Validation of OMI-TOMS and OMI-DOAS total ozone column using five Brewer spectroradiometers at the Iberian peninsula

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[1] This article focuses on the comparison of the total ozone column data from the Ozone Monitoring Instrument (OMI) flying aboard the NASA EOS-Aura satellite platform with ground-based measurement recorded by Brewer spectroradiometers located at five Spanish remote sensing ground stations between January 2005 and December 2007. The satellite data are derived from two algorithms: OMI Total Ozone Mapping Spectrometer (OMI-TOMS) and OMI Differential Optical Absorption Spectroscopy (OMI-DOAS). The largest relative differences between these OMI total ozone column estimates reach 5% with a significant seasonal dependence. The agreement between OMI ozone data and Brewer measurements is excellent. Total ozone columns from OMI-TOMS are on average a mere 2.0% lower than Brewer data. For OMI-DOAS data the bias is a mere 1.4%. However, the relative difference between OMI-TOMS and Brewer measurements shows a notably lower seasonal dependence and variability than the differences between OMI-DOAS and ground-based data. For both OMI ozone data products these relative differences show significant dependence on the satellite ground pixel solar zenith angle for cloud-free cases as well as for cloudy conditions. However, the OMI ozone data products are shown to reveal opposite behavior with respect to the two antagonistic sky conditions. No significant dependency of the ground-based to satellite-based differences with respect to the satellite cross-track position is seen for either OMI retrieval algorithm.

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1. Introduction

[2] A continuous validation effort of satellite instrument data by the observations made with well-calibrated and well-maintained ground-based instruments is mandatory in order to assess the quality and accuracy of satellite data and to clarify local to regional specific sources of uncertainties. Such ground-based instruments requiring repetitious and careful instrumental calibration may provide the appropriate high-quality ozone measurements for such comparisons and the consequent satellite instrument performance characterization.

[3] The Ozone Monitoring Instrument (OMI) [*Levelt et al.*, 2006] flying aboard the NASA EOS-Aura satellite platform continues the global total ozone column data recorded established by the NASA Total Ozone Mapping Spectrometer (TOMS) series of satellite instrument since 1978. Over the last decade, TOMS ozone data have been extensively compared with ground-based measurements mostly obtained using Dobson and Brewer spectroradiometers [*McPeters and Labow*, 1996; *Masserot et al.*, 2002; *Bramstedt et al.*, 2003; *Vanicek*, 2006]. Two retrieval algorithms, OMI-TOMS and OMI Differential Optical Absorption Spectroscopy (OMI-DOAS), are currently used to produce OMI total ozone column. The first exhaustive validation of OMI ozone data against Dobson and Brewer reference data can be found in the work of *Balis et al.* [2007]. This validation showed an excellent agreement, better than 1% for OMI-TOMS data and better than 2% for OMI-DOAS data, where satellite ozone data were compared with respect to the ground-based measurements from 18 reference instruments located at stations in Europe, Canada, Japan, and United States, and in the Antarctic. *McPeters et al.* [2008] compared OMI total ozone column data with an ensemble of 76 Dobson and Brewer instruments located in the Northern Hemisphere, showing that the OMI-TOMS (OMI-DOAS) total ozone column averages 0.4% (1.1%) higher than the station average. Here the

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systematic differences between the Dobson and Brewer systems as revealed in the work of *Balis et al.* [2007] partially cancel leading to more advantageous results. In addition, several studies have recently compared OMI and ground-based total ozone column data for specific locations. Among them, *Buchard et al.* [2008] compared total ozone column measurements performed by ground-based instruments located at two French sites with OMI-TOMS and OMI-DOAS ozone data, showing that the relative differences were mostly within 5% and 7%, respectively. *Ialongo et al.* [2008] compared OMI ozone using ground-based high-quality data at Rome (Italy), also showing good agreement for all sky conditions with a bias of −1.8% for OMI-TOMS and −0.7% for OMI-DOAS.

[4] The main objective of this paper is to compare total ozone column data provided by both OMI satellite retrieval algorithms with spatially and temporally collocated ground-based measurements from five well-calibrated and well-maintained [*Redondas et al.*, 2002] Brewer spectroradiometers in the Iberian Peninsula. In our analyses we use the data recorded between January 2005 and December 2007. Although global-scale validation exercises have been carried out before [e.g., *Balis et al.*, 2007; *McPeters et al.*, 2008], the present work can be considered as complementary since the OMI ozone data over the Iberian Peninsula have not been evaluated before in detail while this is a region of relevant interest for Europe. Furthermore, in our work the new version of the OMI data set, named collection 3, has been used. The aforementioned publications have all worked with the previous data version that by that work was shown to contain various shortcomings now solved in collection 3. In this sense, a coherent calibration and revised dark current correction are used in collection 3. Finally, the total ozone column records through the Direct Sunlight (DS) Brewer measurements can potentially maintain a precision of 1% over long time intervals whenever the instruments are properly calibrated and regularly maintained [*World Meteorological Organization*, 1996]. Because of their history of good maintenance, the Spanish Brewer spectroradiometers have excellent accuracy [*Labajo et al.*, 2004]. Thus, this network was successfully used to perform exhaustive validation exercises of satellite total ozone data derived from the Global Ozone Measurements Experiment (GOME) onboard ESA's Second European Sensing Satellite (ERS-2) for the period 1995–2005 [*Antón et al.*, 2008], and derived from the GOME-2 instrument onboard Meteorological Operational satellite program (MetOp-A) for the period 2007–2008 [*Antón et al.*, 2009].

