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Validation of the Aura Ozone Monitoring Instrument total column ozone product

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[1] This paper is an overview of the validation of the total column ozone data products from the Ozone Monitoring Instrument (OMI) on board the NASA EOS-Aura satellite. OMI is an imaging UV/visible spectrometer that maps global ozone on a daily basis. There are two ozone products from OMI, one derived using the traditional TOMS retrieval algorithm and another derived using a Differential Optical Absorption Spectroscopy algorithm that is being developed to take advantage of the hyperspectral capabilities of OMI. Validation is primarily performed through comparison with a network of Dobson and Brewer ground stations and secondarily through campaigns conducted specifically to validate Aura. Comparison with an ensemble of 76 Northern Hemisphere ground stations shows that OMI-TOMS total column ozone averages 0.4% higher than the station average, with station-to-station standard deviation of ±0.6%. The comparison shows that the OMI-TOMS ozone was stable over the 2-year period with no evidence of drift relative to the ground network. The OMI-DOAS product is also stable but with a 1.1% offset and a seasonal variation of ±2%. During four aircraft validation campaigns using the NASA DC-8 and WB-57 aircraft, ozone above the aircraft was measured using an actinic flux instrument and compared with OMI ozone. These comparisons showed agreement within 2% over a broad range of latitude and viewing conditions. Only during the high-latitude flights did the OMI-DOAS ozone show the effects of a solar zenith angle dependent error.

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1. Introduction

[2] Scientific data validation is an essential prerequisite for establishing credibility for satellite data and subsequent use for scientific research. Validation should be viewed as a process, not a task that can be completed. There is no point at which a satellite data set can be declared "validated." Rather, validation is an ongoing process of comparing the results of the remote sensing measurements performed by a satellite instrument on the Earth atmosphere with correlative data comprised of individual measurements of the satellite data products by ground-based, airborne or space-borne sensors that are colocated in space and time. Over time the state of the satellite instrument will be changing, the composition and behavior of the Earth atmosphere may be changing, the availability of correlative data will be changing, and the scientific questions raised and pursued with the derived satellite data products may be changing. Establishing the quality of the satellite data product record therefore requires a continuous approach.

[3] The purpose of this paper is to report on the status of the validation of 2 1/2 years of OMI ozone data in the context of continuing the long-term ozone data record, for which purpose the quality of the OMI ozone data must be accurately established. Here we provide key examples of validation activities with correlative data obtained by ground-based and airborne platforms in order to present an overarching view on the validation status of OMI total ozone column data. Other papers in this *Journal of Geophysical Research* special section on Aura validation will provide detailed descriptions on how several of these validation results were achieved.

2. Measurement

[4] OMI, the Ozone Monitoring Instrument flying on Aura, is the latest of a series of ozone mapping instruments. In terms of the long-term ozone data record OMI can be considered an advanced version of the total ozone mapping spectrometer (TOMS). A series of TOMS instruments flew

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on Nimbus 7 (November 1978 to May 1993), Meteor 3 (August 1991 to December 1994) and Earth Probe (August 1996 to December 2005). OMI continues this time series of global total column ozone measurements.

[5] OMI is the Dutch-Finnish contribution to EOS-Aura. OMI is a nadir viewing, wide swath, ultraviolet-visible (UV-VIS) imaging spectrometer that provides daily global measurements of the solar radiation backscattered by the Earth's atmosphere and surface, along with measurements of the solar irradiance. Full instrument details of OMI have been given elsewhere [*Levelt et al.*, 2006], but details relevant to ozone retrieval are summarized here. Unlike the heritage TOMS instruments which measure ozone at six discrete wavelengths from 306 nm to 380 nm [*McPeters et al.*, 1998], OMI measures the complete spectrum from 270 nm to 500 nm at an average spectral resolution of 0.5 nm. OMI combines the advantages of GOME and SCIAMACHY [*Burrows et al.*, 1999], measurement of the complete spectrum in the ultraviolet/visible wavelength range, with the advantages of TOMS, complete spatial coverage of the Earth. Each of the two OMI optical channels, UV and VIS, has a two-dimensional CCD detector. One dimension of the CCD is used to cover the spectrum, while the other gives spatial coverage. The UV channel consists of two subchannels: the UV-1, ranging from 270 to 310 nm, and the UV-2, ranging from 310 to 365 nm. The total ozone retrieval is based on measurements from the UV-2 detector. The VIS-channel covers the range from 365 to 500 nm.

[6] The nadir pointing telescope of OMI has a very large field of view of 114° perpendicular to the flight direction of the satellite. This gives OMI a swath width of 2600 km, consisting of 60 individual pixels along the swath. The instrument achieves complete daily global coverage of the sunlit Earth. The state of the art CCD detectors render a very high spatial resolution of 13 km × 24 km at nadir. The small ground pixel size enables OMI to look "in between" the clouds, giving better reach into the troposphere for retrieving tropospheric composition information than any other UV-VIS backscatter instrument flown to date.

[7] The radiometric accuracy of the OMI reflectance spectrum at the wavelengths used for ozone retrieval is on the order of 0.1% [*Dobber et al.*, 2008]. The ratio of the useful signal to the noise signal (i.e., the S/N ratio) depends on the viewing conditions and on the atmospheric conditions and is highly wavelength dependent. In UV/VIS satellite instruments stray light is a well-known problem, especially stray light from longer wavelengths that is detected at shorter wavelengths. After a correction is calculated based on the point spread function applied to the measured radiances at longer wavelengths, the stray light error is estimated to be less than 0.2% at the wavelengths used for retrieval of total column ozone.

