Comparison and covalidation of ozone anomalies and variability observed in SBUV(/2) and Umkehr northern midlatitude ozone profile estimates

I. Petropavlovskikh,[1] Changwoo Ahn,[2] P. K. Bhartia,[3] and L. E. Flynn[4]

Received 15 November 2004; revised 21 January 2005; accepted 31 January 2005; published 19 March 2005.

[1] This analysis presents comparisons of upper-stratosphere ozone information observed by two independent systems: the Solar Backscatter UltraViolet (SBUV and SBUV/2) satellite instruments, and ground-based Dobson spectrophotometers. Both the new SBUV Version 8 and the new UMK04 profile retrieval algorithms are optimized for studying long-term variability and trends in ozone. Trend analyses of the ozone time series from the SBUV(/2) data set are complex because of the multiple instruments involved, changes in the instruments' geo-location, and short periods of overlaps for inter-calibrations among different instruments. Three northern middle latitudes Dobson ground stations (Arosa, Boulder, and Tateno) are used in this analysis to validate the trend quality of the combined 25-year SBUV/2 time series, 1979 to 2003. Generally, differences between the satellite and ground-based data do not suggest any significant time-dependent shifts or trends. The shared features confirm the value of these data sets for studies of ozone variability.
Citation: Petropavlovskikh, I., C. Ahn, P. K. Bhartia, and L. E. Flynn (2005), Comparison and covalidation of ozone anomalies and variability observed in SBUV(/2) and Umkehr northern midlatitude ozone profile estimates, *Geophys. Res. Lett.*, *32*, L06805, doi:10.1029/2004GL022002.

1. Introduction

[2] Many studies have been conducted for monitoring and detection of upper stratospheric ozone trends and behavior using a variety of ground and satellite instruments and their inter-comparisons [*Stratospheric Processes and Their Role in Climate* (*SPARC*), 1998; *Reinsel*, 2002; *Steinbrecht et al.*, 2004, and references therein]. However, a consensus of ozone trends has not been made due to inconsistent results from different instruments with different data analysis approaches and lack of global/temporal coverage for systematically validating ozone trends, in both latitudes and altitudes as suggested by *Weatherhead et al.* [2004]. A long-term record from the Solar Backscattered Ultraviolet (SBUV) instruments containing daily global total column ozone and stratospheric profile ozone data is available for trend analysis from 1979 to the present. However, data from the NOAA series of SBUV/2 instruments has been de-emphasized because questions about the stability of their calibration raised concerns about their reliability to provide accurate assessments of trends and changes in stratospheric ozone behavior [*SPARC*, 1998; *World Meteorological Organization* (*WMO*), 2002].

[3] NASA Goddard Space Flight Center/Atmospheric Chemistry and Dynamics Branch has developed new Version 8 (V8) algorithms for TOMS and SBUV data [*Bhartia et al.*, 2004]. Furthermore, better instrument characterization and calibration from both "hard" and "soft" methods [*Deland et al.*, 2004] have been used to stabilize the calibration from instrument to instrument so that data from multiple SBUV instruments can be used together in a consistent 25-year time series. Of equal importance, the V8 algorithm is designed to reduce the influence of the *a priori* on ozone trends by optimizing the retrieval of inter-annual variability and trends. Therefore, the SBUV(/2) data reprocessed with this new algorithm can be used for trend analysis with more accuracy than has been possible before [*McPeters et al.*, 2004]. These data have been validated with ground-based measurements such as microwave, lidar, sonde, Dobson/Brewer, and SAGE satellite. The V8 data generally showed agreement within ±5% on average for mean profile differences, while stability of the total ozone record was approximately ±1% over 25 years [*Ahn et al.*, 2004; *McPeters et al.*, 2004]. Did we see any N16 seasonality in the differences?

[4] The purpose of this study is to investigate and evaluate upper-stratospheric ozone variability by comparing monthly anomalies of Umkehr with those of V8 SBUV over three Umkehr stations—Arosa, Switzerland (46.77°N, 9.67°E), Boulder, USA (40.02°N, 105.25°W), and Tateno, Japan (36.05°N, 140.13°E)—and also to provide information on the newly reprocessed V8 SBUV and Umkehr data as a guideline for their use in long-term trends analysis.