[5] The paper is organized as follows. The satellite and ground-based measurements are described in sections 2.1 and 2.2, respectively. Section 2.3 introduces the methodology. The results and discussion are presented in section 3 and, finally, section 4 summarizes the main conclusions.

2. Data and Methodology

2.1. Satellite Measurements

[6] The OMI satellite instrument is a contribution of the Netherlands's Agency for Aerospace Programs (NIVR) in collaboration with the Finnish Meteorological Institute (FMI) to the NASA EOS-Aura satellite platform launched in July 2004. The OMI ment is a nadir-viewing wide-swath UV/VIS hyperspectral spectrometer measuring solar light reflected and backscattered from the Earth's atmosphere and surface in the wavelength range from 270 nm to 500 nm with a spectral resolution of 0.45 nm in the ultraviolet and 0.63 nm in the visible. The OMI total ozone column data used in this work were obtained from the OMI-TOMS and OMI-DOAS algorithms.

[7] OMI-TOMS algorithm is based on the long-standing NASA TOMS V8 retrieval algorithm [*Bhartia and Wellemeyer*, 2002], which has been used to process data from a series of four TOMS instruments flown since November 1978. This algorithm uses measurements at four discrete 1 nm wide wavelength bands centered at 313, 318, 331 and 360 nm, and it applies an empirical correction to remove errors due mainly to aerosols and clouds. In addition, the OMI-TOMS algorithm uses a cloud height climatology that was derived using infrared satellite data.

[8] OMI-DOAS algorithm developed at Royal Dutch Meteorological Institute (KNMI) [*Veefkind et al.*, 2006] is based on the Differential Optical Absorption Spectroscopy (DOAS) technique. The algorithm uses ∼25 OMI measurements in the wavelength range 331.1 nm to 336.6 nm, and it takes advantage of the hyperspectral feature of the OMI instrument to reduce errors due to aerosols, clouds, surface effects, and sulfur dioxide from volcanic eruptions. The OMI-DOAS algorithm also has improved correction for cloud height, using cloud information derived from OMI measurements in the 470 nm O_2-O_2 absorption band.

[9] A detailed analysis of the similarities and differences between OMI-TOMS and OMI-DOAS total ozone column data can be found in the recent work of *Kroon et al.* [2008]. Here both OMI ozone products are obtained in the new version of the OMI level 1 (radiance and irradiance) and level 2 (atmospheric data products) data set named collection 3. The main improvements with respect to the previous data collection (collection 2) are (1) sophisticated and optimized radiometric calibration, (2) improved dark current corrections, and (3) improved stray light corrections.

[10] Please visit the NASA DISC at http://disc.gsfc.nasa.gov/Aura/OMI/ for EOS Aura OMI level 2 orbit data. Please visit the Aura Validation data Center at http://avdc.gsfc.nasa.gov for EOS-Aura OMI station overpass data. Please consult the OMI README files for the latest OMI data product information.

2.2. Ground-Based Data

[11] The five Brewer spectroradiometers employed in our study belong to the Spanish Brewer spectrophotometer network which is operated by the Spanish Agency of Meteorology (AEMet). The ground-based stations are from north to south: Coruña (43.33°N, 8.42°W), Zaragoza (41.01°N, 1.01°W), Madrid (40.45°N, 3.72°W), Murcia (38.03°N, 1.17°W) and El Arenosillo (37.06°N, 6.44°W). Periodic checks and tests (daily, weekly and monthly) are performed to guarantee the accuracy and quality of the total ozone column measurements. In addition, the absolute calibration was established by intercomparison with the traveling reference Brewer 017 from the International Ozone Services (IOS) and the Brewer 150 from the Regional Brewer Calibration Centre–Europe (RBCC-E) every 2 years. In this way the ozone calibration is traceable to the triad of reference Brewer spectrophotometers maintained by MSC

Table 1. Parameters Obtained in the Correlation Analysis Between OMI-TOMS Data and Brewer Measurements as Gathered Over the Iberian Peninsula During Three Consecutive Years, 2005–2007[a]

