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Validation of Ozone Monitoring Instrument total ozone column measurements using Brewer and Dobson spectrophotometer ground-based observations

D. Balis,[1] M. Kroon,[2] M. E. Koukouli,[1] E. J. Brinksma,[2] G. Labow,[3] J. P. Veefkind,[2] and R. D. McPeters[3]

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[1] In this paper we present validation results of the total ozone column data products of the Ozone Monitoring Instrument (OMI) on board the NASA EOS-AURA satellite through comparisons with ground-based observations by Dobson and Brewer spectrophotometer instruments. Quality-controlled and archived total ozone column data from these ground-based instruments located at stations worldwide have been used to validate more than 2 a of total ozone column observations from OMI. There are two operationally available satellite total ozone column data products, based on the OMI-TOMS and the OMI-DOAS retrieval algorithms, respectively. Validation with ground-based data focused on global comparisons and seasonal dependence and the possible dependence on latitude and solar zenith angle. Our results show a globally averaged agreement of better than 1% for OMI-TOMS data and better than 2% for OMI-DOAS data with the ground-based observations. The OMI-TOMS data product is shown to be of high overall quality with no significant dependence on solar zenith angle or latitude. The OMI-DOAS data product shows no significant dependence on latitude except for the high latitudes of the Southern Hemisphere where it systematically overestimates the total ozone value. In addition a significant dependence on solar zenith angle is found between OMI-DOAS and ground-based data. Comparisons of satellite and ground-based data tend to show a marginal seasonal dependence even though it remains unclear whether this dependence originates from the ground-based or spaceborne observations.

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1. Introduction

[2] The Ozone Monitoring Instrument (OMI) [*Levelt et al.*, 2006] is one of four instruments aboard the NASA EOS-Aura satellite, launched on 15 July 2004 [*Schoeberl et al.*, 2006]. OMI is a compact nadir viewing, wide swath, ultraviolet-visible (UV/Vis) imaging spectrometer that was contributed to the Aura mission by Netherlands and Finland. With its high spatial resolution and daily global coverage, OMI promises highly interesting scientific results that can make a marked contribution to our understanding of stratospheric and tropospheric chemistry and climate change. Concerning total ozone column measurements there are two satellite data products available. The OMI-TOMS data product is based on the long-standing TOMS V8 retrieval algorithm [*Bhartia et al.*, 2004]. The OMI-DOAS data product is a DOAS type algorithm [*Veefkind et al.*, 2006] developed specifically by the Royal Netherlands Meteorological Institute (KNMI) for deriving the total column of ozone from spectral radiances and irradiances measured by the Ozone Monitoring Instrument. Although both algorithms infer total ozone column data for OMI ground pixels, they differ in many aspects of their approach.

[3] During the previous decade or so numerous studies have been performed where the quality of satellite total ozone data were compared with ground-based data or with data from certain validation campaigns, which helped to identify features and problems in the comparisons and which also helped to improve the algorithms and revise the satellite data. *McPeters and Labow* [1996] compared TOMS V7 total ozone column data from Nimbus 7 with 30 Northern Hemisphere Dobson and Brewer stations and found that over a time period of 14.5 a, TOMS V7 data agreed within ±1% with the ground-based observations. *Bramstedt et al.* [2003] reported that TOMS V7 from Earth Probe-TOMS, hereafter EP-TOMS, overestimated total ozone over the Southern Hemisphere on the average by more than 2%. DOAS type algorithms were operationally applied to satellite data for the first time to GOME-1 data

[1]Laboratory of Atmospheric Physics, Physics Department, Aristotle University of Thessaloniki, Thessaloniki, Greece.
[2]Royal Netherlands Meteorological Institute, De Bilt, Netherlands.
[3]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

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and then to SCIAMACHY. There were various versions of GOME data that were publicly available and their validation [e.g., *Lambert et al.*, 1999; *Bramstedt et al.*, 2003] helped to identify many limitations of these earlier versions. The most recent GOME version 4.0 [*Van Roozendael et al.*, 2006] was compared with ground-based data from WOUDC and NDACC [*Balis et al.*, 2007]. For solar zenith angles smaller than 70 degrees the accuracy of GOME was found to be comparable to that obtainable from ground-based stations, i.e., between −1.0% and 1.5%, while for solar zenith angles greater than 70, larger discrepancies of up to 5% were found. Recently, *Lamsal et al.* [2007] showed that systematic errors of 10% in GOME ozone data at high solar zenith angles can be introduced by the choice of climatological profiles of the temperature and ozone.

[4] The purpose of this study is to gauge the quality of the OMI DOAS and OMI TOMS total ozone column data product by comparing the satellite observation of total ozone column with spatially and temporally collocated ground-based observations by Dobson and Brewer instruments. The satellite data used in this study is OMI-DOAS and OMI-TOMS collection 2 which are publicly available at the NASA Data and Information Services Center (DISC).

1.1. Short Description of OMI-TOMS Product

[5] The OMI-TOMS algorithm uses just two wavelengths (317.5 nm and 331.2 nm under most conditions, and 331.2 nm and 360 nm for high ozone and high solar zenith angle conditions). The longer of the two wavelengths is used to derive the surface reflectivity. The shorter wavelength is strongly absorbed by ozone and is used to derive total ozone columns. The algorithm also calculates the aerosol index from the difference in surface reflectivity derived from the 331.2 nm and 360 nm measurements. The aerosol index primarily provides a measure of absorption of UV radiation by smoke and desert dust. However, surface effects, such as sea glint and ocean color, can also enhance the aerosol index, and some types of (nonabsorbing) aerosols can produce negative aerosol index values. The aerosol index is used to correct the total ozone derived by the basic algorithm.