3. OMI Total Ozone Retrieval Algorithms

[8] The total column ozone product from OMI is unusual in that it is computed using two distinct algorithms, the TOMS algorithm, hereafter referred to as OMI-TOMS, and a Differential Optical Absorption Spectroscopy (DOAS) algorithm, hereafter referred to as OMI-DOAS. The version 8 algorithm used to process data from the series of TOMS instruments is used for the OMI-TOMS retrieval, partly because after 20 years of development it is a very robust algorithm but mainly in order to maintain continuity with a TOMS data record that dates back to November 1978. The active focus is on a DOAS algorithm that can take advantage of the high spectral resolution offered by OMI. In principle such an algorithm should have an advantage in being less sensitive to certain instrument calibration uncertainties and less sensitive to aerosols or sun glint. Furthermore, the OMI-DOAS ozone retrieval should be insensitive to the presence of atmospheric trace gases with optical absorption features in the same spectral window, such as sulphur dioxide. A brief description of each of the two algorithms is given.

3.1. OMI-TOMS Algorithm

[9] The TOMS Version 8 algorithm is described by *Bhartia* [2007] and *Bhartia et al.* [2004]. The algorithm uses just two wavelengths to derive total ozone, a weakly absorbing wavelength (331.2 nm) to estimate an effective surface reflectivity (or effective cloud fraction) and another wavelength (317.5 nm) with stronger O_3 absorption to estimate ozone. The derivation uses tables calculated by the TOMS forward model (TOMRAD) which is based on successive iteration of the auxiliary equation in the theory of radiative transfer developed by *Dave* [1964]. This solution accounts for all orders of scattering, as well as the effects of polarization, by considering the full Stokes vector in obtaining the solution. The tables also account for both O_2-O_2 absorption and Raman scattering (the Ring effect). The TOMS V8 algorithm uses the 331.2 nm wavelength to derive surface reflectivity at small solar zenith angles but switches to 360 nm when the ozone absorption at 331.2 nm becomes significant because of high path length. The surface reflectivity is used to estimate fractional cloud cover. The forward model does not account for aerosols explicitly; rather, aerosols are treated as part of the reflecting surface. Aerosols usually increase the apparent reflectivity of the surface, though desert dust, which strongly absorbs the UV radiation, can have an opposite effect.

[10] The forward model treats a cloud as an opaque Lambertian surface. Transmission through and around clouds is accounted for by a mixed-Lambertian surface model. Effective cloud pressure is taken from a latitude dependant climatology derived using IR data. In the future a cloud climatology derived from the OMI O_2-O_2 and Raman cloud height retrievals will be used.

3.2. OMI-DOAS Algorithm

[11] The OMI-DOAS algorithm uses the Differential Optical Absorption Spectroscopy (DOAS) method to derive total column ozone. The algorithm consists of three steps. First, the DOAS method [*Veefkind et al.*, 2006] fits the reference differential absorption spectrum of ozone to the ratio of the measured Earth radiance spectrum to the solar irradiance spectrum to obtain the slant column density. In the second step the slant column density is translated into the vertical column density using the so-called air mass factor (AMF). The third step consists of a correction for cloud effects.

[12] The slant column density is determined by fitting an analytical function to the measured Earth radiance and solar

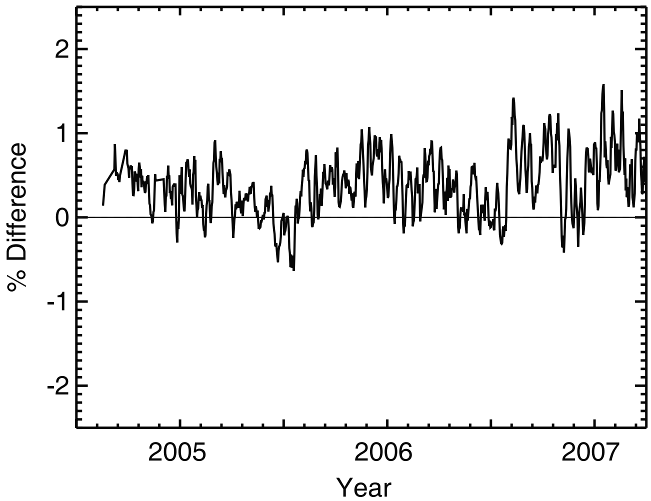

Figure 1. A comparison of the OMI TOMS ozone product with ozone from a network of 76 Northern Hemisphere Brewer and Dobson stations.

irradiance data. This fit is applied to data taken in a certain wavelength range called the fit window. A polynomial function, which serves as a high-pass filter, is applied to account for scattering and absorption that vary gradually with the wavelength, e.g., scattering by molecules, aerosols, and clouds.

[13] The air mass factor (AMF) is used to translate the slant column density into a vertical column density. The AMF depends on the Sun-satellite geometry, as well as on the "state of the atmosphere," on the ozone profile, on clouds and aerosol properties, on surface reflectivity properties, etc. The AMF is best determined using a radiative transfer model in conjunction with climatology.

[14] In cloudy cases in which part of the ozone column is masked by clouds, a cloud correction is used where cloud fraction and cloud pressure are determined by the OMI O_2-O_2 cloud product. This cloud model represents clouds as Lambertian surfaces with an albedo of 0.80, placed at the cloud pressure. It was found by *Koelemeijer and Stammes* [1999] that this value for the cloud albedo gives the best results for ozone retrieval using DOAS. It is also consistent with the TOMS 340/380 reflectance ratio. This cloud model considers all clouds to be thick, single layer clouds. Partly cloudy pixels are treated as the weighted sum of a clear and a cloudy pixel.