	N	Slope	R^2	RMSE (%)	MBE (%)	MABE (%)
Madrid	693	0.99 ± 0.01	0.98	1.53	−2.4 ± 1.5	2.5 ± 1.3
	(693)	(0.95 ± 0.01)	(0.96)	(2.27)	(−1.2 ± 2.3)	(2.1 ± 1.6)
Murcia	912	0.97 ± 0.01	0.98	1.51	−2.1 ± 1.5	2.2 ± 1.3
	(912)	(0.94 ± 0.01)	(0.95)	(2.36)	(−1.2 ± 2.4)	(2.4 ± 1.8)
Coruña	801	0.96 ± 0.01	0.96	2.32	−1.8 ± 2.4	2.3 ± 1.9
	(801)	(0.97 ± 0.01)	(0.94)	(2.73)	(−1.5 ± 2.7)	(2.3 ± 2.1)
Zaragoza	916	0.99 ± 0.01	0.97	1.91	−2.5 ± 1.9	2.7 ± 1.6
	(916)	(0.95 ± 0.01)	(0.94)	(2.72)	(−1.6 ± 2.7)	(2.4 ± 2.1)
Arenosillo	975	0.99 ± 0.01	0.98	1.53	−1.5 ± 1.6	1.8 ± 1.2
	(975)	(0.97 ± 0.01)	(0.95)	(2.13)	(−0.8 ± 2.1)	(1.7 ± 1.5)
Iberian Peninsula	4140	0.99 ± 0.01	0.97	1.83	−2.0 ± 1.8	2.2 ± 1.5
	(4140)	(0.96 ± 0.01)	(0.95)	(2.40)	(−1.4 ± 2.4)	(2.1 ± 1.8)

[a]Results for the OMI-DOAS correlation are shown in parentheses. The parameters are the following: the number of data, N; the slope of the regression, Slope; the coefficients of correlation, R^2; the root mean square errors, RMSE; the mean bias error, MBE; and the mean absolute bias error, MABE.

(Meteorological Service of Canada) at Toronto [*Fioletov et al.*, 2005]. When Brewer spectrophotometers are properly calibrated and regularly maintained as is the case of the Spanish Brewer Network, the total ozone column records obtained through DS measurements can potentially maintain an estimated accuracy of 1% over long time intervals. The five intercomparisons carried out at El Arenosillo station with the reference traveling standard Brewer instrument confirm the reliability of Spanish Brewer calibration [*Redondas et al.*, 2002; *Labajo et al.*, 2004]. A detailed description of the methodology used by the Brewer spectrophotometers to measure the total ozone column amount from direct sunlight can be found in the works of *Kerr et al.* [1984] and *Kerr* [2002].

2.3. Methodology

[12] In this work, daily averages of the ground-based total ozone column data obtained for solar zenith angles lower than 75 degrees are compared with satellite ozone values obtained during overpass. The use of daily averaged Brewer data instead of, for example, hourly averaged Brewer data centered around the OMI overpass is feasible owing to the well known long-term chemical stability of stratospheric ozone. In this work, the most accurate Brewer total ozone column data obtained through DS measurements are used and these measurements are exclusively recorded during cloud-free conditions. There are days without DS Brewer measurements around the OMI overpass time caused by the local presence of clouds whereas DS measurements are performed on other hours of the day. Therefore, we use the daily averaged data for obtaining the highest number of Brewer-OMI data pairs. However, daily averages could increase the noise (spread) of the comparisons between ground-based and satellite total ozone column data due to possible daily fluctuations in tropospheric ozone which may constitute of 6–20% of the total ozone column [*Kourtidis et al.*, 2002].

[13] For each day of Brewer observations the single OMI ground pixel most closely collocated with the location of the Brewer station is selected as the best match. Thus in this work, the distance between the satellite pixel center and the ground-based location is always smaller than 90 km.

[14] Time series of both satellite and ground-based total ozone column data extend from January 2005 to December 2007. Table 1 shows the number of pairs (N) of Brewer-OMI data sorted by location.

[15] In addition to the analysis of individual stations, this paper focuses on the comparison between Brewer and OMI data using the Spanish Brewer network as a whole. This data set is named the "Iberian Peninsula." *McPeters et al.* [2008] showed that the use of the network as a whole in intercomparison exercises between satellite and ground-based data provide more stable results than the station-by-station analysis. Local environment variables such as vegetation, elevation, albedo, aerosols, clouds and local meteorological parameters will be averaged out when combining data to one daily comparison. Also, the "Iberian Peninsula" data set covers more than 6° in latitude, thereby averaging stratospheric ozone layer variations over a comparable spatial scale.