1.2. Short Description of the OMI-DOAS Product

[6] In the DOAS (Differential Optical Absorption Spectroscopy) implementation for OMI the ozone vertical column is determined in three steps. In the first step the actual DOAS fitting is performed, resulting in the so-called slant column density, which is the amount of ozone along an average photon path from the Sun, through the atmosphere, to the satellite. In the second step the air mass factor is calculated, which is needed to convert the slant column density into a vertical column. In the last step a correction is performed for clouds. All the results from intermediate steps are also contained in the product. The OMI DOAS spectral fitting uses a 5 nm wide fit window centered on 334.1 nm. This window has been selected on the basis of the very low temperature sensitivity shown by this wavelength. In the spectral fitting, the inelastic rotational Raman scattering, as well as the effective ozone temperature are explicitly accounted for. The air mass factor is determined by applying the DOAS fit to simulated OMI spectra, a method that is often referred to as the empirical air mass factor. The cloud information needed to derive accurate air mass factors and for correction factors for cloudy and partly cloudy conditions, is obtained from the OMI cloud product which is derived from the O_2-O_2 absorption band around 477 nm. The OMI-DOAS retrieval algorithm was developed specifically for OMI. From the start of the OMI data record validation results have been employed to identify algorithm shortcomings and to provide insights into where satellite data retrieval improvements were needed. As a result, OMI-DOAS data of collection 2 has been processed with different versions of the retrieval algorithm. From September 2004 to October 2005 all data have been processed with v0.9.4. From October 2005 onward version v1.0.1 has been in operation. Even though the two data sets did not span the same time period, there were indications for small improvements in the seasonal and solar zenith angle dependence of the new version of OMI-DOAS. In this study we therefore analyzed only data from version 1.0.1.

2. Ground-Based Correlative Data

[7] In the present study, archived total ozone column measurements from the WMO/GAW network that are routinely deposited at the WOUDC in Toronto, Canada (http://www.woudc.org) were used as ground reference. The WOUDC archive contains total ozone column data mainly from Dobson and Brewer UV spectrophotometers and from M-124 UV filter radiometers. A well maintained and calibrated Dobson spectrophotometer measures the ozone column with an estimated accuracy of 1% for direct Sun observations and 2–3% for zenith sky or zenith cloud observations for Sun elevation higher than 15° [*Basher*, 1982]. However, it is worth taking into consideration that the calibration of the operational Dobson spectrometers are deduced by transfer from a standard instrument by side by side measurements hence these values might be a bit too optimistic. The Dobson spectrophotometer is a large and manually controlled two-beam instrument based on the differential absorption method in the ultraviolet Huggins band where ozone exhibits strong absorption features. The measurement principle relies on the ratio of the direct sunlight intensities at two standard wavelengths. The most widely used combination is the AD double pair, recommended as the international standard for midlatitudes. Since 1957, Dobson spectrophotometers have been deployed operationally in a worldwide network. The Brewer grating spectrophotometer is in principle similar to the Dobson, however, it has an improved optical design and is fully automated. The ozone column abundance is determined from a combination of five wavelengths between 306 nm and 320 nm. Since the 1980s, Brewer instruments are part of the ground-based networks as well. Most Brewers are single monochromators, but a small number of systems are double monochromators with improved stray light performance.

[8] In general, spatial and temporal coincidences offered by the Dobson and Brewer networks are sufficient to cover a wide geographical extent for the validation of a satellite sensor, however, with better coverage over land with respect to sea and over the Northern Hemisphere compared to the Southern Hemisphere. Total ozone column data from a large number of stations have already been used extensively both

Table 1. List of Brewer Stations Used in the Comparisons[a]

WMO ID	Station Name	Latitude, deg	Longitude, deg	Elevation	Country
314	Belgrano	−77.87	−34.63	255	Antarctica
322	Petaling Jaya	3.1	101.65	46	Malaysia
349	Lasha	29.4	91.03	3633	China
287	Funchal	32.65	−17.05	59	Portugal
332	Pohang	36.03	129.38	0	Korea
295	Mt. Waliguan	36.17	100.53	3816	China
213	El Arenosillo	37.1	−6.73	41	Spain
346	Murcia	38	−1.17	69	Spain
82	Lisbon	38.77	−9.13	105	Portugal
261	Thessaloniki	40.52	22.97	4	Greece
305	Rome University	41.9	12.52	0	Italy
65	Toronto	43.78	−79.47	198	Canada
326	Longfenshan	44.75	127.6	0	China
301	Ispra	45.8	8.63	0	Italy
35	Arosa	46.77	9.67	1860	Switzerland
100	Budapest	47.43	19.18	140	Hungary
99	Hohenpeissenberg	47.8	11.02	975	Germany
331	Poprad-Ganovce	49.03	20.32	0	Slovakia
96	Hradec Kralove	50.18	15.83	285	Czech Republic
338	Regina	50.21	−104.67	0	Canada
53	Uccle	50.8	4.35	100	Belgium
316	Debilt	52	5.18	0	Netherlands
174	Lindenberg	52.22	14.12	98	Germany
76	Goose	53.32	−60.38	44	Canada
21	Edmonton	53.57	−113.52	668	Canada
279	Norkoping	58.58	16.12	0	Sweden
123	Yakutsk	62.08	129.75	98	Russia
284	Vindeln	64.25	19.77	0	Sweden
267	Sondrestrom	67	−50.98	150	Greenland
262	Sodankyla	67.37	26.65	179	Finland
315	Eureka	79.89	−85.93	10	Canada

[a]First column denotes WMO station number. Note the very few stations on the Southern Hemisphere.

for trend studies [e.g., *World Meteorological Organization* (*WMO*), 1998, 2002, 2006] as well as for validation of satellite total ozone data [e.g., *Lambert et al.*, 1999, 2000; *Fioletov et al.*, 1999; *Bramstedt et al.*, 2003; *Labow et al.*, 2004; *Weber et al.*, 2005; *Balis et al.*, 2007]. *Van Roozendael et al.* [1998] have shown that Dobson and Brewer data can agree within 1% when the major sources of discrepancy are properly accounted for. Dobson measurements suffer from a temperature dependence of the ozone absorption coefficients used in the retrievals which might account for a seasonal variation in the error of ±0.9% in the middle latitudes and ±1.7% in the Arctic, and for systematic errors of up to 4% [*Bernhard et al.*, 2005]. The error of individual total ozone measurements for a well maintained Brewer instrument is about 1% [e.g., *Kerr et al.*, 1988]. Despite the similar performance between the Brewer and Dobson stations, small differences within ±0.6% are introduced because of the use of different wavelengths and different temperature dependence for the ozone absorption coefficients [*Staehelin et al.*, 2003]. The atmospheric temperature seasonal changes result in a seasonal variation of the Brewer ozone data, where the contribution of the systematic offset is less than 1% [*Van Roozendael et al.*, 1998]. Dobson and Brewer instruments might also suffer from long-term drift associated with calibration changes. Additional problems arise at solar elevations lower than 15°, for which diffuse and direct radiation contributions can be of the same order of magnitude. Assuming that the Dobson and Brewer instruments are well calibrated, and that measurements are filtered to avoid air mass dependence, the total ozone columns can be corrected for temperature dependence using formulae given by *Komhyr et al.* [1993]. However, in this study no corrections have been applied to the data to account for their temperature dependence.

