed, although a bias of about 3% was still present due to a prelaunch calibration error in TOMS. TOMS data processed with version 6 were used by *WMO* [1992, 1995] and for the 1979–1991 period yielded a trend result similar to those from the ground-based network. Both TOMS and ground-based data demonstrated a statistically significant decline of 4% per decade over the 12-year period ended in 1991.

[39] Low ozone values in the winter-spring of 1992 and 1993 over the northern hemisphere yielded even larger values of the trends over northern midlatitudes (−4.8% per decade) for the 1979–1994 period reported by *WMO* [1995]. "Trend acceleration" was also noted, that is, the impact of the negative trend increases in the 1980s over the 1970s [*WMO*, 1995; *Harris et al.*, 1997]. The 1992 and 1993 Nimbus 7 TOMS data demonstrated a 2.5% decline against the ground-based network and were not used by

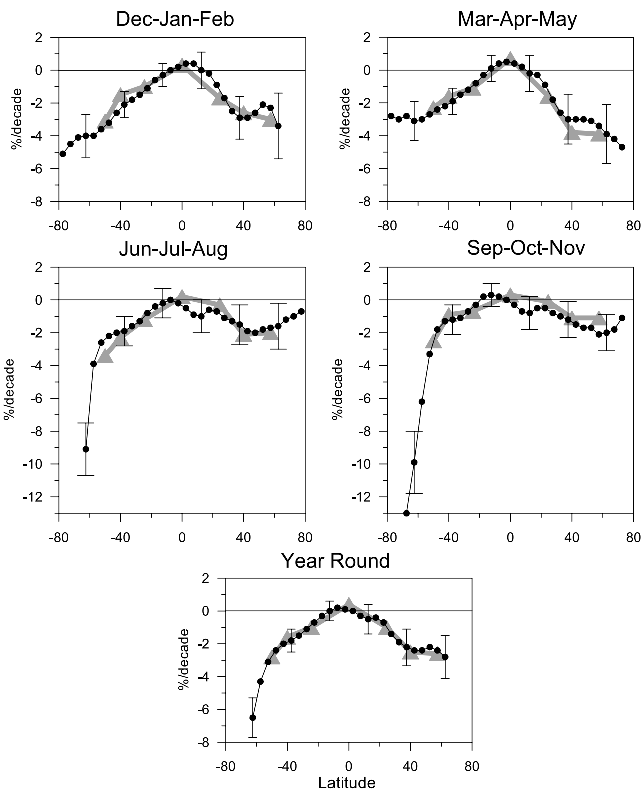

Figure 11. Total ozone trends by season and year-round over the period 1/1979–12/2000. Ground-based total ozone trends from Figure 10 (thick, gray line with triangles) and ozone trends estimated from the merged satellite data set with 2σ error bars are shown.

Table 1. Total Ozone Year-Round Trends Over Midlatitudes in Percent Per Decade With 95% Confidence Limits[a]

Period	Southern Midlatitudes	Northern Midlatitudes	Data Source	Reference
		Previous Estimates		
11/1978–10/1985	−7.1 ± 5.1	−3.9 ± 4.9	TOMS calibrated by comparison with ground-based data	[*WMO*, 1990a]
11/1978–11/1987	−5.4 ± 4.0	−1.3 ± 3.3	Same	[*WMO*, 1990a]
1/1979–3/1991	−5.4	−3.1	TOMS version 6	[*WMO*, 1992]
1/1979–5/1991	−4.5 ± 2.1	−4.0 ± 2.1	TOMS version 6	[*WMO*, 1995]
1/1979–5/1991	−3.8 ± 1.3	−3.9 ± 0.7	Dobson network	[*WMO*, 1995]
1/1979–5/1991	−4.9 ± 2.3	−3.3 ± 2.4	SBUV-SBUV/2 Version 6	[*WMO*, 1995]
1/1979–2/1994	−3.2 ± 1.3	−4.8 ± 0.8	Dobson network	[*WMO*, 1995]
1/1979–5/1994	−4.9 ± 1.5	−4.6 ± 1.8	SBUV-SBUV/2 Version 6	[*WMO*, 1995]
1/1979–12/1997	−2.6	−3.7	Ground-based network	[*WMO*, 1999]
1/1979–12/1997	−3.1±1.6	−3.3 ± 1.7	TOMS version 7	[*WMO*, 1999]
		This Study		
1/1979–12/2000	−2.5 ± 0.9	−2.3 ± 1.3	Ground-based zonal mean data set	
1/1979–12/2000	−2.6 ± 0.8	−2.4 ± 1.2	Merged satellite data set	
1/1979–12/2000	−2.6 ± 0.9	−2.5 ± 1.2	NIWA assimilated data set	
1/1979–12/2000	−3.3 ± 0.8	−3.0 ± 1.6	SBUV-SBUV/2 data set	
1/1979–12/2000	−2.3 ± 0.9	−3.2 ± 1.6	TOMS version 7 zonal means	
1/1979–12/2000	−2.0 ± 0.9	−3.0 ± 1.5	Zonal means estimated from TOMS overpass	