[16] A linear regression analysis was performed for each station location individually and for the "Iberian Peninsula" data set. Regression coefficients, coefficients of correlation (R^2) and the root mean square errors (RMSE) were obtained. In addition the mean bias error (MBE) and the mean absolute bias error (MABE) between OMI retrievals and Brewer measurements were calculated for each data set. These parameters are obtained by the following expression:

$$\mathrm{MBE} = \frac{100}{N}\sum_{i=1}^{N}\frac{\mathrm{OMI}_i - \mathrm{Brewer}_i}{\mathrm{Brewer}_i} \qquad (1)$$

$$\mathrm{MABE} = \frac{100}{N}\sum_{i=1}^{N}\frac{|\mathrm{OMI}_i - \mathrm{Brewer}_i|}{\mathrm{Brewer}_i}. \qquad (2)$$

The uncertainty of MBE and MABE is characterized by the standard deviation.

3. Results and Discussion

[17] To investigate the proportionality and similarity of the ground-based and satellite-based observations, the Brewer and OMI total ozone column data are fitted using

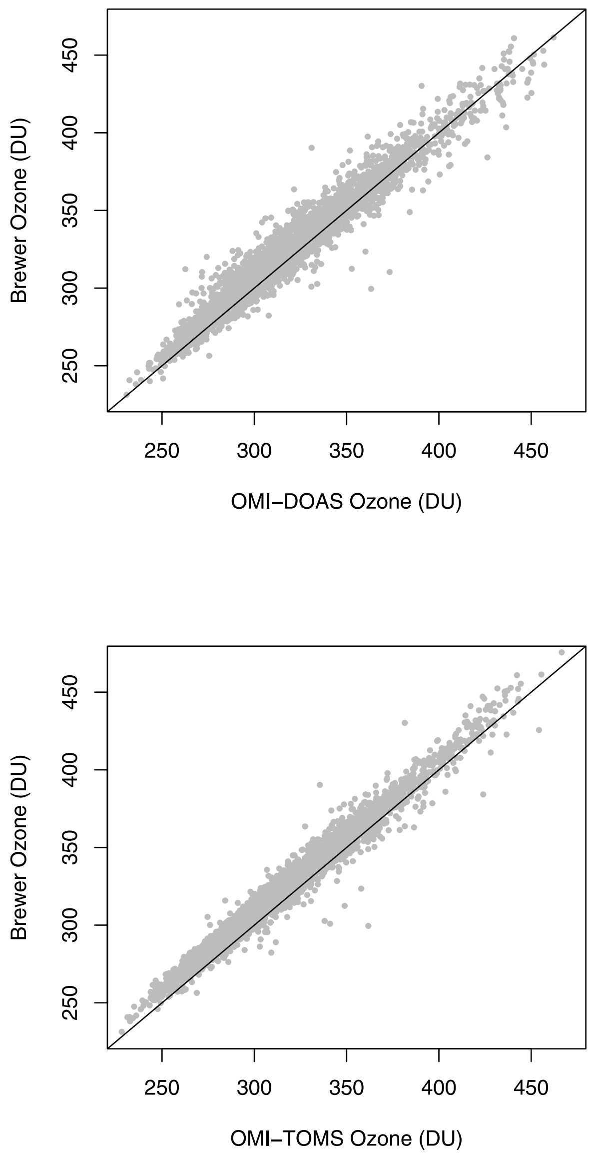

Figure 1. Correlation between Brewer and OMI total ozone column observations gathered over the Iberian Peninsula during three consecutive years (2005–2007). (top) OMI-DOAS versus Brewer and (bottom) OMI-TOMS versus Brewer. The solid line represents the unit slope to which the data comply.

a linear regression analysis. Statistical parameters obtained are shown in Table 1. The correlation between OMI ozone observations and Brewer measurements is significantly high for all stations and for the "Iberian Peninsula" data set. The R^2 values higher than 0.94 are indicative of the ground-based and satellite-based data sets showing similar behavior under the various atmospheric circumstances sampled. The statistical analysis renders slopes very close to unity. The two scatterplots presented in Figure 1 between satellite and ground-based data for the "Iberian Peninsula" data set reveal a high degree of proportionality. The plots indicate that both OMI-TOMS and OMI-DOAS ozone observations slightly underestimate the ground-based total ozone column data. This behavior is corroborated by the negative sign of the MBE parameters for all locations. The underestimation for the "Iberian Peninsula" data set is (2.0 ± 1.8)% for OMI-TOMS and (1.4 ± 2.4)% for OMI-DOAS. It can be seen that the RMSE values and uncertainty of MBE and MABE parameters are significantly lower for OMI-TOMS data than the OMI-DOAS data in all stations. A plausible explanation for this observation is found in the wavelengths used by the respective satellite algorithms which make the algorithms to respond to instrumental errors very differently. OMI-TOMS uses shorter wavelengths where the ozone absorption cross sections are larger hence OMI-TOMS works with advantageously higher signal-to-noise ratio signals than OMI-DOAS. This makes OMI-DOAS relatively more sensitive to the OMI CCD detector dark current correction resulting in striping features hence explaining the higher spread in the statistics. On the other hand, the MABE parameter is lower than 2.7% in all locations, with a value of this parameter for the "Iberian Peninsula" data set of (2.2 ± 1.5)% and (2.1 ± 1.8)% for OMI-TOMS and OMI-DOAS, respectively. Please note that the MBE and MABE values present similar absolute values. This reveals the presence of a bias with a small statistical spread. The uncertainty of MABE parameters is lower than 2.1%, indicating the statistical significance of the reported values. *Bhartia and Wellemeyer* [2002] reported that the relative uncertainty of OMI-TOMS ozone data is around 2% for solar zenith angles lower than 70 degrees. In addition, according to *Veefkind et al.* [2006], the relative uncertainty on this OMI-DOAS total ozone column is lower than 3% for all conditions. Therefore, the results of the intercomparison of OMI instrument with Spanish Brewer spectroradiometers indicates that the satellite ozone observations agree very well with the ground-based data. When comparing the MBE values of each station, it is noted that the station-to-station biases is lower than 1.1% for OMI-TOMS data and than 0.8% for OMI-DOAS data. This result shows that the reliability of the Spanish Brewer Network is high.

