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A comparison of 40 years of SBUV measurements of column ozone with data from the Dobson/Brewer network

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[1] Total column ozone data from the Nimbus-4 Backscatter UltraViolet (BUV) instrument, Nimbus-7 Solar Backscatter Ultraviolet (SBUV) instrument, as well as from seven NOAA SBUV/2 instruments have been newly reprocessed with the Version 8.6 ozone retrieval algorithm. This yields a coherent data set that, unlike the Total Ozone Mapping Spectrometer ozone record, has no data gaps or significant time periods with large uncertainties due to calibration issues from 1979 to the present. The column ozone data from the first 3 years of the BUV record (1970–1972) is of high quality and can be used to extend the satellite ozone record back over 40 years. With the new algorithm, an improved total column ozone value is calculated by summing up the profile information as opposed to a single direct column measurement, and the algorithm is optimized for the detection of long-term trends. The results from this processing of these data have been systematically compared to total ozone data from Brewer and Dobson spectrophotometers for many individual ground stations as a function of time, satellite solar zenith angle, and latitude. The time series comparisons show an agreement within ± 1% over the past 40 years with the bias approaching zero over the last decade. The aerosols associated with the eruption of Mt Pinatubo in 1991 produced an underestimation of ozone for our retrievals at high slant columns while the near-nadir values were relatively unaffected. There is very little systematic offset between the satellite and ground-based measurements as a function of latitude with the Nimbus-4 BUV data (1970–1976) showing the largest offsets. The comparisons as a function of satellite solar zenith angle show consistent behavior for all instruments. Comparisons with ozonesonde data show good agreement in the integrated column up to 25 hPa with differences of no more than 5%.

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1. Introduction

[2] Satellite measurements of stratospheric ozone began in April 1970 with the launch of the Nimbus-4 spacecraft with the Backscatter UltraViolet (BUV) instrument onboard [*Heath et al*., 1973]. The nadir viewing instrument, which measured radiation reflected from the Earth's atmosphere directly beneath it, operated nominally, yielded 14 orbits of data per day, until mid-1972 when several of the satellite's power arrays failed. Sporadic data were collected until May 1977 when the instrument failed entirely. The BUV instrument was the predecessor to the Nimbus 7 Solar Backscatter UltraViolet (SBUV) and the NOAA series of SBUV/2 instruments [*Heath et al*., 1975], which are all of similar design. The Nimbus 7 SBUV instrument began operation in October 1978 and ended in July 1990 [*Fleig et al*., 1990] (http://www.lib.muohio.edu/multifacet/record/mu3ugb1645458). The NOAA series of SBUV/2s began operations with the launch of NOAA-9 in January 1985 and then the sequential launches of NOAA-11, 14, 16, 17, 18, and 19, the last four of which are still in operation at the time of publication. For this study, we do not use data from NOAA-19, which was launched in February 2009, as the record is too short to establish a statistically useful comparison to ground stations. The instruments are all double monochromators that measure backscatter radiances from the Earth in 12 narrow wavelength bands between 250 and 340 nm with a triangular slit function that is 1.1 nm at full-width half maximum [*Fleig et al*., 1990]. The equator crossing times of the NOAA satellites precess from their launch point of either 1:30 P.M. or 10:30 A.M. with the exception of NOAA 18, which is currently stable. We include all data with solar zenith angles less than 84° in this study. Ozone column values used in this study come from the summation of the profile values, which yields a more accurate total column than the two wavelength "Total Ozone Mapping Spectrometer (TOMS)-like" total column retrievals, which were used in the past.

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Table 1. The 33 Northern Hemisphere Station Locations Used in the Comparisons to Satellite Ozone Record From 1979 to Present

Station Name	Station Latitude	Station Longitude	WMO Station Number
Arosa, Switzerland	46.77	9.67	35
Aswan, Egypt	23.58	32.27	245
Belsk, Poland	51.50	20.47	68
Bismark, ND, USA	46.77	−100.75	19
Boulder, CO, USA	40.02	−105.25	67
Bucharest, Romania	44.48	26.13	226
Cairo, Egypt	30.08	31.28	152
Caribou, ME, USA	46.87	−68.02	20
Churchill, Canada	58.55	−94.07	77
Edmonton, Canada	53.55	−114.10	21
Fresno, California	36.71	−119.43	244
Goose Bay, Canada	53.32	−60.38	76
Haute Provence, FR	43.55	5.45	40
Hohenpeissenberg, Germany	47.80	11.02	99
Hradec Kralove, Czech Rep	50.18	15.83	96
Kagoshima, Japan	31.63	130.60	7
1957–2005 Mt Waliguan 2005–present	36.17	100.5	295
Kuming, China	25.02	102.68	209
Lerwick, England	60.13	−1.12	43
Nashville, TN, USA	36.25	−86.57	106
New Delhi, India	28.67	77.22	10
Okinawa, Japan	26.20	127.68	190
Oslo, Norway	59.91	10.72	165
Potsdam, Germany	52.37	13.08	50
Debilt, Netherlands	52.00	5.18	316
Quetta, Pakistan	30.18	66.95	11
Reykjavik, Iceland	64.13	−21.90	51
Sapporo, Japan	43.05	141.33	12
Xianghe, China	39.77	117.00	208
Tateno, Japan	36.05	140.13	14
Thessaloniki, Greece	40.65	22.90	261
Toronto, Canada	43.78	−79.47	65
Uccle, Belgium	50.80	4.35	53
Vigna Di Valle, Italy	42.08	12.22	55
Rome, Italy	41.90	12.52	305
Wallops Isl, VA, USA	37.85	−75.52	107

2. Satellite Observations and Retrieval Algorithm

[3] The BUV and SBUV measurements occur every 32 s only in the nadir direction, and each measurement has a field of view (FOV) of 188 km square [*Frederick et al*., 1986]. The orbits are such that there are approximately 100 measurements per orbit (about 1 every 1.85° in latitude) with the longitudinal separation between orbits being close to 26°. All the data have been processed with the new Version 8.6 retrieval algorithm [*Bhartia et al*., 2012], which is a refinement on the Version 8 algorithm released in 1996 [*Bhartia et al*., 1996]. There are over 1400 measurements made on a given day for each instrument except for Nimbus-4 BUV, which had had a multitude of power problems starting in 1972. The daily coverage in 1970 and 1971 was fairly complete with only single orbits or a small group of orbits missing. From mid-1972, when several of the satellite's solar power arrays failed, the data coverage was sporadic throughout the end of the mission in May 1977. Power conservation techniques led to a reduction of Southern Hemisphere coverage from mid-1973 onward as well as some significant missing data westward of the International Date Line.