[a] Trends in this study were estimated for the 35°–60°S and 35°–60°N zones.

WMO [1995]. The SBUV-SBUV/2 data were used instead to estimate global and zonal trends. The SBUV-SBUV/2 trend estimates were almost identical to those from the ground-based network over northern midlatitudes; however, the ground-based network reported a weaker decline over the southern midlatitudes than SBUV-SBUV/2. This was mostly due to the combination of NOAA 11 SBUV/2 error at high zenith angles and the sampling problem caused by the precessing orbits of the NOAA satellites [*Hollandsworth et al.*, 1995; *Fioletov et al.*, 1997a].

[40] Most of the Dobson records used by *WMO* [1992] and *WMO* [1995] were provisional reevaluations or were early revisions by the stations' authorities. The process of reevaluation of the Dobson data [see *WMO*, 1993], started in the late 1980s, was mostly completed by 1997, resulting in a higher quality of ground-based records available from the WOUDC. These data and TOMS measurements processed with a new version 7 algorithm [*Herman et al.*, 1996; *McPeters et al.*, 1996] were used by *WMO* [1999]. The analysis revealed that ozone values in 1995–1997 were higher than would be expected from a linear trend model based on the 1979–1991 record, indicating a reduction in the slope of the downward trend.

[41] A further reduction of the slope can be seen in the linear trends if the analysis period is extended to 2000. The decline over northern middle and high latitudes for the 1979–2000 period is not as strong as in the 1979–1997 period, especially in the spring season. Table 1 shows that the ground-based, merged satellite, and NIWA data sets demonstrate nearly identical results. The accumulated ozone loss for the entire 1979–2000 period is about 5.3% over northern midlatitudes and 5.7% over southern midlatitudes, and trend values are much larger than their 95% uncertainty estimates. The trend estimates from all six data sets agree within their 95% uncertainty limits. Somewhat different results for TOMS and SBUV-SBUV/2 data sets are mostly related to gaps in the data, which do not exist in the three other data sets. The TOMS trends are also affected by the previously mentioned errors in the Earth Probe record in 2000 and should be interpreted with caution.

[42] The rate of ozone decline was not the same over different time intervals and the estimates of trends are dependent on the time period for the data set. Sliding 11-year trends were calculated to estimate ozone changes over different time intervals (Figure 12). This type of plot was used, for example, by *WMO* [1992] to demonstrate the acceleration of the ozone decline in the late 1980s. The first interval in Figure 12 was from 1964 to 1974 and the last interval was from 1990 to 2000. The year-round trends were calculated using the "standard" trend model. The set of 44 Dobson/Brewer stations, TOMS overpasses over the same sites, and the merged satellite data set were used for this analysis. As mentioned the 11-year solar cycle-related variations are a substantial contributor to the overall ozone variability. The amplitude of the solar cycle was estimated using the entire 35-year period and that amplitude was substituted into the statistical model.

[43] Figure 12 shows that the most rapid decline, up to −5% per decade for the year-round trend, occurred in the 11-year periods ending between 1992 and 1997 for the 35°–60°N zone and between 1985 and 1993 for the 35°–55°S zone. The most recent 11-year trends have much smaller magnitudes. There was practically no decline over the 1988–2000 period over northern midlatitudes.