[18] The linear regression analysis between satellite and ground-based total ozone column data is also made for each month. The results show a notable seasonal dependence with a fair agreement during summer, and an excellent agreement during winter. The analysis between OMI-TOMS and Brewer total ozone column data reveals the correlation coefficients to vary between 0.83 in June and 0.98 in January for the "Iberian Peninsula" data set. The analysis between OMI-DOAS and Brewer data shows this coefficient to vary between 0.70 in June and 0.97 in January. This seasonal dependence may be due to the fact that dynamic total ozone range sampled in winter is much lager than in summer, affecting to the values of the coefficients of correlation but not to RMSE values which present similar values during summer and winter months. Other complementary reason to explain this seasonal dependence could be related to the fact that daily averaged Brewer data are averaged over all possible diurnal fluctuations in the total ozone column caused mainly by the variability of the tropospheric ozone layer. The OMI satellite instrument takes a 2-s snapshot above the location of the specific ground station. Thus, it can pick up a local and temporal fluctuation that the Brewer could also see when not averaged over a long period of time. Photochemical and transport processes produce a high diurnal variability of the tropo-

Table 2. Parameters Obtained in the Monthly Correlation Analysis Between OMI-TOMS Data and OMI-DOAS Data for the "Iberian Peninsula" Data Set During Three Consecutive Years, 2005–2007[a]

	N	Slope	R^2	RMSE (%)	MBE (%)	MABE (%)
January	333	1.03 ± 0.01	0.98	1.81	−2.3 ± 5.8	2.5 ± 1.6
February	328	1.01 ± 0.01	0.97	1.90	−1.3 ± 6.5	1.9 ± 1.3
March	374	1.03 ± 0.01	0.97	1.94	−1.0 ± 6.6	1.8 ± 1.3
April	364	1.00 ± 0.01	0.94	2.30	−0.4 ± 8.3	1.7 ± 1.5
May	370	0.95 ± 0.02	0.90	2.24	0.0 ± 7.7	1.7 ± 1.5
June	366	0.93 ± 0.03	0.75	2.59	0.4 ± 8.2	1.8 ± 1.9
July	377	0.93 ± 0.02	0.81	2.11	0.8 ± 6.5	1.5 ± 1.7
August	362	0.98 ± 0.02	0.83	1.83	1.0 ± 5.5	1.5 ± 1.4
September	279	0.97 ± 0.03	0.81	2.21	0.6 ± 6.5	1.6 ± 1.7
October	370	0.96 ± 0.02	0.87	1.91	−0.4 ± 5.4	1.5 ± 1.2
November	342	1.02 ± 0.01	0.96	1.66	−1.9 ± 4.7	2.1 ± 1.4
December	321	1.03 ± 0.01	0.96	1.83	−2.0 ± 5.9	2.1 ± 1.6

[a]The parameters are the following: the number of data, *N*; the slope of the regression, Slope; the coefficients of correlation, R^2; the root mean square errors, RMSE; the mean bias error, MBE; and the mean absolute bias error, MABE.

spheric ozone in summer time over the Iberian Peninsula [*Gimeno et al.*, 1999; *Zurita and Castro*, 1983] which could reduce the representativeness of the daily averaged Brewer data for the snapshot OMI data.