[15] From the start of the OMI data record validation results have been employed to identify OMI-DOAS algorithm shortcomings and to provide insights into where the retrieval needed improvements. As a result, the retrieval algorithm is continuously improved and hence 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 onwards algorithm version v1.0.1 has been in operation. Based on validation results with the Polar-AVE campaign data set, the OMI-DOAS algorithm has been further optimized for reprocessing the OMI-DOAS data set to collection 3 (not shown in this paper, see *Kroon et al.* [2008b] for first results from the ECS collection 3 processing).

4. Validation Against Ground-Based Data

[16] The most reliable validation of the OMI total column ozone product comes from comparison with ground observations, the Dobson/Brewer network. *Balis et al.* [2007] compares OMI ozone with Dobson and Brewer separately. Their comparisons, as noted in the discussion of Figure 7, show that the results for Dobson and Brewer are mostly very similar. In this study we aggregate Dobson and Brewer in the interest of increasing the number of matches. Our experience has shown that while individual ground stations may have offsets and time dependencies, these errors cancel surprisingly well in a large ensemble of stations and errors in the satellite observation of a few tenths of a percent can be reliably detected [*McPeters and Labow*, 1996]. The network as a whole is more reliable for validation than a handful of good stations. As will be shown in Figure 1, an OMI-TOMS comparison with a network of 76 stations has an uncertainty of only 0.61%. In contrast, comparison of TOMS with a single good Dobson station, the world standard instrument at Mauna Loa [*McPeters and Komhyr*, 1991] has an uncertainty of about ±1.5%, while a comparison of OMI-TOMS with 15 selected "good" stations has an uncertainty of about ± 0.94%.

[17] Since 1958 Dobson spectrophotometers have been deployed in a worldwide network. The Dobson spectrophotometer measures the ozone column amount with an accuracy of 2–3% [*Komhyr et al.*, 1989] for Sun elevation higher than 15°. It 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 sunlight intensities at two standard wavelengths. The most widely used combination is the direct sun AD double pair (305.5–325.4; 317.6–339.8 nm), recommended as international standard for midlatitudes. 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 four wavelengths between 310 and 320 nm. Since the late 1980s, Brewer instruments have been operated in ground-based networks as well. Most Brewers are single spectrometers, but a small number of systems are double spectrometers with improved stray light performance.

[18] The Dobson and Brewer data used in the comparison were the data available through early 2007 from the World Ozone and Ultraviolet Radiation Data Center (WOUDC) Meteorological Service of Canada, Toronto, Canada. Usually each reported observation is an average for the day, not a single measurement at the time of the satellite overpass. All Dobson observation codes, both direct sun and zenith sky, are used in the comparisons that follow in order to maximize the number of matches. It was felt that the lower quality of some observations was offset by better coverage in winter high latitudes.

[19] The comparisons shown here were done using OMI overpass data, available from the Aura Validation Data Center (AVDC) (available at http://avdc.gsfc.nasa.gov/Data/

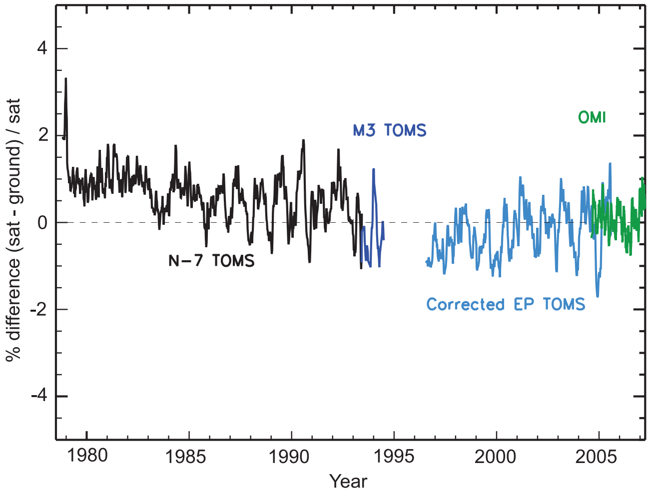

Figure 2. OMI ozone in the context of the Nimbus 7 TOMS and Earth Probe TOMS time series. All compared to an ensemble of 30 Northern Hemisphere Dobson stations that have coverage over the 26 year period.

Aura/index.html). OMI measures ozone at 60 individual locations across the orbital track to give complete interorbit coverage. Each day the single OMI pixel most nearly colocated with the ground station's location is selected as the best match. Near nadir this pixel is 13 km × 24 km, but at the outermost scan positions a pixel is approximately 125 km wide. At high latitudes a given ground location can be viewed from multiple orbits. In that case a pixel with very high optical path will be rejected in favor of one with a slightly poorer spatial coincidence but with a lower optical path.

4.1. OMI-TOMS Versus Dobson and Brewer

[20] Figure 1 shows the result of a comparison of OMI-TOMS overpass ozone data with data from an average of 76 Northern Hemisphere midlatitude (25°N to 55°N) Dobson and Brewer stations. Over 48,000 daily measurements from the ground stations were matched against the OMI overpass data for the time period September 2004 through December 2006. It is useful to restrict the comparison to a single hemisphere because seasonally dependent errors will cancel if data from two hemispheres are averaged together, giving a false impression of the quality of the data. Problems arising from observations at very high solar zenith angles (high latitude stations) will be examined separately. Weekly averages of the percent difference are plotted. Figure 1 shows that OMI agreed remarkably well with the ground network, with OMI averaging 0.38% higher with ±0.61% standard deviation and exceeding a 1% bias only in the fall of 2006. There is no evidence for significant change in the OMI calibration over the period of comparison.