2. Description of Data Sets

[5] Measurements from Umkehr and SBUV systems are very similar in their physical content, and therefore, easily compared. Umkehr data are processed using the newly updated UMK04 algorithm (http://www.srrb.noaa.gov/research/umkehr) and SBUV(/2) data with the Version 8 algorithm (http://daac.gsfc.nasa.gov/data/dataset/TOMS/DVD-ROMs/). The algorithms were developed simultaneously, and include similar features, such as a stable *a priori* from an updated ozone climatology [*McPeters et al.*, 2003], and similar concepts of forward and inverse models. Both systems also have pressure-based retrieval coordinates enabling us to do a direct layer ozone compar-

[1]National Oceanic and Atmospheric Administration, Boulder, Colorado, USA.
[2]Science Systems and Applications, Inc., Lanham, Maryland, USA.
[3]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[4]National Environmental Satellite Data and Information Service Headquarters, NOAA, Camp Springs, Maryland, USA.

0094-8276/05/2004GL022002$05.00

Table 1. Version 8 Data Availability From NASA and NOAA Instruments[a]

Instrument	Coverage Dates	Daily Coincidences		
		Arosa	Boulder	Tateno
Nimbus 7 SBUV	11/1978–6/1990	700 (134)	956 (131)	806 (127)
NOAA 9 SBUV/2 (descending orbit)	1/1992–2/1998	361 (57)	449 (54)	423 (53)
NOAA 11 SBUV/2	12/1988–3/2001[b]	793 (115)	965 (115)	893 (112)
NOAA 16 SBUV/2	10/2000–12/2003	52 (9)	137 (18)	183 (20)

[a]The last three columns show the number of daily coincidences of SBUV and Umkehr measurements for three stations for the time period of each SBUV instrument. The numbers in parentheses denote the number of monthly coincidences.
[b]Reduced coverage in 1995 and 1997 due to terminator crossing.

ison. This avoids difficulties in converting ozone density versus altitude to layer ozone versus pressure as needed, for example, with comparisons to SAGE data. Uncertainties in the temperature data used to determine the pressure versus altitude conversion can be a source of error in trend analysis as pointed out by *Wang et al.* [1996, and references therein].

[6] Table 1 shows the periods with measurements for each SBUV instrument used in this study. The overlaps among periods between the satellite instruments were used to assess the instruments' performance. Despite collective efforts for calibration of the SBUV(/2) instruments, some instrument/calibration problems such as chopper-wheel non-synchronization for the Nimbus-7 time period (1987–1990) and grating drive problems for NOAA-9 and NOAA-11 still remain in the reprocessed data (see DVD for details). In-depth analyses of data by *McPeters et al.* [1994] argued that non-synchronization problem of Nimbus-7 SBUV instrument is simply manifested as increased noise. However, significant spacecraft orbital drift and grating drive position problems of NOAA-9 and NOAA-11 after 1996 create potential sources of error in the combined SBUV(/2) data set. Evaluation and reassurance of the trend quality of the combined SBUV dataset are provided in this paper.

[7] The best single daily match-up data between SBUV(/2) and Umkehr are selected based on the minimum distance satellite retrievals within 1000 km and 12 hr of the Umkehr measurement (see Table 1 for a number of daily coincidences for three Umkehr stations). For layer ozone (Dobson Unit) comparisons the Umkehr and SBUV profiles are combined into a 7-Layer Scheme denoted as follows: 4^- (combined Umkehr layers 0, 1, 2, and 3), Umkehr layers 4, 5, 6, 7, and 8, and 8^+ (integrated ozone information in Umkehr layer 8 and above). Table 2 shows the pressures and approximate altitudes of layers. This broad layer system is capable of monitoring long-term changes in monthly mean tropospheric and stratospheric ozone levels. Errors in the retrieved layer ozone have low correlation, and influence from the *a priori* information is kept to the minimum. We will discuss ozone variability measured by the combined SBUV(/2) and Umkehr system in layers 6, 7 and 8. These layers are chosen to study inter-annual variability of stratospheric ozone, which is mostly controlled by chemistry and, thus, by anthropogenic emissions.