[19] To analyze the potential influence of the differences between the two OMI ozone products on the satellite to ground-based comparison, both OMI products were compared for the "Iberian Peninsula" data set. A detailed analysis of correlation between OMI-TOMS and OMI-DOAS total ozone column data is performed for each month. Table 2 shows the results of this monthly statistical analysis, indicating that the correlation presents a notable seasonal dependence with a fair agreement during summer, and an excellent agreement during winter. The correlation coefficients vary between 0.75 in June and 0.98 in January. In addition, the RMSE parameter changes between 1.8% (5.8 DU) for January and 2.6% (8.1 DU) for June, indicating that the agreement between both OMI total ozone column products is significantly higher in winter than in summer. The parameters MBE and MABE are also shown in Table 2 for each month. It is observable that the parameter MBE presents positive values between June and September. Thus, the total ozone data provided by the OMI-TOMS algorithm overestimates, on average, the OMI-DOAS total ozone data during summer. The mean bias absolute error is smaller than 2.5% for all months, showing that the differences between the total ozone observations obtained from both OMI algorithms are reduced. Figure 2 shows the scatterplots between OMI-TOMS and OMI-DOAS total ozone column data for two different time periods (January and June) for the "Iberian Peninsula" data set. Please note that the dynamic range sampled in winter is much lager than in summer while at the same time the spread around the 1:1 line is bigger in summer than in winter. This observation supports the observed statistical behavior of the comparison from the mathematical point. The larger winter dynamic range over the Iberian Peninsula may be generally explained by two dynamical processes: horizontal isentropic advection from regions with different climatological ozone mixing ratios and/or (local) adiabatic vertical displacement of isentropes [*Koch et al.*, 2005; *Wohltmann et al.*, 2005; *Antón et al.*, 2007]. The larger spread in summer may be explained by the stronger diurnal variability of the tropospheric ozone layer.

[20] It is known that in the middle latitudes and hence over the Iberian Peninsula the total ozone column presents a strong seasonal variability mainly caused by dynamical factors such as the Dobson-Brewer circulation [*Salby and Callaghan*, 1993; *Nikulin and Karpechko*, 2005]. This fact is clearly shown in Figure 3 (top) which presents the time series of the OMI total ozone column data retrieved by both satellite algorithms shown as the running average over ten days of the daily mean OMI data at the Iberian Peninsula. In addition, here the excellent agreement between OMI-TOMS and OMI-DOAS total ozone column data over an appreciable dynamic range can be observed. The daily mean differences in the total ozone column derived from the two OMI algorithms vary from 0 to 18 DU (0–5%). On average, the OMI-DOAS reports 1.7 DU (0.5%) more than OMI-TOMS, with one standard deviation of ±7.3 DU (±2.3%). The time series of the relative and absolute differences between both OMI total ozone column products for the "Iberian Peninsula" data set is shown in Figure 3 (bottom). This plot is obtained using the running average over 10 days of the daily mean differences with a maximum of five values per day, i.e., collocated OMI overpasses over five individual stations. A strong seasonal pattern can be observed with a notable overestimation (underestimation) of the OMI-DOAS values during summer (winter) relative to OMI-TOMS data. This observation may originate from details of both algorithmic approaches as described by *Kroon et al.* [2008] where effects may vary differently with season. In the presence of clouds the OMI ozone data products come up with different cloud height and radiative cloud fraction estimates originating from different algorithmic approaches leading to different tropospheric "ghost columns" added. This effect may vary between summer and winter. Furthermore, surface albedos are obtained from different satellite-based climatologies and cloud parameters are estimated from different spectral ranges.

[21] Figure 4 shows the 10-day running average of the daily mean relative differences between satellite and ground-based total ozone column observations for the Iberian Peninsula for two antagonistic sky conditions: cloud-free cases ($CF^{TOMS} = 0$, $CF^{DOAS} < 15\%$) and cloudy cases ($CF^{TOMS} > 0.5$, $CF^{DOAS} > 50\%$). The parameter CF is the effective radiative cloud fraction as obtained from the OMI observations [*Stammes et al.*, 2008]. The OMI-TOMS