[21] Figure 2 is a similar time series comparing the OMI data record with the historical record from the series of TOMS instruments [*McPeters and Labow*, 1996]. Here the comparison is against an ensemble of 30 Northern Hemisphere Dobson stations, the only stations that have nearly complete coverage over the 1978–2006 time period. The comparison shows that OMI is very consistent with the historical TOMS record and can be used to extend the trend analysis time series. The change in character seen beginning in 1983 is possibly due to a change in Nimbus-7 instrument calibration, while the feature in early 1979 is due to rapid instrument changes occurring shortly after launch. The remaining small seasonal cycle is most likely due to the ground instrumentation and the fact that the effective peak height and temperature of the ozone layer is assumed to be constant at a given station in the Dobson and Brewer retrievals while TOMS and OMI use a monthly ozone-weighted temperature climatology [*McPeters et al.*, 2007] which more accurately represents the atmospheric seasonal change. The Earth Probe TOMS ozone data after 2001 are not considered trend quality since the instrument has suffered severe degradation which was impossible to correct using purely internal calibration methods. The degradation has been corrected to first order by applying a latitude-dependent correction based on NOAA-16 SBUV/2 ozone values. The EP ozone differences after 2001 are shown only for completeness and should not be considered for trend evaluation.

[22] The OMI-TOMS ozone values have also been compared to the worldwide network of ground stations as a function of variables including latitude, solar zenith angle, reflectivity, and total column ozone. The dependence of OMI against these variables is contrasted with the behavior of Earth Probe TOMS in the following figures.

[23] Figure 3 shows the performance of OMI-TOMS (2004–2006) as a function of latitude, along with the EP TOMS (1996–2001) latitude dependence (in blue) for comparison. Standard deviations are plotted for OMI-TOMS but, in the interest of clarity, not for EP-TOMS. In the version 7 TOMS algorithm there were large differences between the satellite and ground station ozone values in the southern polar region. The error was identified as an improper assumption of cloud cover over snow/ice conditions in the OMI-TOMS retrievals and corrected. When there is cloud over snow and ice, the ozone calculation is more accurate if it is assumed that no clouds are present, since many photons that enter the cloud end up being

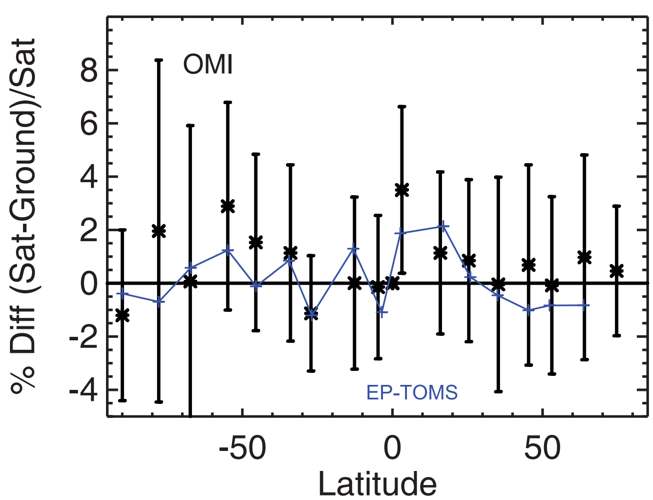

Figure 3. The latitude dependence of OMI-TOMS from a comparison with 93 Dobson and Brewer stations worldwide. Average OMI differences from ground stations are plotted for 10° zones with standard deviations. A similar comparison with EP TOMS for the period 1996–2001 (shown in blue) is plotted without standard deviations for clarity.

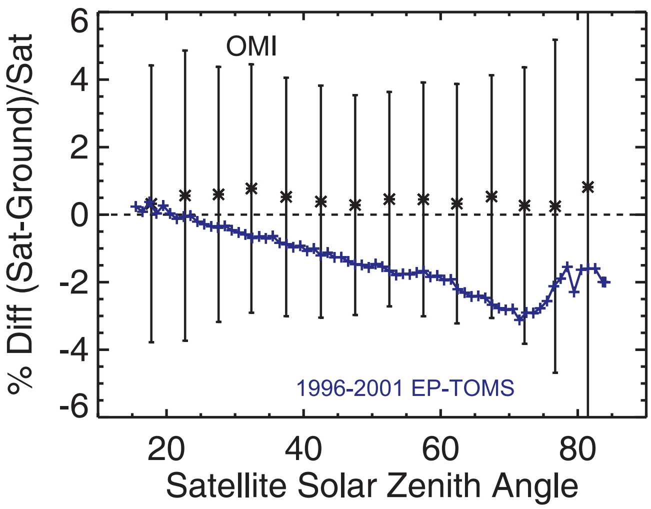

Figure 4. The solar zenith angle dependence of OMI-TOMS from a comparison with 74 Northern Hemisphere ground stations contrasted with a similar comparison for EP TOMS (plotted in blue).

reflected at the surface. At other latitudes, particularly in the southern midlatitudes, the OMI differences appear larger than EP-TOMS due to the short time series and small number of stations. The largest remaining systematic differences occur in the northern tropics where there are very few locations where ozonesondes are launched and therefore the tropospheric a priori is likely to be inaccurate in the satellite retrievals.

[24] Figure 4 shows comparisons of ozone as a function of satellite solar zenith angle (SZA) for Northern Hemisphere stations (25°N to 55°N) for OMI-TOMS and for Earth-probe TOMS. While the EP-TOMS SZA dependent error increases to almost −3% by 70° solar zenith angle, OMI has no apparent SZA dependence. This plot demonstrates the remarkable stability of the OMI instrument and the robustness of the retrieval algorithm even when the optical path lengths get very large. The implication of this plot is that the solar zenith angle dependence seen in EP TOMS was not an algorithmic effect but an instrumental effect.