[44] All of the analysis above was based on the total ozone zonal averages. Analysis of satellite data demonstrates that the ozone trends are predominantly zonal although there are some longitudinal differences in the ozone decline. Figure 13 shows seasonal trends estimated using gridded (5° latitude by 10° longitude) merged satellite data for the period 1979–2000. As stated earlier there is no decline in zonal mean ozone over the 25°S–25°N zone. Figure 13 clearly shows that the year-round trend in this region is close to zero at all longitudes. The strongest decline over the northern hemisphere occurred in the spring season (March–May) over the subpolar region of Siberia

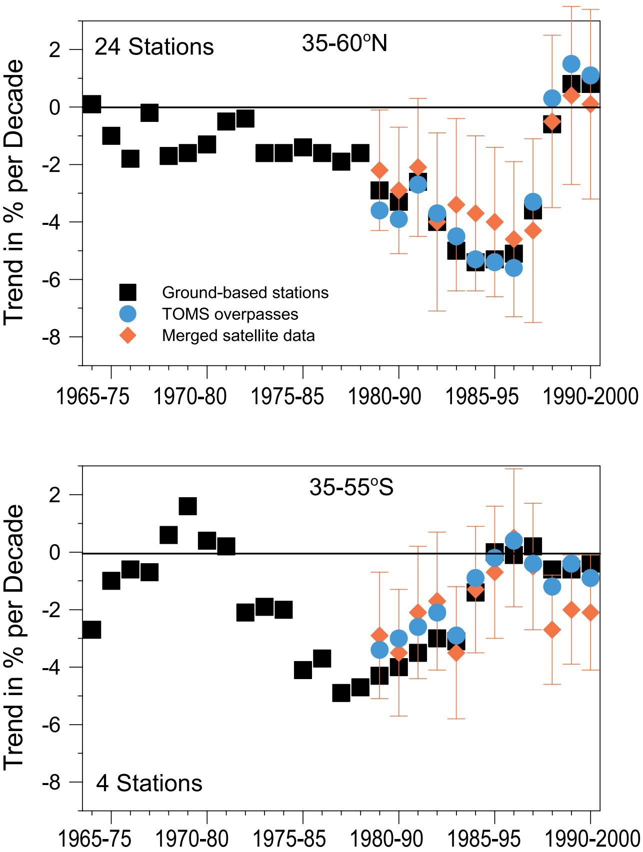

Figure 12. Sliding 11-year trends estimated from ground-based station observations (black squares), TOMS overpass data (blue circles), and zonal averages from merged satellite data set (red diamonds). Seasonal, QBO, and solar cycles have been removed. Each point was obtained by fitting a linear 11-year trend though the given time period, that is, 1965 through 1975 or 1990 through 2000. The 35°–55°S zone was chosen for the southern hemisphere because there are no ground-based stations with long-term records between 55°S and 60°S.

(−7% per decade), northern Europe and the Canadian Arctic. The same longitudinal pattern was shown by *WMO* [1999, Figure 1–19] for the 1979–1997 period, however, the slope of the linear trend was larger in magnitude by up to 2% per decade. These longitudinal differences are partially related to large relative deviations in winter-spring that occurred when areas of relatively low ozone amounts, typically associated with the polar vortex, were transported over the regions with high climatological ozone values. However, the ozone decline there is not limited to the polar vortex area alone [*Randel and Wu*, 1995]. The summer and fall decline over the northern hemisphere is smaller and more uniform with longitude. The longitudinal differences are also smaller, about 2% per decade, in summer and fall. The year-round trends also show little longitudinal dependence (within 2%) that was mostly related to the longitudinal difference of the spring trends. Very large September–November trends over the southern high latitudes are related to the "ozone hole." The "ozone hole" is more often located over the south Atlantic causing some longitudinal differences in the trends.