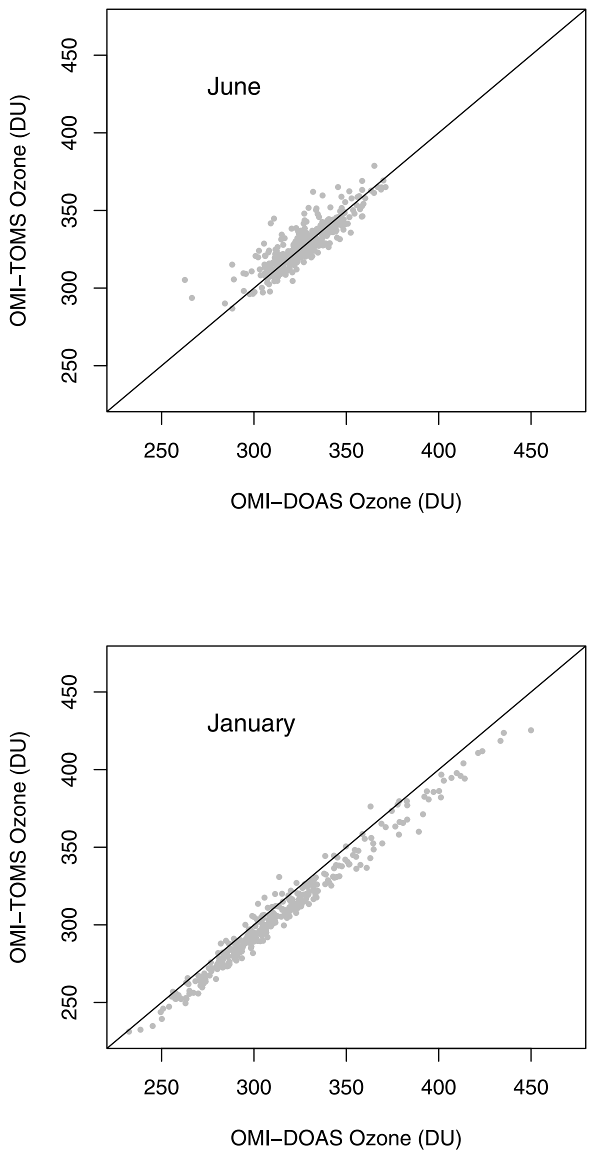

Figure 2. Correlation between OMI-TOMS and OMI-DOAS total ozone column data for (top) June and (bottom) January at the Iberian Peninsula. The solid line represents the unit slope. Note the smaller dynamic range sampled in summer while the spread around the 1:1 line is larger.

data product ingests CF from the rotational Raman algorithm whereas the OMI-DOAS algorithm calculates CF for a comparable spectral window. Both cloud products use a Lambertian cloud model with albedo 0.8. In our work, the percentage of cases selected is about 55% for cloud-free conditions and 16% for cloudy conditions which shows the prevalence of cloudless situations over the Iberian Peninsula. The comparison between OMI-DOAS and Brewer data show a 3–4% amplitude seasonal dependence, with the largest differences occurring in the summer. On the other hand, for OMI-TOMS data, the seasonality is notably smaller as the seasonal amplitude does not exceed 1–1.5%. This higher amplitude for OMI-DOAS-Brewer differences than for OMI-TOMS-Brewer differences may be partially due to the seasonal behavior in the OMI-TOMS–OMI-DOAS differences shown in Figure 3 (bottom). Fundamentally, the observations from ground-based and satellite platforms are different. The optical path they have in common is the incoming solar light “slant” path; however, the satellite also observes the vertical column right above the ground-based station to which the Brewer system is blind. An ozone gradient present between these two observational paths that are dependent on season may very well induce such a seasonal trend.

[22] Figure 4 shows that there is a notable influence of clouds in the differences between ground-based and satellite total ozone column data, mainly for OMI-DOAS algorithm. In order to analyzing in detail this influence, the relative

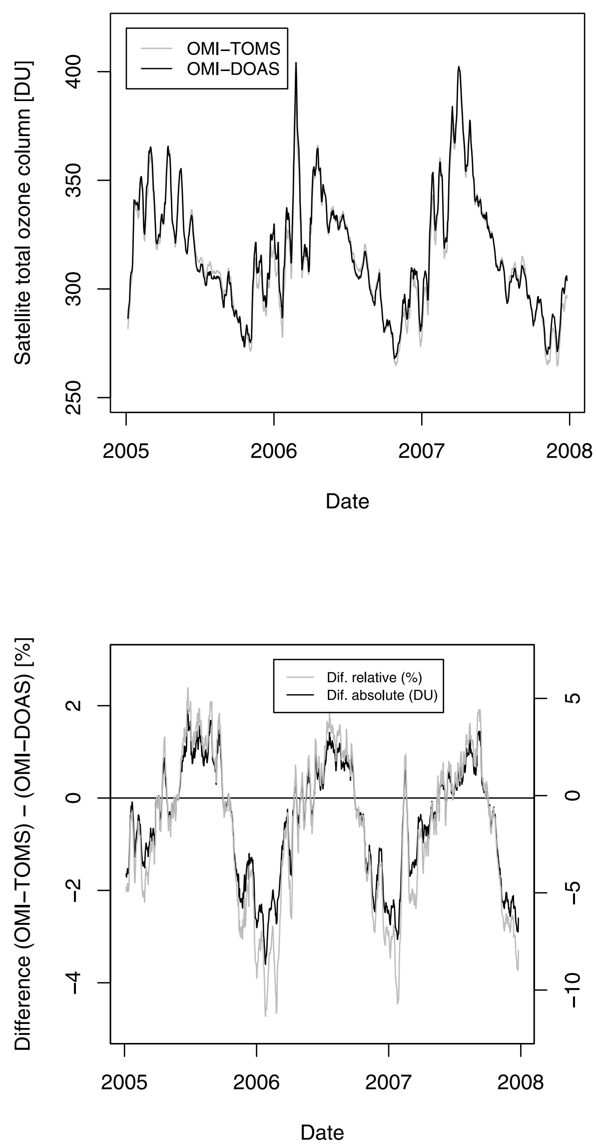

Figure 3. (top) Evolution of the satellite total ozone column data retrieved by OMI-TOMS and OMI-DOAS algorithms shown as the running average over 10 days of the daily mean OMI data at the Iberian Peninsula. (bottom) Evolution of the relative and absolute differences between both OMI total ozone column data shown as the running average over 10 days of the daily mean differences at the Iberian Peninsula.