[25] A similar comparison (not shown) as a function of satellite-derived 331nm reflectivity shows that agreement is good for both OMI and EP-TOMS across all reflectivity values, well within the standard deviation of the comparison. Agreement is within ±1% except at the highest reflectivities ($R_{331} > 70\%$) where the deviation increases to −2%. The agreement even there is good considering that the ground-based measurement was probably made with a direct sun measurement through a "hole in the clouds" while the satellite makes the corresponding measurement when there is a significant amount of cloudiness in the instrument's field of view. Since the satellite is only sensitive to the amount of ozone above the cloud, the cloud height and ozone amount below the cloud must be inferred from climatological tables. The excellent agreement for both OMI and EP TOMS shows that the radiative transfer-based tables used for the ozone retrievals are quite accurate.

[26] OMI-TOMS and EP TOMS ozone values have also been compared to the ozone values from ground stations as a function of total ozone. Previous (version 7) TOMS comparisons showed a significant dependence on total ozone. The comparison in Figure 5 shows a small dependence for EP TOMS (version 8) but almost no dependence for OMI-TOMS. The half percent offset is not unexpected for different instruments comparing to the ground network in different time periods. Preliminary results of the SAUNA campaign (discussed in section 5.2) confirm that the general slope of the curve between 350 and 500 Dobson Units is mostly due to stray light effects in the Dobson and single monochromator Brewers (MK II and MK IV models), which cause an underestimation of the measured column ozone under conditions of high ozone and high path length. High ozone values usually occur at high latitudes when solar zenith angles are large. It should be noted that these curves are averages of thousands of coincident measurements and that each Dobson instrument has a unique signature and this type of comparison could possibly be used to diagnose instrument problems such as stray light or mu (zenith angle) dependence. The fact that the OMI-TOMS curve is slightly more "flat" than EP-TOMS at low ozone amounts is likely due to an EP TOMS detector linearity issue that shows up at high absolute signal levels (low ozone). Again, the performance of the OMI instrument appears to be very good.

4.2. OMI DOAS Versus Dobson and Brewer

[27] Comparisons here use ozone processed using the v1.0.1 DOAS algorithm, which has been used to produce OMI data since October 2005. Figure 6 is a time series comparison of OMI-DOAS overpass ozone matched to a network of 62 Northern Hemisphere stations. Somewhat fewer stations are used because some stations had periods of missing data in 2006 that brought the stations below our percent coverage requirement. This is a comparison similar to that of Figure 1 but for OMI-DOAS ozone instead of OMI-TOMS ozone. The comparison shows that DOAS ozone averages 1.1% higher than the ground network in the northern midlatitudes, a somewhat bigger offset than the TOMS product. Of more concern is the ±2% amplitude seasonally dependent difference, with the largest differences

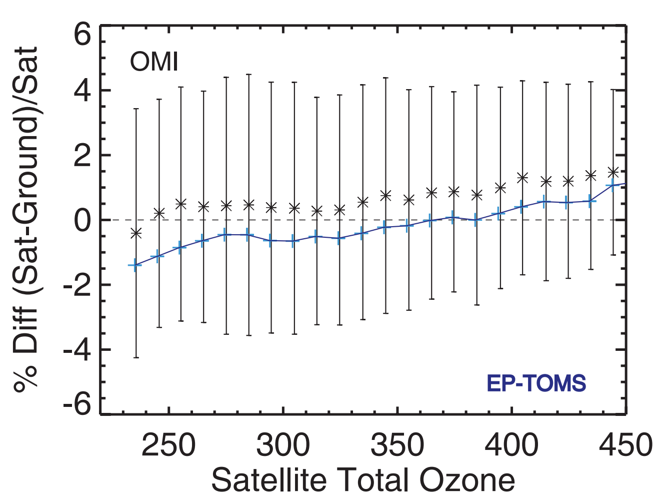

Figure 5. The dependence on total column ozone of OMI-TOMS and EP TOMS (in blue) from a comparison with 74 Northern Hemisphere ground stations.

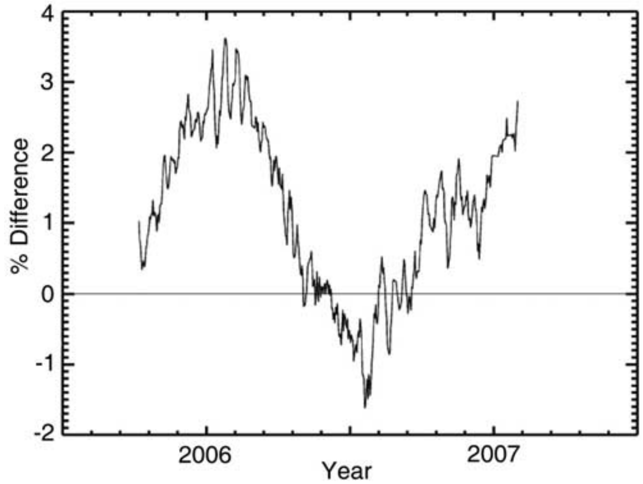

Figure 6. A comparison of the OMI-DOAS ozone product with ozone from a network of 62 Northern Hemisphere stations.

occurring in the winter, possibly indicating a solar zenith angle dependent error. There is no evidence for secular change in the difference, but the time series is too short for a clear conclusion given the magnitude of the seasonal component.