[9] To prepare the ground-based data set for OMI validation, we investigated the quality of the total ozone values of each station and instrument that deposited data at WOUDC for any time period after 2004. First we considered the outcome from the most recent Dobson intercalibration campaigns [*WMO*, 2000] (see also the Dobson Forum Web pages at http://www.chmi.cz/meteo/ozon/dobsonweb/calibrations.htm). Stations that were reported to be problematic were excluded from the comparisons. For all the other stations we examined a series of plots and statistics based on OMI, GOME and EP-TOMS comparisons for each station. Comparisons using direct Sun ultraviolet measurements, which offer a greater accuracy (∼1%) than those based on zenith-sky data, were performed separately. For each station we checked time series of the percent relative differences with all three satellite data, on a daily basis and on a monthly mean basis, in order to detect possible drifts of a ground-based instrument, i.e., in cases where at one station the differences with all three satellites showed systematically a trend. Next we studied the distribution and scatter of these differences. If this distribution was not normal for all three comparisons we excluded this station from the summary comparisons. In addition we examined the correlation between the ground-based data and collocated OMI, GOME and EP-TOMS data. Stations that systematically showed small correlation coefficients were also excluded from the summary comparisons. In a few cases, there were systematic inconsistencies between comparisons from neighboring stations, when examining the results from all three satellites. However, we should note here that the

Table 2. List of Dobson Stations Used in the Comparisons[a]

WMO ID	Station Name	Latitude, deg	Longitude, deg	Elevation	Country
111	Amundsen-Scott	−89.98	−24.8	2835	Antarctica
268	Arrival Heights	−77.83	166.4	250	Antarctica
101	Syowa	−69	39.58	21	Antarctica
339	Ushuaia	−54.85	−68.31	7	Argentina
29	Macquarie Island	−54.48	158.97	6	Australia
342	Comodoro Rivadavia	−45.78	−67.5	43	Argentina
256	Lauder	−45.03	169.68	370	New Zealand
253	Melbourne	−37.48	144.58	125	Australia
91	Buenos-Aires	−34.58	−58.48	25	Argentina
159	Perth	−31.95	115.85	2	Australia
343	Salto	−31.58	−57.95	31	Uruguay
340	Springbok	−29.67	17.9	1	South Africa
27	Brisbane	−27.47	153.03	5	Australia
265	Irene	−25.25	28.22	1524	South Africa
200	Cachoeira-Paulista	−22.68	−45	573	Brazil
191	Samoa	−14.25	−170.57	82	USA
84	Darwin	−12.47	130.83	0	Australia
219	Natal	−5.83	−35.2	32	Brazil
175	Nairobi	−1.27	36.8	1710	Kenya
214	Singapore	1.33	103.88	14	Singapore
216	Bangkok	13.73	100.57	2	Thailand
245	Aswan	23.97	32.45	193	Egypt
209	Kunming	25.02	102.68	1917	China
190	Naha	26.2	127.67	29	Japan
152	Cairo	30.08	31.28	35	Egypt
11	Quetta	30.18	66.95	1799	Pakistan
7	Kagoshima	31.63	130.6	283	Japan
14	Tateno	36.05	140.13	31	Japan
106	Nashville	36.25	−86.57	182	USA
341	Hanford	36.32	−119.63	73	USA
213	El Arenosillo	37.1	−6.73	41	Spain
252	Seoul	37.57	126.95	84	Korea
107	Wallops Island	37.87	−75.52	4	USA
208	Shiangher	39.77	117	13	China
67	Boulder	40.02	−105.25	1634	USA
12	Sapporo	43.05	141.33	19	Japan
226	Bucharest	44.48	26.13	92	Romania
19	Bismarck	46.77	−100.75	511	USA
35	Arosa	46.77	9.67	1860	Switzerland
20	Caribou	46.87	−68.02	192	USA
99	Hohenpeissenberg	47.8	11.02	975	Germany
53	Uccle	50.8	4.35	100	Belgium
116	Moscow	55.75	37.57	187	Russia
284	Vindeln	64.25	19.77	0	Sweden
105	Fairbanks	64.8	−147.89	138	USA
199	Barrow	71.32	−156.6	11	USA

[a]First column denotes WMO station number.

main objective of this paper is not to assess the quality of the entire WOUDC database and therefore it is likely that in certain regions (e.g., tropics, low latitudes) with limited coverage from ground-based stations and limited knowledge on the calibration history of an instrument, the above criteria would not be sufficient to exclude a station from the comparisons. So over these regions the comparison results should be treated with caution. Finally from the above mentioned selection procedure, 29 Brewer and 47 Dobson stations were considered for the comparisons with OMI-DOAS and OMI-TOMS total ozone column data presented below. These stations are sorted with increasing latitude and listed in Tables 1 and 2.

3. Results and Discussion

[10] Following the discussion of the previous section, updated time series of the differences have been generated for each of the selected stations which cover the time period January 2005 to December 2006, and features like offsets, scatter, seasonal dependence and solar zenith angle dependence have been examined. Collocation criteria were based on a spatial window of 150 km, comparing measurements performed within the same day. The total ozone data available at WOUDC are mostly daily averages and thus no specific temporal window has been selected. In the summary statistics shown in the next paragraphs only direct Sun ground-based measurements have been used as a reference.