[8] The single daily match-up data in each layer are deseasonalized by subtracting the climatological ozone layer amount (SM) from monthly mean (MM) ozone for each layer producing monthly mean anomalies in % defined as

$$\mathrm{MMA} = [(\mathrm{MM} - \mathrm{SM})/\mathrm{SM}] * 100.$$

The climatology here is computed as mean value of either SBUV or Umkehr ozone data selected for each of the twelve calendar months over the entire 1979–2003 period. It is expected that use of monthly averages will reduce errors caused by differences in the geophysical data collocation. This method provides adequate information for analysis of long-term ozone trends and anomalies (departures from the mean) by accounting empirically for seasonal oscillations in the data. The QBO, solar cycle, and other natural oscillations continue to influence the data, and we have not constructed a full statistical model to improve trend analysis. Caution must be exercised to avoid a misinterpretation of the magnitude and sign of trends varying with a chosen model and parameters [*Steinbrecht et al.*, 2004; *Weatherhead et al.*, 2004].

[9] The aerosol correction for the Umkehr data was performed by using monthly mean time-series of stratospheric aerosol Optical Depth (OD) (http://www.srrb.noaa.gov/research/aerosol.html). The aerosol corrections as function of altitude and optical depth were recently developed and published in the white paper on Dobson C-pair Umkehr algorithm at http://www.srrb.noaa.gov/research/umkehr. The in-depth study of the Pinatubo eruption [*Chazette et al.*, 1995] suggests that by October 1991 the maximum aerosol load at the middle latitudes was found at 24 km, while one year later most of the aerosols had shifted to below 20 km. Lacking information on the aerosol layer altitude above the Umkehr stations, we simulated the effect of aerosols on the Umkehr measurements as a function of maximum load altitude. A 15 km layer creates the best match to the blended SBUV data at the time of volcanic eruptions. There are still errors in the corrected data, most noticeably in the layer 8 ozone deseasonalized time series (more details are given in the following section).

3. Analyses of Long-Term Changes in Individual Stations

[10] Figure 1 shows monthly anomalies of multiple SBUV data and Umkehr data at individual stations. The data are smoothed by a 5-month running average for each SBUV time period. The results represent the interannual

Table 2. Midpressures and Approximated Altitudes of 7 Layer Scheme[a]

	Layer Number						
	8+	8	7	6	5	4	4–
Pressure at Midpoint, hPa	1.0	3.0	6.0	12.0	24.0	48.0	250.0
Approximate Altitude, km	48.1	39.9	34.9	30.2	25.7	21.2	10.3
RMSD (%)	3.23	4.39	3.21	2.87	3.15	4.35	5.37

[a]Also included are root-mean square deviations (RMSD) of differences between blended SBUV/2 and Umkehr monthly anomalies for each layer.