[4] The ozone values derived from the SBUV measurements have three types of uncertainties: uncertainties in the basic measurements (noise), uncertainties in the physical quantities needed to retrieve ozone values from the measurements (a priori information, atmospheric temperature, cloud information, etc.), and uncertainties in the mathematical procedures used to derive ozone values from the measurements. The noise term for the majority of measurement is less than 0.5% [*Deland et al*., 2012]. Some of the physical parameters used in the V8.6 retrieval are significantly different than in the previous versions of the algorithm. The ozone cross-sections are taken from Brion, Daumont, and Malicet [*Daumont et al*., 1992], which are superior in resolution, temperature dependence, and quality to the Bass and Paur [*Bass and Paur*, 1985] cross-sections used in prior retrievals. A more accurate cloud height climatology has been developed using the UV rotational Raman filling technique [*Vasilkov et al*., 2004] from the Ozone Monitoring Instrument (OMI) onboard the AURA spacecraft. The data set contains the climatological heights of the "optical centroid pressure," which is how deep a UV photon, on average, will penetrate into the cloud. This is significantly more accurate than the previous climatology, which was derived from data in the infrared region, and which is not as applicable for these measurements [*Joiner et al*., 1995]. With this more accurate cloud height climatology, the errors produced by extrapolating ozone amounts under a cloud are minimized. A revised ozone profile climatology has been developed using a merged

Table 2. The 33 Northern Hemisphere Station Locations Used in the Comparisons to Satellite Ozone Record From 1970–1977 for the Nimbus-4 BUV Measurements

Station Name	Station Latitude	Station Longitude	WMO Station Number
Arosa, Switzerland	46.77	9.67	35
Belsk, Poland	51.50	20.47	68
Bismark, ND, USA	46.77	−100.75	19
Boulder, CO, USA	40.02	−105.25	67
Bracknell, UK	51.38	−0.78	102
Cairo, Egypt	30.08	31.28	152
Caribou, ME, USA	46.87	−68.02	20
Churchill, Canada	58.55	−94.07	77
Edmonton, Canada	53.55	−114.10	21
Goose Bay, Canada	53.32	−60.38	76
Green Bay, WI, USA	44.48	−88.13	22
Hohenpeissenberg, Ger	47.80	11.02	99
Hradec Kralove, Czech R	50.18	15.83	96
Kagoshima, Japan	31.63	130.60	7
Kodaikanal, India	10.23	77.47	8
Lerwick, England	60.13	−1.12	43
Lisbon, Portugal	38.78	−9.15	82
Mauna Loa, HI USA	19.53	−155.6	31
Mount Abu, India	24.60	72.70	99
Mont Loius, France	42.5	2.13	70
Nashville, TN, USA	36.25	−86.57	106
New Delhi, India	28.67	77.22	10
Oxford, England	51.75	−1.18	48
Quetta, Pakistan	30.18	66.95	11
Reykjavik, Iceland	64.13	−21.90	51
Resolute, Canada	74.72	−94.88	24
Sapporo, Japan	43.05	141.33	12
Tateno, Japan	36.05	140.13	14
Toronto, Canada	43.78	−79.47	65
Uccle, Belgium	50.80	4.35	53
Varanasi, India	25.32	83.03	74
Vigna Di Valle, Italy	42.08	12.22	55
Wallops Isl, VA, USA	37.85	−75.52	107

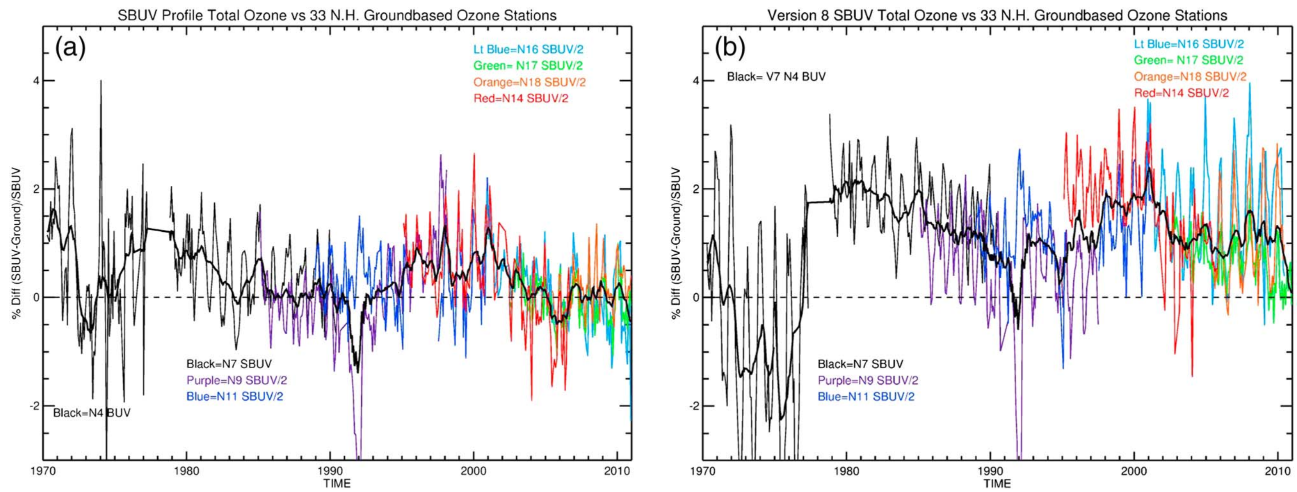

Figure 1. (a) A comparison of all the BUV & SBUV instruments (all processed with Version 8.6 algorithm) to an ensemble of 33 Northern Hemisphere Ground Stations. See Table 1 for list of stations. Each point is a monthly average with a yearly smoother run through the data (thick black line). (b) As in Figure 1a but a comparison of ground-based data to Version 8 SBUV & Version 7 Nimbus 4 BUV data.

product derived from over 37,000 ozonesondes from 1988 to 2010 and AURA Microwave Limb Sounder (MLS) ozone profile data [*McPeters and Labow*, 2012]. These data are aggregated into 10° zonal means with ~1 km up to 65 km vertical resolution. The new climatology is used as the a priori profile for the SBUV Version 8.6 retrievals. The errors associated with the mathematics of the retrieval algorithm, such as related to smoothing error, forward model assumptions, and errors due to geophysical issues such as diurnal variations of mesospheric ozone, a priori errors, and stratospheric aerosols, etc., are discussed in *Bhartia et al*. [2012] and *Kramarova et al*. [2012]. The largest source of errors in the SBUV profile retrievals is the smoothing error. The smoothing error describes the component of vertical ozone variability, which the observation system cannot measure. Between 16 and 1 hPa, the smoothing errors for SBUV monthly zonal mean retrievals are of the order of 1% and increase up to 15–20% in the troposphere. The smoothing errors for total ozone retrievals are mostly less than 0.5%.