3.1. Global Comparisons

[11] Figure 1 shows the mean relative differences between the satellite data and the ground-based total ozone observations separately for the Brewer and Dobson instruments, based on updated comparisons which include data until December 2006. The differences are averaged over 10° latitude bins and the error bars shown correspond to the 2σ standard error on the latitudinal mean. Unless stated other-

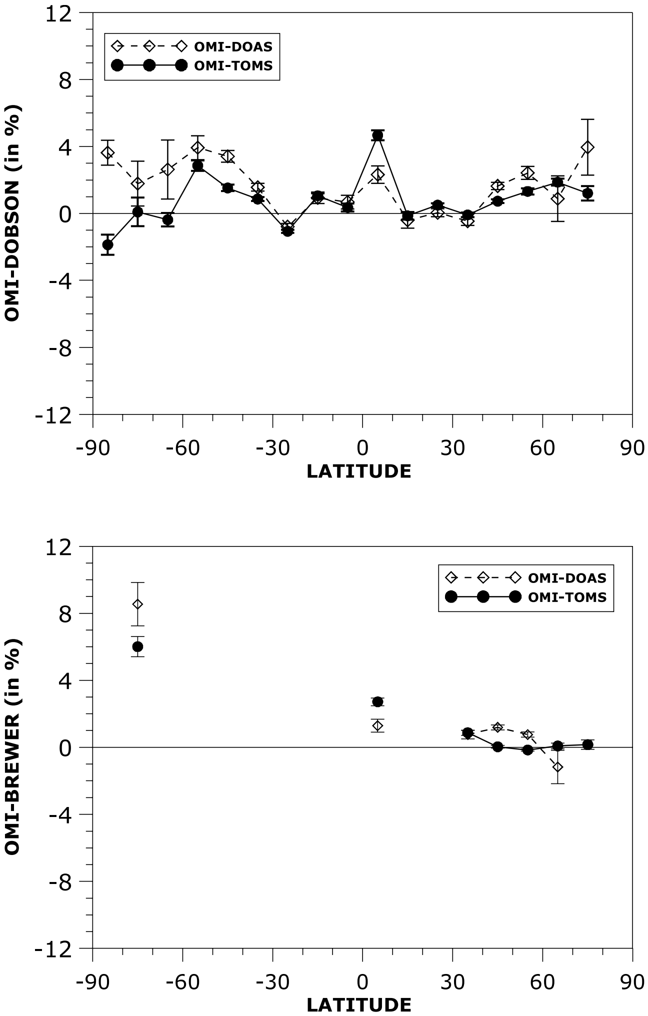

Figure 1. Mean relative differences between OMI satellite (OMI-TOMS and OMI-DOAS) and ground-based total ozone data, plotted separately for (top) Dobson and (bottom) Brewer instruments, as a function of the ground pixel/station latitude. The error bars depict two standard errors on the mean.

wise, in the figures that follow the error bars always depict the 2σ standard error on the mean value. Global average differences can only be estimated from the Dobson comparisons, since there are almost no Brewer instruments in the Southern Hemisphere. On the basis of the year 2006 the average difference between OMI-DOAS and Dobson total ozone column observations, which have a better latitudinal coverage, is 1.65% ± 0.38%, while the average difference between OMI-TOMS and Dobson total ozone column observations based on years 2005 and 2006 is 0.79% ± 0.36%. The errors depict the standard error on the latitudinal mean. We have to note here that if we study separately the years 2005 and 2006 we obtain almost the same results when we consider both years. Large positive differences were found over the equator, corresponding to a single station. These high values over the tropics can also be related to quality issues of the ground-based measurements and therefore these stations have been excluded from the study of *McPeters et al.* [2007]. Over the middle latitudes of both hemispheres both OMI products show a small overestimation which increases with latitude. This feature is more pronounced in the Southern Hemisphere, especially for OMI-DOAS. Over the Antarctic OMI-DOAS overestimates total ozone by 2 to 4% while OMI-TOMS shows an agreement between 0 and −2%.

[12] The average percent difference between OMI-DOAS and Brewer total ozone column observations for the year 2006 is 0.56 ± 0.48%. The corresponding percent difference between OMI-TOMS and Brewer for the years 2005–2006 is 0.61% ± 0.44% for the average of the latitude bands, excluding however the Antarctic station of Belgrano. In these comparisons the results over the equator are based on a single station, however, they are consistent with the Dobson comparisons. The Brewer summary results however are valid only for the Northern Hemisphere and mainly for the latitudes 30–60°N. The differences between the comparisons of OMI-TOMS and OMI-DOAS data with the Dobson data are consistent with the relative OMI-Brewer comparisons but are not directly comparable since they do not represent the same geographical coverage.

3.2. Seasonal Dependence

[13] Figure 2 shows cross sections of the time series of the monthly mean relative differences between satellite and ground-based total ozone observations as a function of latitude. OMI-DOAS comparisons indicate a 1.5% amplitude seasonal dependence for the Brewer comparisons and slightly larger (2%) but in phase for the Dobson comparisons. This amplitude corresponds to the middle latitude of both hemispheres and increases with increasing latitude. This seasonality is similar and in phase with the one found in GOME v4.0-ground comparisons, which was mainly attributed to the different temperature dependence between the satellite retrieval algorithm and the different temperature dependence of the ozone absorption cross sections used in Brewer and Dobson retrievals due to the different wavelengths used [*Balis et al.*, 2007]. OMI-TOMS-Brewer comparisons do not show any seasonality over the middle latitudes of the Northern Hemisphere, while the comparisons over the equator indicate both an offset and a seasonal pattern. Over the Antarctic the comparisons are based also on a single station and therefore should not be considered significant. The OMI-TOMS to Dobson comparisons, however, show a similar seasonality with the OMI-DOAS to Dobson comparisons albeit with a reduced amplitude. Concerning the Southern Hemisphere, OMI-DOAS comparisons with ground-based data (both Brewer and Dobson) show an offset of 2% while the corresponding OMI-TOMS comparisons with the ground-based data have no offset. Over Antarctica OMI-TOMS slightly underestimates the total ozone column while OMI-DOAS overestimates the total ozone column by more than 2%.