[45] Figure 14 shows year-round trends over two 13-year periods 1979–1991 and 1988–2000. The first time interval corresponds to the period used by *WMO* [1992] and the second interval represents a period of the same length but ending in 2000. The decline for the first time interval was substantially stronger than that for the second interval over the 35–65°N zone. Seasonal trends (not shown here) also demonstrate insignificant changes from −3% to +2% per decade over northern midlatitudes over the 1988–2000 period. The only exception was a stronger negative trend over the northern Atlantic in the winter and spring reflected also by the annual trend. In contrast, trends of −4% per decade or more were seen over vast areas south of 35°S at all seasons during 1988–2000. The decline south of 35°S can be seen for both the 1979–1991 and 1988–2000 intervals, although the slope of negative trend was larger over the first interval than over the second. Not surprisingly, the strongest decline, −10% per decade and more, is related to the "ozone hole."

[46] One of the consequences of this difference between ozone trends over northern and southern midlatitudes is the difference in UV irradiation changes for the two regions. Regular spectral UV measurements started in the late 1980s, that is, the period of available data is coincident with the second time interval. The analysis of available UV data demonstrated an increase of summer erythemal UV irradiance over southern midlatitudes [*McKenzie et al.*, 1999], while no statistically significant ozone-related trend in UV was found over northern midlatitudes [*Fioletov et al.*, 2001; *Zerefos*, 2002].

[47] Figures 12 and 14 demonstrate a reduction in magnitude of the downward slope of ozone trends over mid-

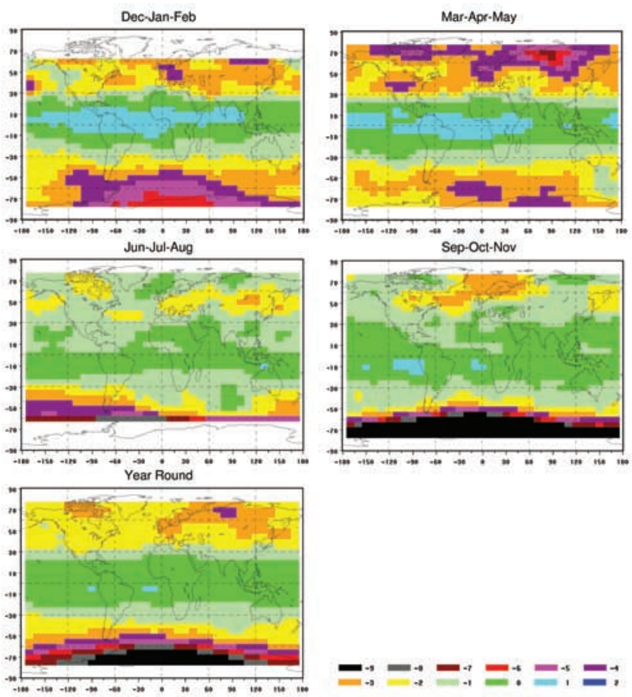

Figure 13. Seasonal and year-round total ozone trends for the period 1979–2000 in percent per decade estimated using the merged satellite data set.