3. Instrument Calibration

[5] The SBUV and SBUV/2 series of instruments were calibrated in the laboratory prior to integration on a spacecraft. The prelaunch calibration procedures include measuring and defining the monochromator wavelength scale, electronic gain ratio, nonlinearity, radiance and irradiance sensitivity, solar diffuser reflectivity, and diffuser angular dependence. The SBUV/2 instruments use an onboard mercury lamp to track postlaunch changes of the diffuser. The

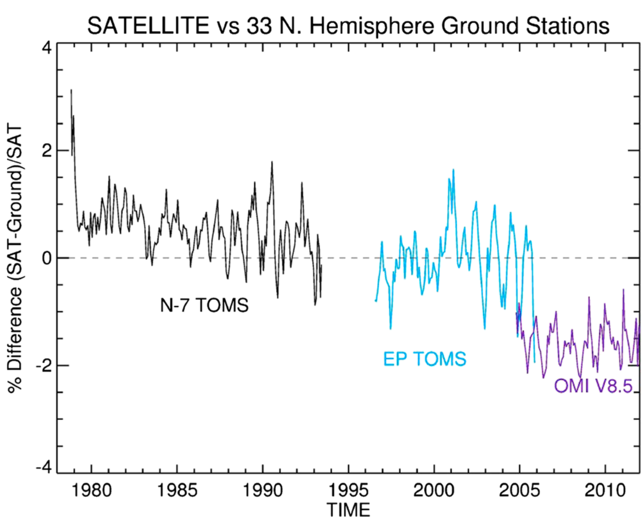

Figure 2. Similar to Figure 1 but for TOMS and OMI data. The TOMS data has been processed with Version 8 algorithm while OMI data uses Version 8.5. We suggest that the SBUV data be used for ozone trend studies.

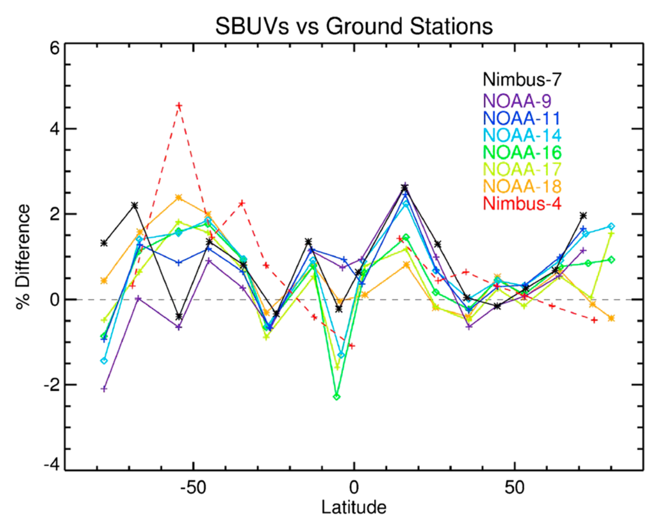

Figure 3. The average offset between each of the satellites and ground station data for each 10° latitude band from 80°S to 80°N. The Nimbus-4 BUV time period (1970–1977 – red dashed line) has far less ground station ozone data to compare to and appears noisier than the more recent instruments.

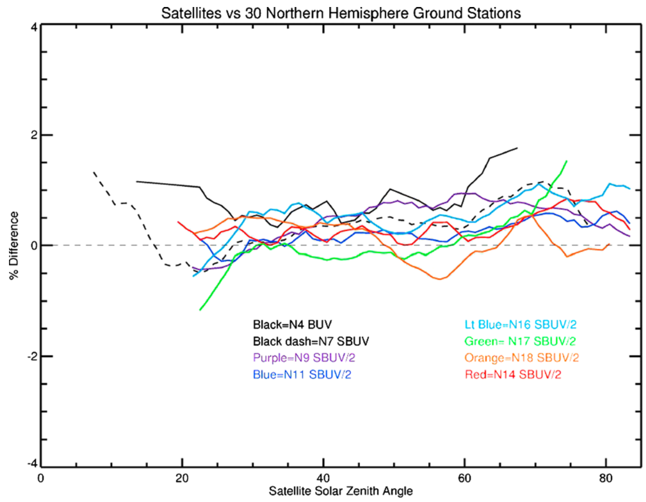

Figure 4. The average offset between each of the satellites and ground station data as a function of satellite solar zenith angle.

radiance and irradiance calibrations are traceable to the National Institute of Standards and Technology lamp radiometric standards and diffuser Bidirectional Reflectance Distribution Function (BRDF) standards [e.g., *Huang et al.*, 1998, *Janz et al.*, 1995]. These instruments measure solar irradiance by deploying a diffuser to reflect sunlight into the instrument. Since the solar-viewing diffuser is the only element not common to the optical path for both measurements, changes in spectrometer sensitivity should cancel out, thus removing the potential impact of errors in absolute radiometric calibration. Changes in sensitivity due to both photomultiplier tube degradation and photomultiplier tube hysteresis are tracked using on-orbit data. For some of the instruments, the solar diffuser degraded in a manner that cannot be properly modeled and/or characterized and therefore a variety of "soft calibration" techniques were employed to characterize the calibration of the instrument [*Deland et al.*, 2012]. Additional long-term calibration for the SBUV/2 instruments was provided by coincident observations with eight flights of the Shuttle SBUV instrument between 1989 and 1996 [*Hilsenrath et al.*, 1995]. Detailed discussion of other calibration issues such as hysteresis, out-of-band stray light, and grating drive errors are found in *Deland et al.* [2012] .

[6] The calibration of Nimbus-4 BUV was much more difficult due to the fact that the diffuser plate used to measure the extraterrestrial solar irradiance was always exposed to space in this early design and consequently darkened very rapidly due to solarization. This made a completely independent calibration impossible. The time dependence of the calibration was established by comparing the radiances measured by the BUV instrument with radiances calculated using a monthly averaged ozone profile created by combining Arosa Umkehr measurements in the middle to upper stratosphere with Payerne ozonesonde measurements in the troposphere and lower stratosphere. A smoothly varying time- and wavelength-dependent calibration correction was derived from this comparison and applied to the BUV data globally.