3.3. Solar Zenith Angle Dependence

[14] Figure 3 shows the solar zenith angle dependence of the relative differences between satellite and ground-based total ozone column observations. OMI-DOAS comparisons with Brewer observations indicate that at larger solar zenith angles OMI-DOAS overestimates the total ozone column by 3% to 5%. This pattern is more pronounced in the Dobson comparisons. Considering that usually large solar zenith

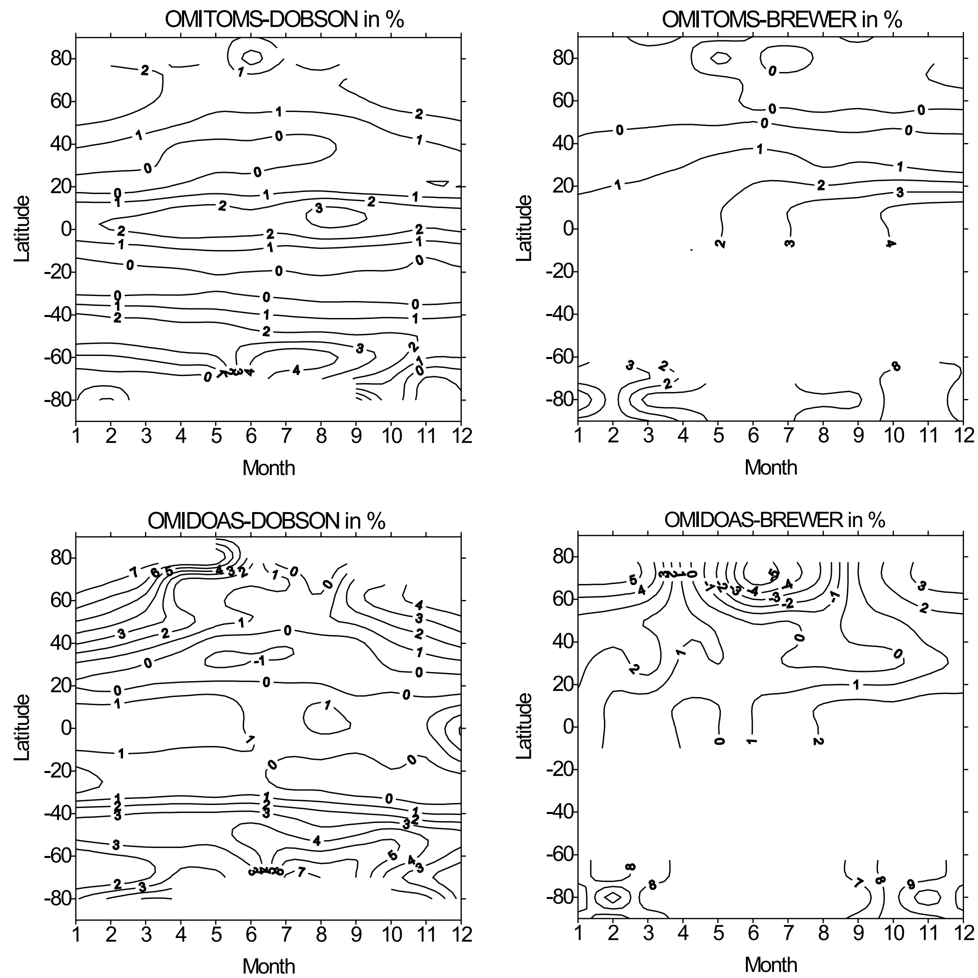

Figure 2. Monthly mean relative differences between satellite and ground-based total ozone data, plotted separately for OMI-TOMS and OMI-DOAS in rows and for Brewer and Dobson instruments in columns. OMI data incorporated cover the whole time period 2005–2006 for OMI-TOMS and the whole 2006 for OMI-DOAS.

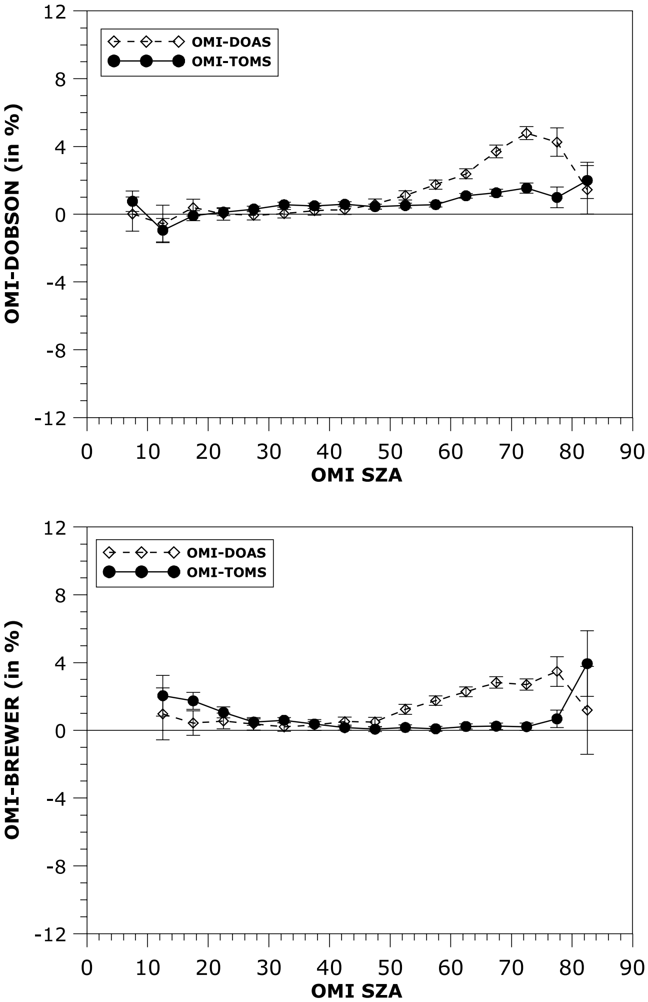

Figure 3. Mean relative differences between satellite (OMI-TOMS and OMI-DOAS) and ground-based total ozone data, plotted separately for (top) Dobson and (bottom) Brewer instruments, as a function of the ground pixel solar zenith angle. The error bars depict the two standard errors on the mean.

angles correspond to winter conditions, this dependence is probably also correlated and associated with the seasonal dependence presented in Figure 2. Ongoing improvements in the calibration of the OMI level 1b data and OMI-DOAS retrievals on test data sets have indicated that the largest part of this dependency is likely to be removed in OMI data collection 3. OMI-TOMS comparisons do not show any significant solar zenith angle dependence for either comparison.