[28] In the study presented elsewhere in this issue, *Balis et al.* [2007] compare OMI ozone with total column ozone measurements from the WMO/GAW network that are routinely deposited at the WOUDC in Toronto. Their study used data from 29 Brewer and 47 Dobson instruments worldwide, though most stations are in the northern hemisphere. The OMI-TOMS and OMI-DOAS algorithms differ in many respects and hence studying these satellite data products separately provides useful insights. Furthermore, the available knowledge of the performance of ground-based instruments provides clear insights into which part of the comparison results is to be attributed to the satellite or to the ground-based observation. *Balis et al.* [2007] have carefully prepared the ground-based data set for OMI validation by investigated the quality of the total ozone data of each station and instrument that deposited data at WOUDC for any period after 2004. Features like offsets, scatter, seasonal dependence, and solar zenith angle dependence have been examined.

[29] Figure 7, which is based on the *Balis et al.* [2007] analysis, shows the solar zenith angle dependence of the relative differences between satellite and ground-based total ozone observations separately for Brewer and Dobson instruments and for OMI-DOAS and OMI-TOMS products. On the basis of comparisons over the whole year 2006, the average difference between OMI-DOAS and Brewer total ozone column observations is 0.56% ± 1.55%.The corresponding difference between OMI-TOMS and Brewer total ozone column observations, based on years 2005–2006 0.6% ± 1.1%. The average difference between OMI-DOAS and Dobson total ozone column observations is 1.65% ± 1.55%. The average difference between OMI-TOMS and Dobson total ozone column observations is

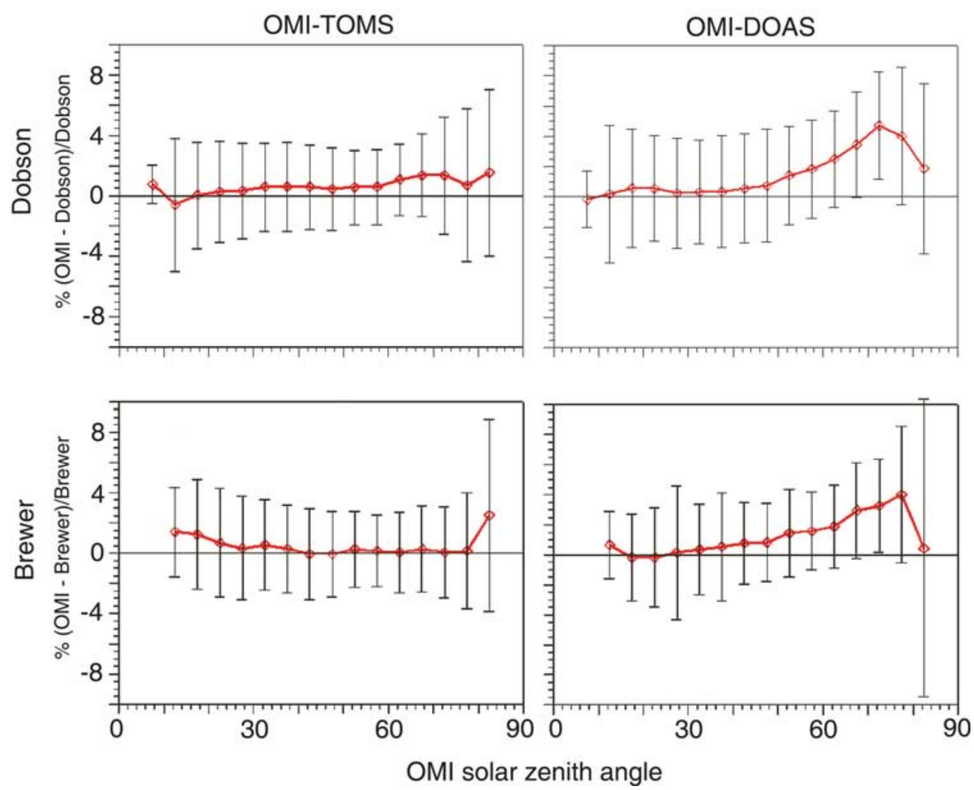

Figure 7. Mean relative differences between satellite and ground-based total ozone data, plotted separately for OMI-TOMS and OMI-DOAS (left and right) for Dobson and Brewer instruments (top and bottom), as a function of the satellite solar zenith angle at the ground pixel.