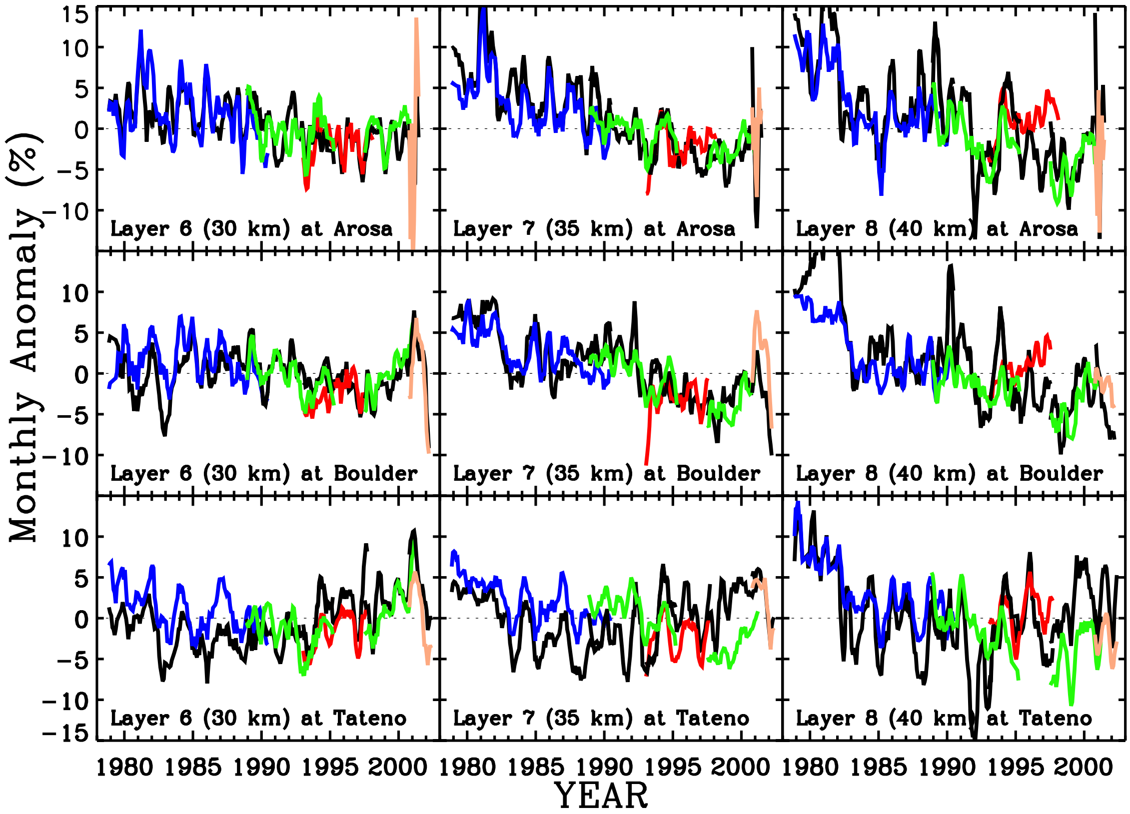

Figure 1. Monthly mean anomalies (MMA) of multiple SBUV and Umkehr over three stations at Umkehr layer 6, 7, and 8. For clarity of time series, data are smoothed by a 5-month running average for each SBUV(/2) time period, separately, and are represented by colors; blue (Nimbus-7), red (NOAA-9), green (NOAA-11), beige (NOAA-16), and black (Umkehr). Note that monthly anomalies in the NOAA-16 time period at Arosa are connected to each point due to insufficient number of samples for adequate calculation of moving average.

variability of upper stratospheric ozone in the northern middle latitudes. Generally, both data sets agree well in terms of inter-annual variability and trends, although a higher variability is found in Umkehr data during winter seasons. There is nearly the same decline in ozone levels (the higher layer shows larger percent trends) observed in both datasets from 1979 to the early 1990s. The QBO and solar cycles are also identifiable, particularly in layer 8 at Arosa station. The higher values and upward trends of NOAA-9 (red) in layer 8 for all three stations could be a spacecraft orbital drift related problem. But, these effects are not observed in lower layers, 6 and 7, which indicates that those could be wavelength-dependent NOAA-9 calibration problems. In the Tateno comparison, the effects of an Umkehr instrument change in 1994 are not easily detected in layer 8 comparisons, but are more obvious in layers 6 and 7. Umkehr monthly anomalies at Tateno show lower values than those of SBUV before 1994, but reversed patterns are found after 1994. At the beginning of the time-series (1979–1981) the elevated MMA are observed by all three ground-based stations in relatively close agreement with SBUV data. However, comparisons over Boulder station show significantly higher Umkehr MMA than detected by SBUV data. This can be explained by lower quality of Umkehr measurements in Boulder at the beginning of its long-term time series, complicated by the interchange of several instruments over the first three years, as well as downgraded quality of manually taken data. In 1982 Boulder Dobson measurements were automated, which allowed taking more measurement per day and helped to reduce operator errors in the quality of measurements. Following implementation of a cloud detector at the un-attended Boulder station in 1988, even higher quality ground-based data were obtained through automated detection and removal of cloud-affected measurements (R. Evans, NOAA/CMDL, personal communications).

[11] All three Umkehr stations still show some residual effects of incomplete stratospheric aerosol corrections (deep troughs in MMA in the years 1983 and 1992). The errors are related to the strong altitude effect of aerosol loads in UMK04 retrieved ozone as discussed in the previous section. For most of the record, the differences between the data sets are smaller than their shared features, providing reassurance for the use of these data sets for long-term trends studies.