3.4. Cloud Fraction Dependence

[15] In Figure 4 the differences between OMI and ground-based data are presented as a function of cloud cover during the satellite measurement. For OMI-TOMS data we used the reflectivity at 360 nm wavelength as an indication of the cloud cover. The differences between OMI-TOMS and coincident Dobson observations (considering both direct Sun and zenith sky observations) do not show any dependence on the reflectivity for values smaller than 90%. For larger reflectivity values OMI-TOMS slightly underestimates the total ozone column by 2% relative to the ground-based data. Concerning the Brewer comparisons there is also no dependence found for reflectivity values smaller than 90%, while for larger reflectivity values there is an indication that OMI-TOMS overestimates ozone by almost 5%. The latter finding is not consistent with the Dobson results. A possible explanation for this inconsistency could be the fact that most routine Brewer observations are direct Sun measurements and thus the comparisons are biased toward clearer cloud conditions, which is not the case with the routine Dobson observations. For the OMI-DOAS comparisons, also shown in Figure 4, we used the cloud fraction product included in the DOAS ozone estimates as a measure of the cloud conditions. There are fewer points to compare relative to the OMI-TOMS since the OMI-DOAS data of version 1.0.1 covers only the second year of time period studied. Neither Brewer nor Dobson comparisons show any significant dependence on the cloud fraction. However, the scatter of the comparisons for overcast conditions is much larger than for values with partial cloud cover. This increased scatter is most probably related to the choice of cloud pressure under cloudy conditions. OMI-TOMS employs a cloud pressure climatology which on average may be correct but will underestimate or overestimate the cloud pressure depending on the cloud scene varying on a day to day basis. OMI-DOAS uses the daily updated OMI O2-O2 cloud pressure data yielding more accurate estimates of the actual situation sampled by the satellite sensor. Dobson and Brewer observations are performed only under clear or cloud free conditions that occur in between clouds. Most likely the effects described above average out to a mean difference that does not show a clear dependence on cloud fraction. However, the scatter around this mean increases with increasing cloud faction.

3.5. Total Column Dependence

[16] In many of the previous validation studies one of the features examined was the dependence on total ozone column of the differences between satellite and ground-based with emphasis for ozone hole conditions [e.g., *Lambert et al.*, 1999; *Balis et al.*, 2007]. The reason for examining such a dependency is the following. The climatology of the vertical distribution of ozone used in various algorithms might leave a signature in the comparisons between satellite and ground-based data especially for extreme cases such as the ozone hole. In this section we check if such signatures are evident in the data. In Figure 5, the total ozone column dependence of the difference between OMI and Dobson total ozone column data is presented. From Figure 5 it is evident that the OMI-TOMS product does not demonstrate any dependence on total ozone column, especially for columnar values below 220 DU which correspond to ozone hole conditions. This finding is consistent with the relative comparisons of TOMS V8 data with ground-based data [*Balis et al.*, 2007]. A small peak observed at 250 DU should be attributed to differences found over the equator, consistent with the results shown in Figure 1. Concerning OMI-DOAS, where the measurements available for comparison purposes covered only 1 a, there is an indication that for extreme low columnar ozone the OMI-DOAS values

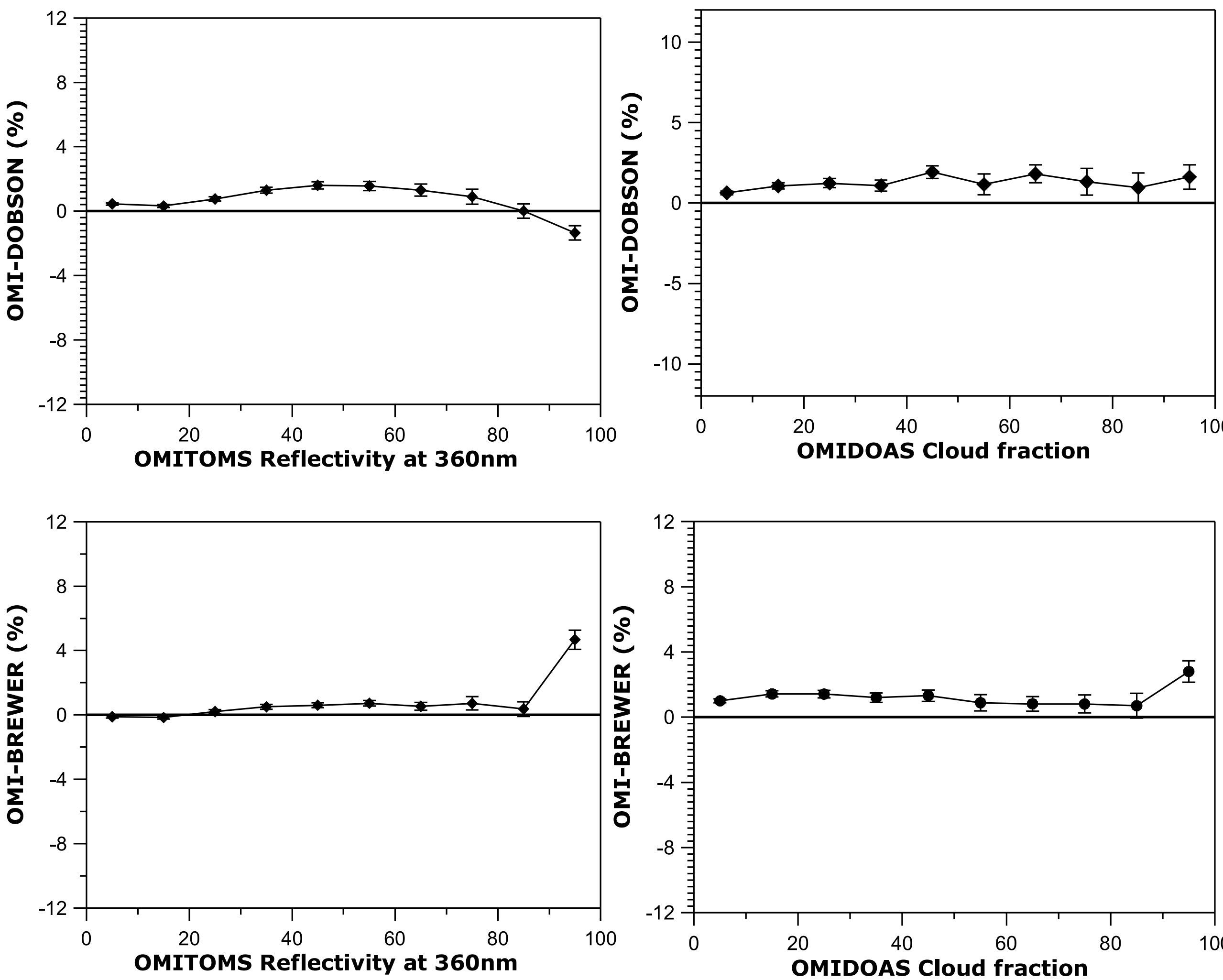

Figure 4. (left) Relative difference between OMI-TOMS and ground-based total ozone as a function of the OMI reflectivity data at 360 nm. (right) Relative difference between OMI-DOAS and ground-based total ozone as a function of OMI-DOAS determined cloud fraction. The error bars depict two standard errors on the mean.