4. Ground-Based Data

[7] The Dobson Spectrophotometer was developed in the 1920s, and a worldwide network of instruments was established for the International Geophysical Year in 1957 [*Dobson*, 1957]. Currently, there are over 60 Dobsons in use around the world and almost all of the data are reported to the World Ozone and Ultraviolet Data Centre (WOUDC) in Toronto, Canada. The ozone value reported is a single "representative" column value per day. The daily ozone values can be derived from direct Sun, zenith sky, and (very rarely) focused Moon observations. The Dobson instrument uses four wavelengths in two pairs to calculate total column ozone. The most commonly used pairs are "AD" (305.5 and 325.4 nm, 317.6 and 339.8 nm) and "CD" pair (311.5 and 332.4 nm, 317.6 and 339.8 nm). The data quality from the Dobsons has gotten progressively better over the decades as more and more intercomparisons and intercalibrations were performed. The error for a reported daily AD direct Sun ozone value is estimated to be about 1% (1 sigma) [*Basher*, 1982]. For zenith sky measurements, it is about 3%. The long-term total ozone measurement precision is believed to be about ± 0.5% (1 sigma) per decade for annual means [*Komhyr*, 1980].

[8] The Brewer Spectrophotometer was developed in the early 1980s and there are now over 100 operational instruments worldwide. The data from both the Dobsons and Brewers are available at the WOUDC: http://www.tor.ec.gc.ca/woudc. The Brewer instrument uses five wavelengths simultaneously (306.3, 310.1, 313.5, 316.8, and 320.0 nm) to measure column ozone [*Kerr et al.*, 1985]. The instruments are routinely calibrated against a reference triad located in Toronto [*Fioletov et al.*, 2005]. One representative ozone value per day is reported to the WOUDC. The errors reported in the column ozone measurement are essentially the same values as those reported by the Dobsons [*Kerr et al.*, 1988]. There are many stations around the world that have either replaced their Dobson instrument with a Brewer or added a Brewer to their infrastructure. If there exists more

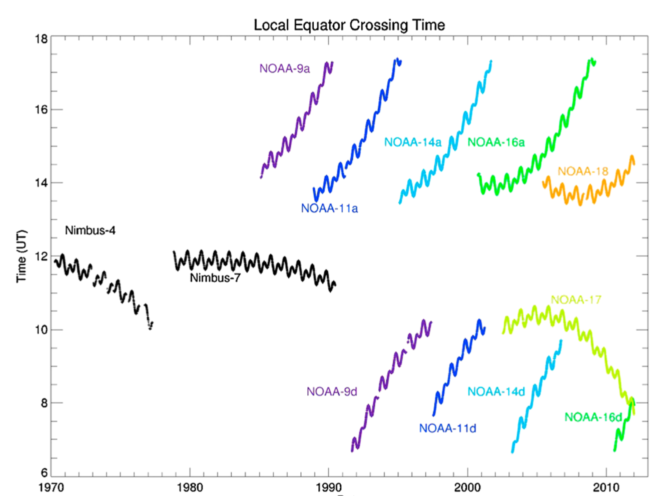

Figure 5. Local equator crossing time of the eight satellites used in this study. The letter "a" indicates ascending node and "d" descending node orbits.

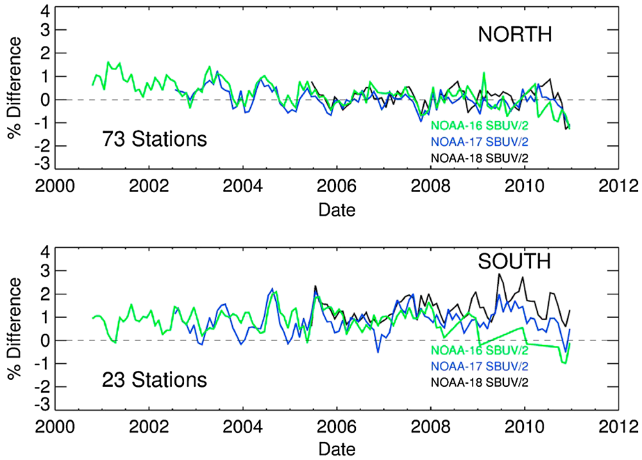

Figure 6. Detailed comparison plot of NOAA 16, 17 and 18 data to Northern and Southern Hemisphere ground stations.

than one instrument at any particular ground station at the same time, the comparisons to the satellite data are calculated separately rather than averaged together for that location.

5. Overpass Algorithm

[9] Because the SBUV instruments view only in the nadir with a small (~180 km square) FOV, it takes about 2 weeks to provide full global coverage unlike the TOMS-like instruments, which provide daily global coverage. The overpass algorithm for the SBUV data has been created to return daily overpass values, even if the SBUV measurements are not directly overhead of the ground station. The SBUV ozone measurements made every 1.85° in latitude (approximately 100 points per orbit) are interpolated along the orbital track to 0.5° yielding approximately 320 interpolated points per orbit. Because successive orbits are spaced 26° apart, a box, ± 2° in latitude and ± 20° in longitude (large enough to encompass two orbits), is chosen around the ground station's location and a weighted 1/distance method is used to calculate the interpolated ozone amount at that location. The weighted ozone values are reported for the total column ozone as well as for 21 SBUV layers, and the values are reported in Dobson Units. There is also a separate overpass product that produces 15 layers from 50.0 to 0.5 hPa in units of volume mixing ratio in parts per million (PPMV) as well as total column ozone.

[10] The weighted distance (in km,) from the ground station is reported with every overpass value and can be used to filter the data. For long-term comparisons to ground station data, it has been found that filtering on the distance parameter is not required as the noise term stays essentially the same as the number of data points gets reduced. A study has been done using OMI overpass data where all matchups are within ~50 km are compared to the SBUV overpasses where the distances are up to 1000 km. The standard deviations of the differences do not increase appreciably as the distance from the station increases. All overpass files for each of the SBUV instruments can be found on the NASA Goddard public FTP site: ftp://toms.gsfc.nasa.gov/pub/sbuv in the overpass subdirectory for each instrument.