4. Analyses of Instrumental Drifts/Shift in Blended SBUV Versus Umkehr Data

[12] The time-dependent drift and trends between multiple SBUV instruments and all three Umkehr station data were analyzed by taking differences of the smoothed monthly anomaly of SBUV and Umkehr data. The last line in Table 2 summarizes results of root-mean square deviations

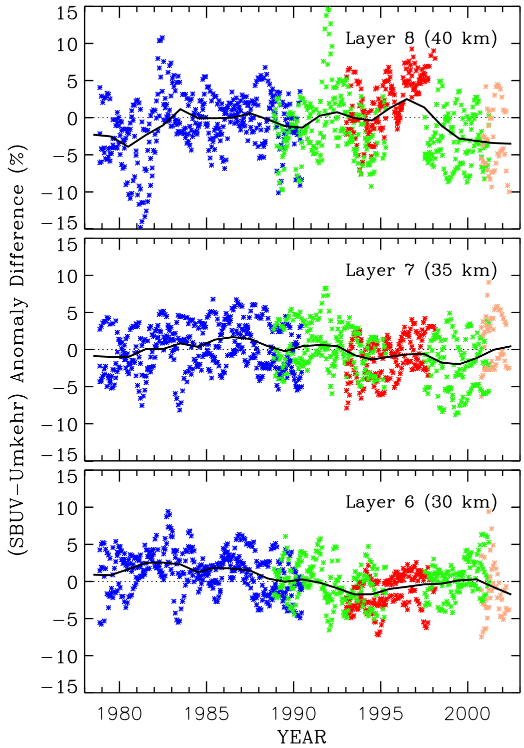

Figure 2. Differences in the smoothed monthly mean anomalies for SBUV and Umkehr for layer 6, 7, and 8. The plot incorporates data from three ground stations (Tateno, Arosa and Boulder). Colors indicate the time periods of SBUV instruments (blue: Nimbus-7, green: NOAA-11, red: NOAA-9, beige: NOAA-16). The black solid line is a 3-year running average of yearly averages of all data. A simple linear fit gives −1.4, −0.7, and 0.1 slopes (% per decade) for layers 6, 7, and 8, respectively.

(RMSD) of 967 monthly anomalies (SBUV(/2)-Umkehr monthly coincidences) for each layer. Figure 2 shows detailed results for layers 6, 7 and 8. The time-series in layers 7 and 8 (33 km–43 km) do not show any significant shifts and trends between the two systems. The residual variability and deviations in data can be explained by (1) incomplete aerosol corrections of Umkehr data around volcano eruption periods (El Chichon: 1982–83, and Pinatubo: 1991–92), and (2) upward trend in NOAA-9 time period (1995–1998) due to a significant NOAA-9 spacecraft drift and associated wavelength-dependent calibration problems, and (3) higher values and trends in Umkehr measurements at Tateno after the change of instrument in 1994 and at Boulder prior to 1982. In layer 6 (30 km), the differences between the two data sets show fairly good agreement with lower variability. The results for Layer 6 would be in better agreement with the other layers if the low Layer 6 Tateno data for 1979 to 1987 (See Layer 6 for Tateno in Figure 1) were adjusted up.

5. Conclusions

[13] Both ground-based Dobson Umkehr and combined SBUV/(2) satellite time-series show no major discord in two types of independent measurements from 1979 through 2001 time period. Moreover, anomaly analyses of blended SBUV and Umkehr show the well-known decrease in ozone in the 1980s and early 1990s in northern middle latitudes. The anomaly differences between the satellite and ground-based data are within ±5% in layers 6, 7 and 8. Although, results for individual stations vary, the northern midlatitude combined SBUV/2 and Umkehr data comparisons do not suggest long-term time dependent shifts or trends at the 2% per decade level. The SBUV/2 and Umkehr records are being extended by current measurements and their monitoring of ozone layer and its anticipated recovery will continue. The long-term ground-based measurements provide a solid source of information for satellite validation efforts, such as detection of potential NOAA-9 SBUV/2 calibration problems. They can be used to track the ozone levels relative to the late 1970s. The results described in this paper provide a good reference for assurance of the trend quality of combined SBUV/(2) data. The method helps to detect potential drifts and shifts in both the multiple satellite record and ground-based record at individual Umkehr stations. Moreover, this method provides information for the improvement of aerosol correction in ground-based data.

[14] **Acknowledgments.** All Umkehr data used in this publication are archived at the WMO ozone and UV data center (WOUDC) in Toronto, Canada. Hard work by personnel of Dobson stations in Boulder, USA (NOAA/CMDL), at Arosa, Switzerland (MeteoSwiss), and in Tateno, Japan (Japan Meteorological Agency) is greatly appreciated. This work was funded by OMI Satellite Science Team Project (EOS/AURA satellite) from NASA/Goddard.