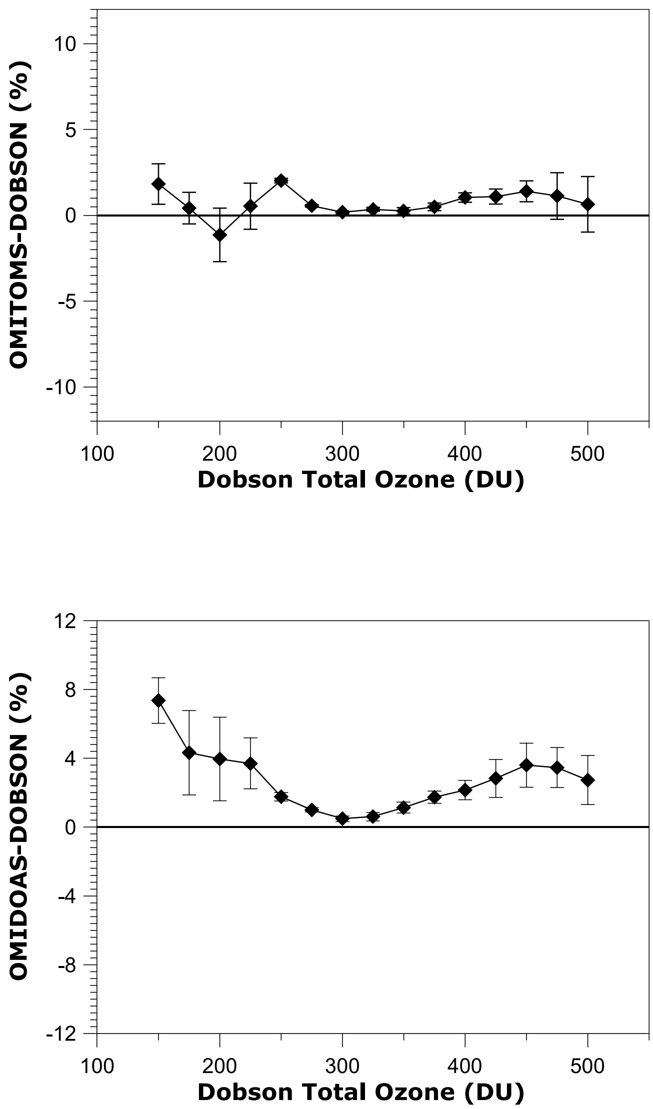

Figure 5. Relative difference of OMI and Dobson observations as a function of the Dobson estimated columnar ozone (top) for OMI-TOMS and (bottom) for OMI-DOAS. The error bars depict two standard errors on the mean.

tend to systematically overestimate the Dobson observations on the average by about 5%. There is also an overestimation of OMI-DOAS ozone by almost 2% for values larger than 450 DU.

4. Conclusions

[17] OMI total ozone column data extracted from the OMI level-1b data by two retrieval algorithms, OMI-TOMS and OMI-DOAS, were compared to the total ozone column recordings by ground-based Dobson and Brewer networks. On the basis of two full years of OMI data we conclude that the OMI-TOMS product compares very well to the ground-based measurements. With respect to the worldwide Dobson network, a global average bias of 0.8% is found for OMI-TOMS if the tropics are excluded. When considering individual station averages, biases are within 3%, with respect to both Brewer and Dobson instruments. Above 35°N, comparisons are considerably better, with differences within 1%. There is no significant dependence on solar zenith angle, cloud fraction and reflectivity on the total ozone column. With respect to Brewer instruments, which are almost all located in the Northern Hemisphere, a "global" average difference of 0.6% is found. Time series of globally averaged differences between OMI-TOMS and ground instruments show an annual variation with amplitude of 1.5% with respect to Dobson instruments, and almost no annual variation with respect to Brewer instruments. It should be noted that annual cycles in the recording by ground-based instruments are expected and may contribute to the differences observed. For the second algorithm we conclude that OMI-DOAS and Brewer total ozone column observations agree within 0.7%, while the respective OMI-DOAS to Dobson comparisons, which have a better latitudinal coverage, are within 1.65%. OMI-DOAS comparisons show a seasonal dependence with amplitude of 1.5% for the Brewer comparisons and slightly larger, 2%, but in phase, for the Dobson comparisons. OMI-DOAS comparisons with Brewer observations indicate that at larger solar zenith angles OMI-DOAS overestimates the total ozone column by 3% to 5%. This pattern is more pronounced in the Dobson comparisons. OMI-DOAS data overestimate ozone for ozone columns smaller than 220 DU, resulting in an overestimation of ozone over the Antarctic. Comparisons of airborne observations with preliminary OMI-DOAS collection 3 total column ozone data by M. Kroon et al. (OMI total ozone column validation with Aura-AVE CAFS observations, submitted to *Journal of Geophysical Research*, 2007) demonstrated that the solar zenith angle dependence has been greatly suppressed by the recent algorithm and calibration improvements. Marginal improvements have been identified between the two OMI-DOAS versions operationally applied, which mostly resulted in a slightly smaller offset for the latest OMI-DOAS version v1.0.1. As also demonstrated by *McPeters et al.* [2007] OMI-TOMS data can be considered of high quality and can thus be used as the continuation of the long TOMS record. OMI-DOAS data are expected to substantially improve when the new collection of recalibrated level 1b data will be used for the DOAS algorithm.

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References

Balis, D., et al. (2007), Reprocessing the 10-year GOME/ERS-2 total ozone record for trend analysis: the new GOME Data Processor Version 4.0, Validation, *J. Geophys. Res.*, *112*, D07307, doi:10.1029/2005JD006376.