6. Comparisons of Total Column Ozone With Dobson and Brewer Network

[11] The ground-based network of stations measuring column ozone is continually changing so a baseline of 33 Northern Hemisphere stations that have been in operation has been chosen to compare to the entire 40+ year satellite data record. The stations were limited to the Northern Hemisphere so that any possible seasonally dependent errors would not cancel out in the differences (assuming that the Southern Hemisphere differences have similar seasonally dependent errors that are out of phase with the North). These stations are listed in Table 1. Since 1980, only 3 of the 33 chosen stations have stopped taking measurements, Kagoshima (Japan), Potsdam (Germany), and Vigna Di Valle (Italy) and had to be joined with data sets from Mount Waliguan (China), Debilt (Netherlands), and Rome (Italy). The ground-based data before 1978 used to compare to the Nimbus-4 BUV data are of lesser quality and quantity, but are still very useful for inferring instrument performance. These stations are listed in Table 2. Some of these early ground-based data sets are being analyzed and reprocessed as an ongoing project of the WMO in order to increase data quality [*Fioletov et al.*, 2008]. Figure 1a shows the comparisons of all the satellite instruments to the ensemble of 33 Northern Hemisphere ground stations listed in Tables 1 and 2. The monthly mean comparisons show a remarkable agreement between the satellites and ground-based ozone data. The thick black line is an annual running mean. The Nimbus-4 BUV comparisons are, as expected, of lower quality because of reduced satellite coverage after 1972, but the agreement is still mostly within ± 2% with a small positive bias. The fact that a somewhat different set of stations had to be used for this time period seems to have little effect. The post-1980 data record shows a ± 1% agreement with essentially no offset. The apparent small downward trend from ~2000 to present is not fully understood at this time but may have to do with better calibration of ground-based instrumentation as well as three well characterized SBUV

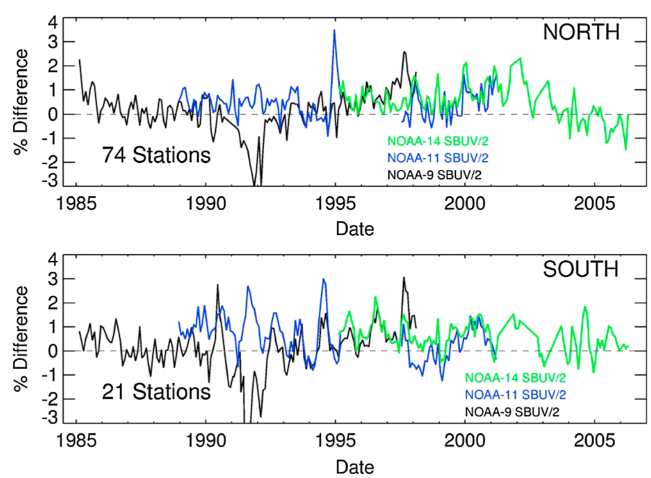

Figure 7. Same as Figure 6, but for NOAA 9, 11 and 14. The Mt Pinatubo eruption has a large effect on the NOAA 9 retrievals due to the high solar zenith angles associated with being in an early morning equator crossing time (see Figure 4). NOAA-11 is not similarly affected.

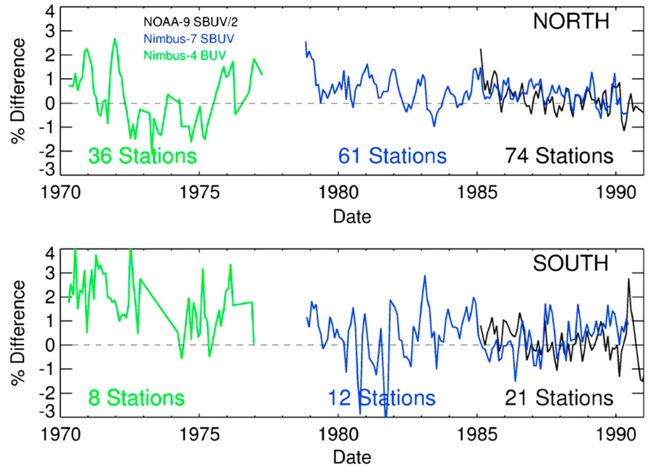

Figure 8. Comparisons of Nimbus 4, Nimbus 7 and NOAA 9 data to ground stations. The number of different ground stations in the Northern Hemisphere are 36, 61, and 74 for N4, N7 and N9 respectively and 8, 12, and 21 for the Southern Hemisphere.

instruments (NOAA-16, 17, and 18). Figure 1b shows the same comparisons but to the previous versions of the satellite data, Version 8 for the SBUV series and Version 7 for the Nimbus 4 instrument.

[12] The effect of the eruption of Mount Pinatubo is very apparent in the NOAA-9 data. The satellite was in an early morning equator crossing time (~7:30 A.M.) orbit that required long atmospheric path lengths for the ozone retrievals while NOAA-11 (2:00 P.M.) shows little to no effect due to the aerosol loading in the atmosphere. This is what is expected theoretically as the effect on the ozone retrieval depends on the aerosol scattering angles [*Bhartia et al.*, 1993; *Torres and Bhartia*, 1995]. The assumption that the ground-based instruments are not sensitive to the effects of aerosols are discussed in *Basher* [1982].

[13] A time series comparison of the current TOMS and OMI data to the same 33 Northern Hemisphere stations is shown in Figure 2. The satellite data are the currently available Version 8 TOMS [*Bhartia et al.*, 2004] for Nimbus-7 (1980–1993) and Earth Probe (1996–2005) and Version 8.5 AURA OMI [*Bhartia and Wellemeyer*, 2002] data (all data found via FTP on toms.gsfc.nasa.gov). The comparison plot is on the same relative scale as Figure 1 and shows some larger differences. There is a notable data gap from 1993 to 1996 between the end of Nimbus-7 and the beginning of Earth Probe TOMS. The data record after 2001 for EP-TOMS has been directly tied to the SBUV/2 instruments. This was done because the scanning mirror and/or fore optics degraded in a manner that would not allow us to calibrate the instrument properly, so corrections were made, to the best of our ability, to reduce the solar zenith angle and scan dependent errors. However, residual errors still remain and the later part of the EP-TOMS data record is not considered trend quality. The OMI data have been processed with a slightly different algorithm. The Version 8.5 algorithm has an active cloud height retrieval as opposed to a climatological lookup table for the previous Version 8 TOMS data. This allows us to place the proper amount of ozone beneath the clouds and thus retrieve a more accurate total column ozone amount. The offset between OMI and EP-TOMS is almost 1%, and it is not known why this occurs at this time. This offset makes trend studies using the TOMS and OMI data set more problematic. Therefore, it is recommended that the community use the Version 8.6 SBUV total column ozone time series for all long-term ozone trend studies since the record is longer and there are no data gaps or significant disagreements between instruments. There are plans in the near future to transfer the calibration from the SBUV instruments to all the TOMS data and reprocess the entire TOMS data record. The SBUV data, being the reference, should still be used for any long-term ozone trend calculations.