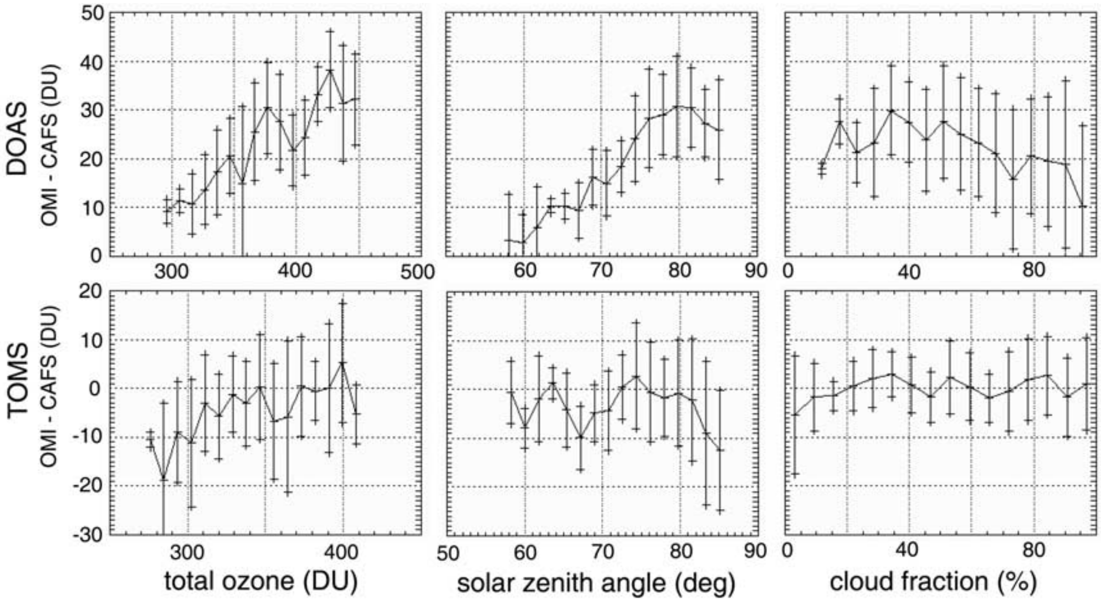

Figure 8. The OMI-CAFS total column ozone difference plotted as a function of OMI ozone (left), solar zenith angle (center) and cloud fraction (right). Data averaged from all Polar AVE high-latitude flights. Upper and lower rows depict results using OMI DOAS and OMI TOMS, respectively.

0.79% ± 1.5%. OMI-DOAS comparisons with Brewer observations indicate that at larger solar zenith angle OMI-DOAS overestimates total ozone column by 3% to 5%. This pattern is more pronounced in the Dobson comparisons. Considering that large solar zenith angles usually correspond to winter conditions, this dependence is probably associated with the seasonal dependence seen in Figure 6. OMI-TOMS comparisons do not show a significant solar zenith angle dependence (Figure 4).

5. Validation Against Campaign Data

[30] In addition to validation against the ground network, OMI ozone has been validated using data from aircraft campaigns and from a ground campaign designed to establish the accuracy of ozone retrievals at high latitudes. A series of aircraft flights specifically to validate Aura were collectively known as the Aura Validation Experiment (AVE) flights. The SAUNA campaign in northern Finland was held in March 2006 to establish the accuracy of ground-based instruments (Brewer and Dobson) and satellite instruments under conditions of high ozone and large solar zenith angles.

5.1. Aircraft Validation

[31] To date there have been four AVE validation campaigns. During the AVE campaigns that took place in October/November of 2004 and in June of 2005 the NASA WB-57 aircraft was flown from a base in Houston, Texas to validate midlatitude ozone retrievals. In January/February 2005 an AVE campaign that focused on winter polar validation was flown out of Portsmouth, New Hampshire, using the NASA DC-8 aircraft. A tropical AVE Campaign was held in January/February of 2006 flying the WB-57 aircraft from San Jose Airport, Costa Rica. Each NASA aircraft carried a suite of in situ sampling and remote sensing instrumentation. Ozone lidars, both up-looking and down-looking, were flown only on the DC-8.

[32] For the purpose of OMI validation, measurements by the CCD Actinic Flux Spectrometer (CAFS) instrument [*Shetter et al.*, 2003] have proven to be very useful. The CAFS instruments are designed to measure spectrally resolved downwelling or upwelling actinic flux, but the measurements can also be used to derive total column ozone above the aircraft. During the AVE campaigns the wavelength range was limited to 280 nm to 400 nm with an optical filter to improve the stray light rejection of the spectrometer and to enhance the UV short wavelength measurements. The CAFS measurement and its comparison with OMI are described in detail by *Kroon et al.* [2008a] elsewhere in this publication. A brief summary of their results is given here.

[33] CAFS has been flown on both the WB-57 and the DC-8. Along the flight track the observations by CAFS are compared to the average of OMI observations within a specified distance from the geographical location of the aircraft. These colocated CAFS and OMI measurements are subsequently analyzed for column ozone differences as a function of various parameters relevant to the campaign, such as aircraft altitude, tropospheric ozone climatology and latitude, and parameters relevant to OMI retrievals such as cloud fraction, solar zenith angle, and latitude. Since CAFS measures the ozone column above the aircraft while OMI measures total column to the ground, comparison requires that a below-aircraft amount be added to CAFS. They find that the TOMS 4D V8 climatology [*McPeters et al.*, 2007] performs well for estimating the ozone column below the aircraft altitude. During DC-8 flights the down-looking ozone lidar allows them to verify that the residual error from using climatology for this purpose usually is at the 1% level.

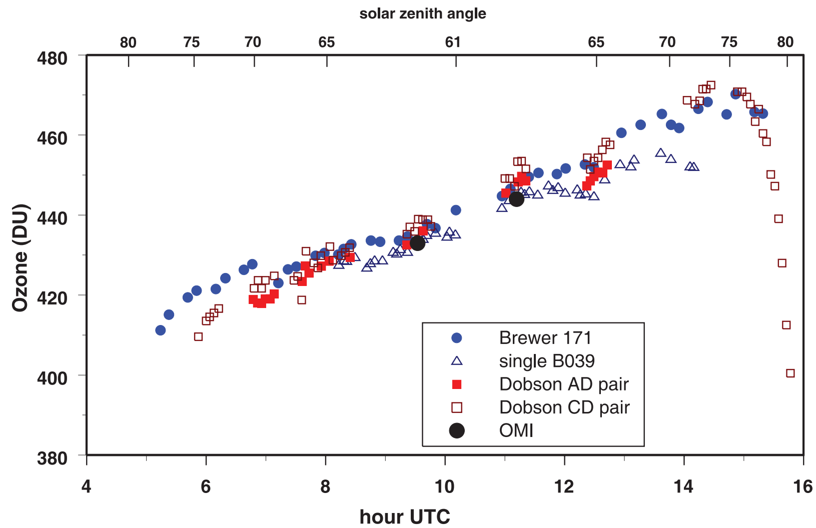

Figure 9. Preliminary comparisons from one day during the SAUNA campaign, 5 April 2006. Comparison for Dobson AD observations, Dobson CD, single Brewer (B39), and double Brewer (B171). Two OMI overpass observations are also shown.