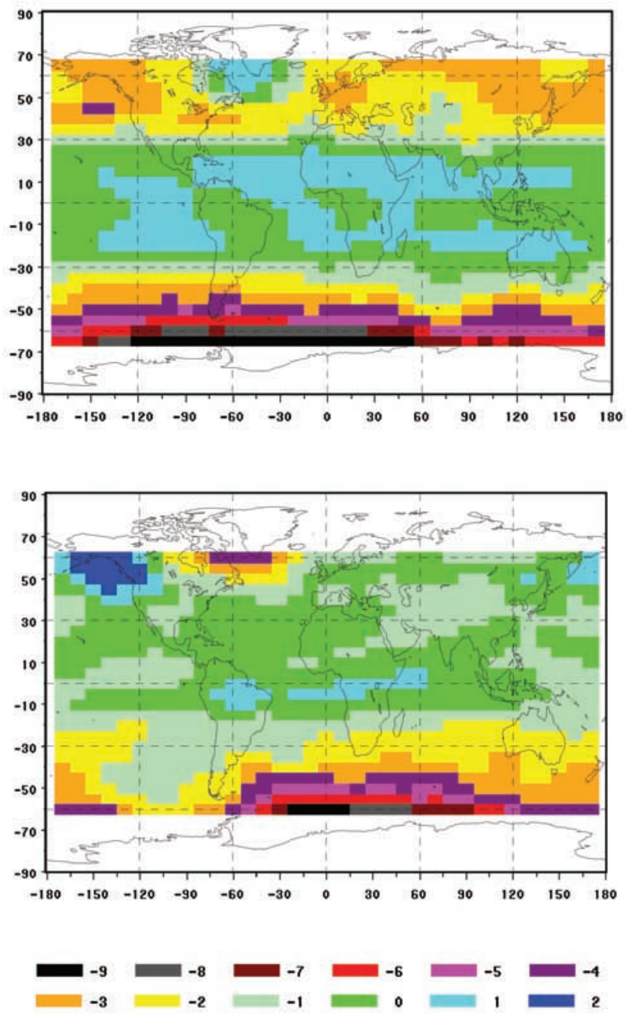

Figure 14. Total ozone trends for the 1979–1991 (top) and 1988–2000 (bottom) periods in percent per decade estimated from the merged satellite data set.

latitudes during the 1990s. It is expected that a reduction in the rate of ozone decline should occur in the recent years because of the leveling off of the stratospheric chlorine loading [*Anderson et al.*, 2000]. The reduction of the slope in the 1990s compared to the 1980s could be an indication of this slowdown. However, the large ozone variability and ozone anomalies in 1992–1993 over northern midlatitudes and in 1985 over southern midlatitudes could largely contribute to the difference in the observed ozone trends over the different periods. There have also been changes in aerosol loading during the 1990s [e.g., *Stevermer et al.*, 2000]. Large concentrations of stratospheric aerosols following Mount Pinatubo eruption in 1991 facilitated ozone destruction, especially at high latitudes, while aerosol loading in the late 1990s was one of the lowest for the entire 1964–2000 period. A near zero or even small positive slope of the linear trend seen for some periods in the 1990s over midlatitudes cannot be considered as an indication of an ozone recovery. Trends must be greater than about 3% per decade in order to be statistically significant when midlatitudinal zonal averages for intervals of 10–12 years are calculated. Since the late 1980s no positive trends of that slope have been observed yet. *Weatherhead et al.* [2000] estimate, that the expected rates of ozone recovery, 3.6 DU per decade for southern and 2.1 DU per decade for northern midlatitudes, would require 20 and 30 years respectively to detect these positive trends with 95% statistical significance.

5. Concluding Remarks

[48] Several groups have developed data sets that include measurements from various data sources. These data sets have been used to estimate global and zonal total ozone. While ground-based and satellite data agree within to 1% over northern midlatitudes, there is a 2–3% systematic difference over tropical and equatorial region and over southern midlatitudes. The difference is even larger, about 5%, over Antarctica. However, when the systematic differences are removed, observed temporal ozone changes typically agree to within ±0.5%, that is, the differences among the data sets are much smaller than the observed natural short-term ozone variations as well as the long-term decline of the area-weighted global total ozone amount.

[49] Ozone fluctuations in equatorial and tropical regions (25°S–25°N) are mostly affected by the QBO- and 11-year solar cycle and there is no sign of long-term decline. Annual ozone trends for the 1979–2000 period are statistically significant south of 35°S and north of 35°N, although there is a substantial difference between ozone changes over northern and southern middle and high latitudes. The strongest decline and the largest variability occurred over the 35°N–60°N zone during the winter-spring season, and the decline in fall is smaller. The largest negative deviations there occurred in 1993 and 1995. Over the 35°S–60°S zone, the ozone decline shows less seasonal dependence and the largest deviations at these latitudes were observed in 1985 and 1997.

[50] All data sets show changes in the rate of the total ozone decline between the 1980s and 1990s. Global and 60°S–60°N ozone amounts were fairly constant during the 1990s, however the level of the 1990s is about 3% lower (2% for 60°S–60°N) than the level of the late 1970s. The rate of ozone decline in the 1980s over midlatitudes was between 3% and 4% per decade and was higher than for the entire 1979–2000 period (about 2.5% per decade). However, there are no statistically significant positive trends indicating possible recovery of total ozone.

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