[14] Figure 3 shows the comparisons between the SBUV data and the ground-based data as a function of latitude. Each satellite data set is compared to all stations possible during the lifetime of the instrument. The agreement is within $\pm$ 2% for almost all the 10° latitude bands. There were very few ground measurements taken in the Southern Hemisphere during the lifetime of the Nimbus-4 satellite (1970–1977), so the comparisons shown are of somewhat lesser quality. There were no stations at the time in the latitude range equator to 10° north. The equatorial zone has always been a place where, in the past, there have been few ground stations. Since the advent of the SHADOZ program, an ozonesonde program with data collected from several tropical and subtropical sites [*Thompson et al.*, 2002], it now appears that the agreement is getting significantly better as more stations come on-line and the comparisons are becoming more robust.

[15] Figure 4 shows the comparisons as a function of satellite solar zenith angle for the 33 Northern Hemisphere stations. The agreement is $\pm$ 1% with very little change as the solar zenith angles get large. Previous versions of the SBUV retrievals [*Fleig et al.*, 1990] had a significant solar zenith angle dependence as the angles became greater than ~75°. The implementation of the DBM (Daumont, Brion,

Table 3. The 21 Layers That Are Returned for Each Overpass Location in Dobson Units Per Layer[a]

Bottom of Layer (hPa)	Top of Layer (hPa)	SBUV Layer Number
1013.25	639.3	1
639.3	403.4	2
403.4	254.5	3
254.5	160.6	4
160.6	101.3	5
101.3	63.9	6
63.9	40.3	7
40.3	25.5	8
25.5	16.1	9
16.1	10.1	10
10.1	6.39	11
6.39	4.03	12
4.03	2.55	13
2.55	1.61	14
1.61	1.01	15
1.01	0.639	16
0.639	0.403	17
0.403	0.254	18
0.254	0.161	19
0.161	0.101	20
0.101	TOA	21

[a]The data are available at ftp://jwocky.gsfc.nasa.gov/pub/sbuv.

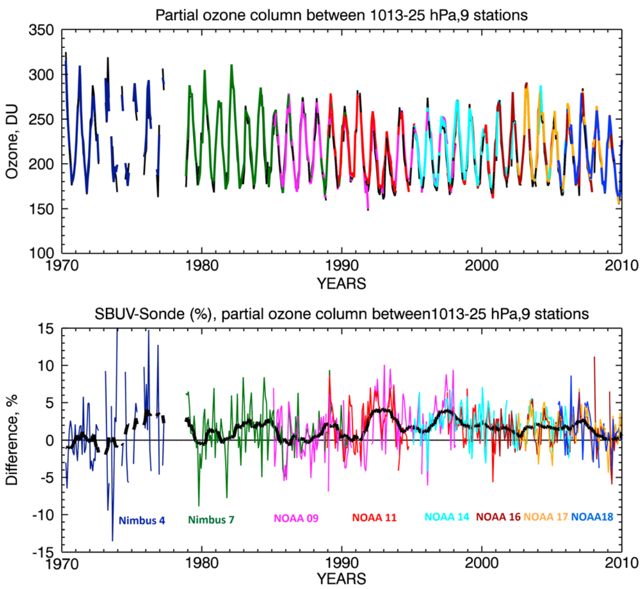

Figure 9. Time series plot showing the comparisons between the SBUV dataset and 9 Ozonesonde stations that cover the period 1970-present. The comparisons are for the integrated column from the surface to 25 hPa.

Malicet) ozone cross-sections [*Daumont et al.*, 1992] have significantly lessened the solar zenith angle (SZA) dependent errors in our retrievals at high view angles. This was shown by a special processing of the NOAA 17 SBUV data where we only changed the ozone cross-sections and kept all the other variables such as calibration and cloud handling the same. The near-noon equator crossing times of Nimbus 4 and Nimbus 7 are the reason that those two instruments have measurements at lower solar zenith angles (SZA <20) than all the other morning and afternoon satellites. Figure 5 shows the local equator crossing times for the eight satellites used in this study.

[16] Figure 6 shows the comparisons of the three most recent SBUV/2 (NOAA 16, 17, and 18) instruments to almost all available Dobson and Brewer data: 73 individual instruments in the Northern Hemisphere and 23 instruments in the Southern Hemisphere. The origin of the seasonal cycle seen in the differences is much debated and could be due to the fact that the ground-based instruments are using the Bass and Paur cross-sections, which have different temperature dependence than the newer BDM cross-sections. It can also be because the ground-based data have an assumed fixed atmospheric temperature in their retrievals while the satellite retrievals utilize a monthly temperature climatology. The increasing (~1%) spread seen at the end of the record in the Southern Hemisphere is probably due to the precessing orbits of NOAA 16 (moving toward late afternoon) and NOAA 17 (moving toward early morning).

[17] Figure 7 shows a similar comparison of three SBUV (NOAA 9, 11, and 14) instruments to almost all available Dobson and Brewer data: 74 individual instruments in the Northern Hemisphere and 21 instruments in the Southern Hemisphere. The aerosols from Mt. Pinatubo affected the NOAA-9 ozone retrievals because the satellite was in an early morning equator crossing time (thus viewing at

Table 4. The Nine Northern Hemisphere Ozonesonde Station Locations Used in the Comparisons to Satellite Ozone Record

Station	Latitude	Longitude	WMO Number
Boulder, CO, USA	40.02	−105.25	67
Churchill, Canada	58.55	−94.07	77
Edmonton, Canada	53.55	−114.10	21
Goose Bay, Canada	53.32	−60.38	76
Hohenpeissenberg, Germany	47.80	11.02	99
Lindenberg, Germany	52.21	14.12	174
Payern, Switzerland	46.83	6.92	156
Resolute, Canada	74.72	−94.88	24
Wallops Isl, VA, USA	37.85	−75.52	107

high slant columns) while the retrievals from NOAA-11 (2:30 P.M.) were minimally affected. Heavy aerosol loading at long path lengths have a tendency to introduce errors on the ozone retrievals [*Torres and Bhartia*, 1995].