Basher, R. E. (1982), Review of the Dobson spectrophotometer and its accuracy, *Global Ozone Res. Monit. Proj.*, *Rep. 13*, World Meteorol. Organ., Geneva, Switzerland, Dec. (Available at http://www.esrl.noaa.gov/gmd/ozwv/dobson/papers/report13/report13.html)

Bernhard, G., R. D. Evans, G. J. Labow, and S. J. Oltmans (2005), Bias in Dobson total ozone measurements at high latitudes due to approximations in calculations of ozone absorption coefficients and air mass, *J. Geophys. Res.*, *110*, D10305, doi:10.1029/2004JD005559.

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.

Bramstedt, K., J. Gleason, D. Loyola, W. Thomas, A. Bracher, M. Weber, and J. P. Burrows (2003), Comparison of total ozone from the satellite instruments GOME and TOMS with measurements from the Dobson network 1996–2000, *Atmos. Chem. Phys.*, *3*, 1409–1419.

Fioletov, V., J. Kerr, E. Hare, G. Labow, and R. McPeters (1999), An assessment of the world ground-based total ozone network performance from the comparison with satellite data, *J. Geophys. Res.*, *104*, 1737–1747.

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*(D9), 11,129–11,140.

Komhyr, W. D., C. L. Mateer, and R. D. Hudson (1993), Effective Bass-Paur 1985 ozone absorption coefficients for use with Dobson ozone spectrophotometers, *J. Geophys. Res.*, *98*, 20,451–20,465.

Labow, G. J., R. D. McPeters, and P. K. Bhartia (2004), A comparison of TOMS, SBUV and SBUV/2 Version 8 total column ozone data with data from ground stations, paper presented at Quadrennial Ozone Symposium, Int. Ozone Comm., Kos, Greece, 1–8 June.

Lambert, J.-C., M. Van Roozendael, M. De Mazière, P. C. Simon, J.-P. Pommereau, F. Goutail, A. Sarkissian, and J. F. Gleason (1999), Investigation of pole-to-pole performances of spaceborne atmospheric chemistry sensors with the NDSC, *J. Atmos. Sci.*, *56*, 176–193.

Lambert, J.-C., et al. (2000), Combined characterization of GOME and TOMS total ozone measurements from space using ground-based observations from the NDSC, *Adv. Space Res.*, *26*, 1931–1940.

Lamsal, L. N., M. Weber, G. Labow, and J. P. Burrows (2007), Influence of ozone and temperature climatology on the accuracy of satellite total ozone retrieval, *J. Geophys. Res.*, *112*, D02302, doi:10.1029/2005JD006865.

Levelt, P. F., G. H. J. van den Oord, M. R. Dobber, A. Malkki, H. Visser, J. de Vries, P. Stammes, J. O. V. Lundell, and H. Saari (2006), The Ozone Monitoring Instrument, *IEEE Trans. Geosci. Remote Sens.*, *44*(5), 1093–1101.

McPeters, R. D., and G. J. Labow (1996), An assessment of the accuracy of 14.5 years of Nimbus 7 TOMS version 7 ozone data by comparison with the Dobson network, *Geophys. Res. Lett.*, *23*(25), 3695–3698.

McPeters, R. D., M. Kroon, G. Labow, E. Brinksma, D. Balis, I. Petropavlovskikh, J. P. Veefkind, P. K. Bhartia, and P. F. Levelt (2007), Validation of the Aura Ozone Monitoring Instrument total column ozone product, *J. Geophys. Res.*, doi:10.1029/2007JD008802, in press.

Schoeberl, M. R., et al. (2006), Overview of the EOS Aura Mission, *IEEE Trans. Geosci. Remote Sens.*, *44*(5), 1066–1074.

Staehelin, J., J. Kerr, R. Evans, and K. Vanicek (2003), Comparison of total ozone measurements of Dobson and Brewer spectrophotometers and recommended transfer functions, *WMO TD 1147*(149), World Meteorol. Organ., Geneva, Switzerland.

Van Roozendael, M., et al. (1998), Validation of ground-based UV-visible measurements of total ozone by comparison with Dobson and Brewer spectrophotometers, *J. Atmos. Chem.*, *29*, 55–83.

Van Roozendael, M., et al. (2006), Ten years of GOME/ERS-2 total ozone data—The new GOME data processor (GDP) version 4: 1. Algorithm description, *J. Geophys. Res.*, *111*, D14311, doi:10.1029/2005JD006375.

Veefkind, J. P., J. F. de Haan, E. J. Brinksma, M. Kroon, and P. F. Levelt (2006), Total ozone from the Ozone Monitoring Instrument (OMI) using the OMI DOAS technique, *IEEE Trans. Geosci. Remote Sens.*, *44*(5), 1239–1244.

Weber, M., L. N. Lamsal, M. Coldewey-Egbers, K. Bramstedt, and J. P. Burrows (2005), Pole-to-pole validation of GOME WFDOAS total ozone with ground-based data, *Atmos. Chem. Phys.*, *5*, 1341–1355.

World Meteorological Organization (1998), Scientific assessment of ozone depletion: 1998, *Global Ozone Res. Monit. Proj.*, *Rep. 44*, Geneva, Switzerland.

World Meteorological Organization (2000), Reports on WMO international comparisons of Dobson spectrophotometers, Parts I–Arosa, Switzerland, 19–31 July 1999, Part II-Buenos Aires, Argentina (29 Nov.–12 Dec. 1999 and Part III-Pretoria, South Africa (18 March–10 April 2000), *WMO TD 1016*, Geneva, Switzerland.

World Meteorological Organization (2002), Scientific assessment of ozone depletion: 2002, *Global Ozone Res. Monit. Proj.*, *Rep. 47*, Geneva, Switzerland.

World Meteorological Organization (2006), Scientific assessment of ozone depletion: 2006, *Global Ozone Res. Monit. Proj.*, *Rep. 50*, Geneva, Switzerland.

D. Balis and M. E. Koukouli, Laboratory of Atmospheric Physics, Physics Department, Aristotle University of Thessaloniki, Box 149, GR-54124 Thessaloniki, Greece. (balis@auth.gr)

E. J. Brinksma, M. Kroon, and J. P. Veefkind, Royal Netherlands Meteorological Institute, P.O. Box 201, NL-3730 AE De Bilt, Netherlands.

G. Labow and R. D. McPeters, NASA Goddard Space Flight Center, Code 916, Greenbelt, MD 20771, USA.