References

Ahn, C., et al. (2004), Validation of V8 SBUV profile data with external data sources (microwave, lidar, and sonde), in *Proceedings of the XX Quadrennial Ozone Symposium, 1–8 June 2004, Kos, Greece*, edited by C. S. Zerefos, pp. 513–514, University of Athens, Athens, Greece.

Bhartia, P. K., et al. (2004), Solar backscattered ultraviolet (SBUV) version 8 profile algorithm, in *Proceedings of the XX Quadrennial Ozone Symposium, 1–8 June 2004, Kos, Greece*, edited by C. S. Zerefos, pp. 295–296, Univ. of Athens, Athens, Greece.

Chazette, P., C. David, J. Lefrère, S. Godin, J. Pelon, and G. Mégie (1995), Comparative lidar study of the optical, geometrical, and dynamical properties of stratospheric post-volcanic aerosols, following the eruptions of El Chichon and Mount Pinatubo, *J. Geophys. Res.*, *100*, 23,195–23,208.

Deland, M. T., et al. (2004), Long-term SBUV and SBUV/2 instrument calibration for version 8 ozone data, in *Proceedings of the XX Quadrennial Ozone Symposium, 1–8 June 2004, Kos, Greece*, edited by C. S. Zerefos, pp. 321–322, Univ. of Athens, Athens, Greece.

McPeters, R. D., T. Miles, L. E. Flynn, C. G. Wellemeyer, and J. M. Zawodny (1994), Comparison of SBUV and SAGE II ozone profiles: Implications for ozone trends, *J. Geophys. Res.*, *99*, 20,513–20,524.

McPeters, R. D., et al. (2003), Ozone climatological profiles for version 8 TOMS and SBUV retrievals, *Eos Trans. AGU*, *84*(46), Fall Meet. Suppl., Abstract A21D-0998.

McPeters, R. D., et al. (2004), The validation of version 8 ozone profile: Is SBUV ready for prime time?, in *Proceedings of the XX Quadrennial Ozone Symposium, 1–8 June 2004, Kos, Greece*, edited by C. S. Zerefos, pp. 113–114, Univ. of Athens, Athens, Greece.

Reinsel, G. C. (2002), Trend analysis of upper stratospheric Umkehr ozone data for evidence of turnaround, *Geophys. Res. Lett.*, *29*(10), 1451, doi:10.1029/2002GL014716.

Stratospheric Processes and Their Role in Climate (SPARC) (1998), *Assessment of Trends in the Vertical Distribution of Ozone*, *SPARC Rep. 1*, World Meteorol. Org., Geneva.

Steinbrecht, W., H. Claude, and P. Winkler (2004), Enhanced upper stratospheric ozone: Sign of recovery or solar cycle effect?, *J. Geophys. Res.*, *109*, D02308, doi:10.1029/2003JD004284.

Wang, H. J., D. M. Cunnold, and X. Bao (1996), A critical analysis of Stratospheric Aerosol and Gas Experiment ozone trends, *J. Geophys. Res.*, *101*, 12,495–12,514.

Weatherhead, E. C., et al. (2004), Methods and results for detecting ozone recovery, in *Proceedings of the XX Quadrennial Ozone Symposium, 1–8*

June 2004, Kos, Greece, edited by C. S. Zerefos, pp. 83–84, Univ. of Athens, Athens, Greece.
World Meterological Organization (WMO) (2002), Scientific assessment of ozone depletion 2002, *Rep. 47*, Geneva.

C. Ahn, Science Systems and Applications, Inc., 10210 Greenbelt Road, Suite 400, Lanham, MD 20706, USA.

P. K. Bhartia, NASA Goddard Space Flight Center, Code 613.3, Greenbelt, MD 20771, USA.

L. E. Flynn, National Environmental Satellite Data and Information Service Headquarters, NOAA, 5200 Auth Road, Camp Springs, MD 20746–4304, USA.

I. Petropavlovskikh, National Oceanic and Atmospheric Administration, R/ARL, 325 Broadway, Boulder, CO 80305–3328, USA. (irina.petro@noaa.gov)