[18] Figure 8 shows the comparisons for Nimbus-4 BUV, Nimbus-7 SBUV, and NOAA 9 SBUV/2 to available ground data. The number of stations available changes greatly as time progresses and new facilities come online. There were only 36 operational Northern Hemisphere stations available during the Nimbus-4 time period. That number nearly doubled to 61 stations for the Nimbus-7 time period and over 70 stations after the mid-1990s. Considering the era when these measurements were made and the sparseness of the data, the 1970s comparisons are remarkably good. The number of individual ground-to-satellite matchups per month for the 33 station baseline comparisons are between 500 and 800 matchups from 1970 to mid-1972, then it drops to 200 to 300 until late 1974 and is only 100 to 200 until the end of the N4 data in May 1977. For all the other instruments there are between 500 and 800 matchups per month.

7. Comparisons of SBUV Ozone With Ozonesonde Data

[19] The satellite profile overpass data also report 21 atmospheric levels in Dobson units per level, which were chosen in order to get two samples per SBUV averaging kernel width [*Bhartia et al.*, 2012]. The level tops and bottoms are listed in Table 3. The comparisons between the monthly mean satellite profile data and monthly mean data from ozonesondes from the surface to 25 hPa are shown in Figure 9. Data from nine Northern Hemisphere ground stations that have a record that spans back to the early 1970s were used in this study. These stations are listed in Table 4. There were three additional Japanese stations that provided data for over 40 years, but they were deemed unusable for these comparisons due to problems with total ozone correction factors [*Morris et al.*, 2013]. The differences are plotted as (SBUV-Sonde)/SBUV in percent and a 12 month smoother (thick black line) has been plotted to show long-term features. The agreement is within ± 5% throughout the entire data record with no significant trend seen in the differences.

[20] The SBUV ozone retrievals above 25 hPa outside of the tropics and above 16 hPa in the tropics (20°S–20°N) show good agreement when compared with SAGE, MLS, ground-based lidars, and microwave spectrometers [*Kramarova et al.*, 2013a]. However, below 25 hPa, the SBUV vertical resolution increases significantly from roughly 5 to 10 km, and

the corresponding smoothing errors grow from 1% to 15%. *Kramarova et al*. [2013b] demonstrated that the smoothing errors could be minimized by combining several layers of data in the troposphere and lower stratosphere. It is recommended using the following layer combinations to get the most information from the SBUV data: surface to 25 hPa or 250 to 25 hPa everywhere outside of the narrow tropical zone. The layer combination of surface (or 250 hPa) to 40 hPa could also be used in the northern middle and high latitudes. In the tropics between 20°S and 20°N, we recommend merging all layers from the surface to 16 hPa. There is little ozone below 250 hPa, and the SBUV retrieval does not provide much information on the vertical distribution of ozone and mostly returns the climatological a priori [*McPeters and Labow*, 2012].

8. Summary

[21] Total column ozone data from the Nimbus-4 Backscatter UltraViolet, Nimbus-7 Solar Backscatter Ultraviolet, as well as from seven NOAA SBUV/2 instruments have been newly reprocessed with the Version 8.6 ozone retrieval algorithm. This processing yields a coherent data set that, unlike the TOMS ozone record, has no data gaps or significant time periods with large uncertainties due to calibration issues (such as the case of Earth Probe TOMS). The column ozone data from the BUV record (1970–1972) is of high quality and can be used to extend the satellite ozone record back over 40 years. It is recommended that the SBUV ozone time series be used in long-term ozone trend analysis. The ozone absorption cross-sections have been changed, a new cloud height climatology derived from OMI measurements of UV rotational Raman filling is now used instead of the previous thermal IR-based cloud data, and all the instrument calibrations have been reexamined and updated in cases that were appropriate. A more accurate total column ozone value is being calculated by summing up the profile information as opposed to a single direct column measurement as was done in the past versions. The newest versions of these data have been systematically compared to total ozone data from Brewer and Dobson spectrophotometers for many individual ground stations as a function of time, satellite solar zenith angle, and latitude. The annual mean time series comparisons to an ensemble of ground stations show an agreement within ±~1% over the past 40 years with the bias approaching zero over the last decade. The aerosols associated with the eruption of Mt Pinatubo in 1991 produced an underestimation of ozone for our retrievals at high slant columns while the near-nadir values were relatively unaffected. There is very little systematic offset between the satellite and ground-based measurements as a function of latitude with the Nimbus-4 BUV data (1970–1976) showing the largest offsets. The comparisons as a function of satellite solar zenith angle show consistent behavior for all instruments. Comparisons with ozonesonde data show good agreement in the integrated column up to 25 hPa with differences no more than 5%.

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References

Basher, R. E. (1982), Review of the Dobson spectrophotometer and its accuracy, *WMO Global Ozone Res. Monit. Proj. Rep.*, *13*, World Meteorol. Organ., Geneva, Switzerland.

Bass, A. M., and R. J. Paur (1985), The ultraviolet cross-sections of ozone. I. The measurements, in *Atmospheric Ozone*, edited by C. S. Zerefos and A. Ghazi, pp. 606–616, D. Reidel, Norwell, Mass.

Bhartia, P. K., and C. G. Wellemeyer (2002), TOMS-V8 total ozone algorithm in OMI Algorithm Theoretical Basis Document, vol II, OMI Ozone Products ATBD-OMI-02 (available at http://eospso.gsfc.nasa.gov/eos_homepage/for_scientists/atbd/index.php).

Bhartia, P. K., J. Herman, R. D. McPeters, and O. Torres (1993), Effect of Mt. Pinatubo aerosols on total ozone measurements from backscatter ultraviolet (BUV) experiments, *J. Geophys. Res.*, *98*, 18,547–18,554.

Bhartia, P. K., R. D. McPeters, C. L. Mateer, L. E. Flynn, and C. G. Wellemeyer (1996), Algorithm for the estimation of vertical profiles from the backscattered ultraviolet technique, *J. Geophys. Res.*, *101*, 18,793–18,806.

Bhartia, P. K., C. G. Wellemeyer, S. L. Taylor, N. Nath, and A. Gopolan (2004), Solar Backscatter Ultraviolet (SBUV) Version 8 profile algorithm, paper presented at Quadrennial Ozone Symposium, Int. Ozone Comm., Kos, Greece, 1–8 June.

Bhartia, P. K., R. D. McPeters, L. E. Flynn, S. Taylor, N. A. Kramarova, S. Frith, B. Fisher, and M. DeLand (2012), Solar Backscatter UV (SBUV) total ozone and profile algorithm, *Atmos. Meas. Tech. Discuss.*, *5*, 5913–5951, doi:10.5194/AMTD-5-5913-2012.