[34] As an example Figure 8 shows the OMI and CAFS data comparisons as gathered for the entire Polar-AVE campaign as a function of various atmospheric parameters. Plotting the total ozone column difference against OMI total ozone column, the OMI ground pixel solar zenith angle, and OMI cloud fractions helps identify uncertainties associated with the satellite retrieval algorithms. CAFS observations were made during eight Polar-AVE flights collocating with 21 Aura-OMI orbits. Temporal collocation between satellite and aircraft measurements is restricted to within ±90 min. For each analysis shown in Figure 8, the vertical lines represent the standard deviation of data points binned into 16 subgroups, while horizontal lines connect mean offsets calculated for each subgroup.

[35] The average difference between OMI DOAS and ~14,000 independent CAFS total ozone column estimates during the Polar AVE campaign is +5.9% with a standard deviation of 3.3%. The rather high average difference is partly caused by the solar zenith angle dependence of the DOAS satellite retrieval errors, shown in the center panel of Figure 8. These flights were mostly at high latitudes and high solar zenith angles. The average difference between OMI TOMS and CAFS total ozone column estimates averages to only −0.1% with a standard deviation of 2.5%. Figure 8 confirms that the OMI TOMS total ozone column data shows no significant dependence on selected atmospheric parameters, whereas the OMI DOAS has a bias at these latitudes that increases with solar zenith angles.

[36] A similar comparison during the Houston and Costa Rica AVE campaigns shows much better average agreement for OMI-DOAS. The average difference between OMI-DOAS and CAFS total ozone column estimates averages −0.7% with a standard deviation of 3.3%, while the OMI-TOMS difference averages −0.2% with a standard deviation of 3.0%. While the average agreement during the mid to low latitude flights appears to be excellent, both OMI-TOMS and OMI-DOAS have significant differences from CAFS depending on ozone amount and cloud fraction. This would be expected because there are uncertainties in both the OMI and CAFS retrievals under certain conditions.

[37] As shown by *Kroon et al.* [2008a], results of the aircraft validation are consistent with the conclusions drawn from ground validation. The results indicate a clear need for improvement of the OMI DOAS total ozone retrieval toward reducing the solar zenith angle dependence. Initial processing using the OMI-DOAS data set collection 3 algorithm (shown in the work of *Kroon et al.* [2008b]) corrects much of the solar zenith angle dependence. The OMI TOMS total column ozone product is shown to be of high quality overall.

5.2. SAUNA Comparison

[38] Comparisons of TOMS ozone with ground data [*McPeters and Labow*, 1996] revealed a discrepancy that increased at high ozone amounts. Further research showed that the difference was a function of optical path, a combination of high ozone and high slant path. In March/April of 2006 the SAUNA campaign was held in Sodankyla, Finland to establish the relative accuracy of ground-based instruments and the OMI instrument on Aura. The campaign was held in Sodankyla, located at 68.4°N, 26.6°E, because one typically sees ozone amounts between 400 and 500 DU there each spring. The main purpose of the campaign was to establish the accuracy of the ground-based instruments under conditions of high ozone and large solar zenith angles so that the ground network could then be used for long-term validation of the satellite instruments.

[39] A detailed report on the SAUNA campaign showing the relative errors of the different ground-based instruments is in preparation, so detailed results are not yet available. Figure 9 shows ozone measurements from Dobson and Brewer instruments along with two OMI overpasses throughout one day. Data show that both Dobson (CD pair) and single Brewer observations are in error at very large optical path. Another preliminary conclusion is that, though it is not possible to do a statistically significant satellite

intercomparison in such a short ground comparison, the OMI-TOMS ozone product during the campaign agreed well with the double Brewer ozone with no indication of increasing error at high ozone amounts.

6. Conclusions and Discussion

[40] On the basis of more than 2 years of OMI data we conclude that OMI-TOMS total column ozone compares very well with ozone measurements from the ground-based network of Dobson and Brewer instruments. Comparison with an average of 76 Dobson and Brewer ground stations between 25° and 55°N, shows that the OMI-TOMS total column ozone averages 0.4% higher than the station average. A similar comparison showed that the OMI-DOAS total column ozone had a 1.1% offset but with a seasonal variation of ±2%. No significant dependence on solar zenith angle or on total column ozone column was found for OMI-TOMS, but the OMI-DOAS solar zenith angle dependence can reach +5% by 75°. A collection 3 OMI-DOAS algorithm now in testing corrects much of the solar zenith angle dependence seen in the current processing (see *Kroon et al.* [2008b]).

[41] Comparing the airborne observations by the CAFS instrument with OMI during four aircraft validation campaigns using the NASA DC-8 and WB-57 aircraft showed good agreement over a broad range of latitude and viewing conditions but significant differences in the OMI-DOAS retrievals at high solar zenith angles. The average difference between OMI-TOMS and CAFS total ozone column estimates was −3.3 DU with a standard deviation of 9.4 DU. The average difference between OMI-DOAS and CAFS total ozone column estimates was +26 DU during high latitude flights with a standard deviation of 9 DU. The large offset was mainly due to solar zenith angle dependence. During low-latitude and midlatitude flights the OMI-TOMS and OMI-DOAS offsets were only −0.2% and −0.7%, respectively, with standard deviations of 3.0% and 3.3%.

[42] Satellite-to-satellite comparisons are not addressed in this paper since that work is still in progress. But the total column ozone from the Tropospheric Emission Spectrometer (TES) on Aura has been compared to OMI by *Osterman et al.* [2008] who find that TES is biased high by 8–15 DU but with "considerable variability" in the bias with latitude.

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