Daumont, M., J. Brion, J. Charbonnier, and J. Malicet (1992), Ozone UV spectroscopy. I: Absorption cross-sections at room temperature, *J. Atmos. Chem.*, *15*, 145–155.

DeLand, M. T., S. L. Taylor, L. K. Huang, and B. L. Fisher (2012), Calibration of the SBUV version 8.6 ozone data product, *Atmos. Meas. Tech. Discuss.*, *5*, 5,151–5,203, doi:10.5194/AMTD-5-5151-2012.

Dobson, G. M. B. (1957), Observers handbook for the ozone spectrophotometer, *Ann. Int. Geophys. Year*, *5*(1), 46–89.

Fioletov, V. E., J. B. Kerr, C. T. McElroy, D. I. Wardle, V. Savastiouk, and T. S. Grajnar (2005), The Brewer reference triad, *Geophys. Res. Lett.*, *32*, L20805, doi:10.1029/2005GL024244.

Fioletov, V. E., G. J. Labow, R. Evans, E. W. Hare, and C. T. McElroy (2008), Performance of the ground-based total ozone network assessed using satellite data, *J. Geophys. Res.*, *113*, D14313, doi:10.1029/2008JD009809.

Fleig, A. J., R. D. McPeters, P. K. Bhartia, B. M. Schlesinger, R. P. Cebula, K. F. Klenk, S. L. Taylor, and D. F. Heath (1990), Nimbus 7 solar backscatter ultraviolet (SBUV) ozone products user's guide, *NASA Ref. Publ., 1234*. [Available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19900007911_1990007911.pdf.].

Frederick, J. E., R. P. Cebula, and D. F. Heath (1986), Instrument characterization for the detection of long-term changes in stratospheric ozone: An analysis of the SBUV/2 radiometer, *J. Atmos. Oceanic Technol.*, *3*, 472–480.

Heath, D. F., C. L. Mateer, and A. J. Krueger (1973), The Nimbus-4 backscatter ultraviolet atmospheric ozone experiment, *Pure Appl. Geophys.*, *106–108*, 1238–1253.

Heath, D. F., A. J. Krueger, H. A. Roeder, and B. D. Henderson (1975), The solar backscatter ultraviolet and total ozone mapping spectrometer for Nimbus G, *Opt. Eng.*, *14*, 323–331.

Hilsenrath, E., R. P. Cebula, M. T. DeLand, K. Laamann, S. Taylor, C. Wellemeyer, and P. K. Bhartia (1995), Calibration of the NOAA-11 Solar Backscatter UltraViolet (SBUV/2) ozone data set from 1989 to 1993 using in-flight calibration data and SSBUV, *J. Geophys. Res.*, *100*, 1351–1366, doi:10.1029/94JD02611.

Huang, L. K., R. P. Cebula, and E. Hilsenrath (1998), New procedure for interpolating NIST FEL lamp irradiances, *Metrologia*, *35*(4), 381–386, doi:10.1088/0026-1394/35/4/27.

Janz, S., E. Hilsenrath, J. Butler, D. F. Heath, and R. P. Cebula (1995), Uncertainties in radiance calibrations of backscatter ultraviolet (BUV) instruments, *Metrologia*, *32*(6), 637–641, doi:10.1088/0026-1394/32/6/48.

Joiner, J., P. K. Bhartia, R. P. Cebula, E. Hilsenrath, R. D. McPeters, and H. Park (1995), Rotational Raman-scattering (ring effect) in satellite backscatter ultraviolet measurements, *Appl. Opt.*, *34*, 4,513–4,225.

Kerr, J. B., C. T. McElroy, D. I. Wardle, R. A. Olafson, and W. F. J. Evans (1985), The automated Brewer spectrophotometer, in *Atmospheric Ozone: Proceedings of the Quadrennial Ozone Symposium*, edited by C. S. Zerefos and A. Ghazi, pp. 396–401, Springer, Hingham, Mass.

Kerr, J. B., I. A. Asbridge, and W. F. J. Evans (1988), Intercomparison of total ozone measured by the Brewer and Dobson spectrophotometers at Toronto, *J. Geophys. Res.*, *93*, 11,129–11,140.

Komhyr, W. D. (1980), Operations handbook—Ozone observations with a Dobson spectrophotometer, *WMO Global Ozone Res. and Monit. Proj. Rep., 5*, World Meteorol. Organ., Geneva, Switzerland.
Kramarova, N. A., P. K. Bhartia, S. M. Frith, R. D. McPeters, and R. S. Stolarski (2013a), Interpreting SBUV smoothing errors: An example using the quasi-biennial oscillation, *Atmos. Meas. Tech. Discuss.*, *6*, 2,721–2,749, doi:10.5194/AMTD-6-2721-2013.
Kramarova, N. A., S. M. Frith, P. K. Bhartia, R. D. McPeters, S. L. Taylor, B. L. Fisher, G. J. Labow, and M. T. DeLand (2013b), Validation of ozone monthly zonal mean profiles obtained from the Version 8.6 solar backscatter ultraviolet algorithm, *Atmos. Chem. Phys. Discuss.*, *13*, 2549–2597, doi:10.5194/ACPD-13-2549-2013.
McPeters, R. D., and G. J. Labow (2012), Climatology 2011: An MLS and sonde derived ozone climatology for satellite retrieval algorithms, *J. Geophys. Res.*, *117*, D10303, doi:10.1029/2011JD017006.
Morris, G. A., G. J. Labow, H. Akimoto, M. Takigawa, F. Hasebe, and T. Koide (2013), On the use of the correction factor with Japanese ozonesonde data. *Atoms. Chem. Phys.*, *13*, 1243–1260, doi:10.5194/ACP-13-1243-2013.
Thompson, A. M., J. Witte, R. D. McPeters, S. J. Schmidlin, F. J. Logan, F. A. Fujiwara, M. Kirchoff, and H. Posny (2002), Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998–2000 tropical ozone climatology, *J. Geophys. Res.*, *108*(D18), 8238, doi:10.1029/2001JD000867.
Torres, O., and P. K. Bhartia, (1995), Effect of stratospheric aerosol on ozone profile from BUV measurements, *Geophys. Res. Lett.*, *22*, 235-238.
Vasilkov, A. P., J. Joiner, K. Yang, and P. K. Bhartia (2004), Improving total column ozone retrievals by using cloud pressures derived from Raman scattering in the UV, *Geophys. Res. Lett.*, *31*, L20109, doi:10.1029/2004GL020603.