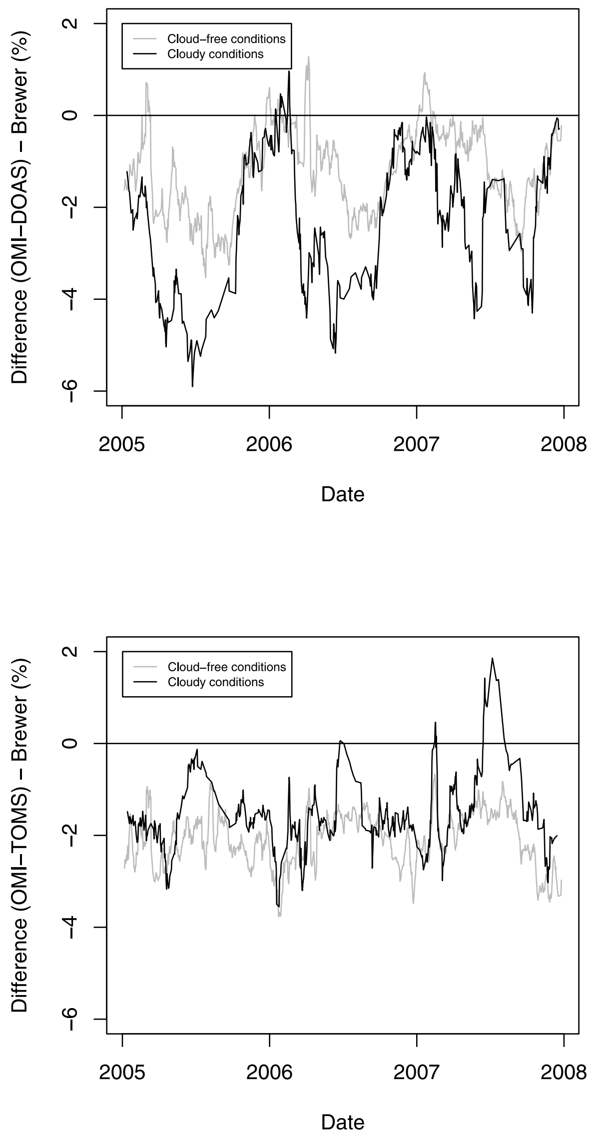

Figure 4. Evolution of the differences between both OMI data and Brewer measurements for cloud-free and cloudy conditions. The plots are obtained using the running average over 10 days of the daily mean relative differences between satellite and ground-based total ozone column observations at the Iberian Peninsula. (bottom) For OMI-TOMS, the number of data points per SZA bin for cloud-free cases and in brackets for cloudy cases varies between 221 (31) for SZA bin centered in 18 (18) degrees and 504 (110) for SZA centered in 25 (53) degrees. (top) For OMI-DOAS, the number of data points varies between 228 (14) data points for SZA bin centered in 18 (18) degrees and 500 (123) for SZA centered in 25 (53) degrees.

differences between satellite total ozone data and ground-based measurements as a function of OMI cloud fraction are shown in Figure 5. The error bars represent the standard deviations which are only plotted for cloud-free cases in the interest of clarity. It can be appreciated that while the cloud-dependent error of OMI-DOAS presents a smooth, negative dependence with the lues (the differences change between −1% for smaller CF values and close to −3.5% for higher CF values), OMI-TOMS has no apparent satellite CF dependence. Figure 5 shows the remarkable stability of the OMI-TOMS algorithm even when the satellite cloud fraction get very large.

[23] Next we analyzed the influence of two geometrical parameters such as satellite solar zenith angle (SZA), and satellite cross-track position (CTP) on the OMI-Brewer differences.

[24] *Buchard et al.* [2008] showed a small dependence on SZA of the relative differences between OMI-TOMS ozone data and Brewer measurements for cloud-free cases. *Balis et al.* [2007] also showed no significant dependence on SZA for either comparison. However, a significant and systematic dependence on SZA was found between OMI-DOAS and ground-based measurements where we note that this work was performed with the previous OMI data collection. In addition, *Antón et al.* [2008] showed that it is necessary to analyze the dependence on SZA of the relative differences between satellite and ground-based ozone for cases with different cloudy situations. This is due to fact that the results obtained using all data could be affected by the compensation of cases with opposite sky conditions. Thus, in order to analyze the influence of SZA on the differences between satellite and ground-based total ozone column data, these differences were calculated as function of the SZA for cloud-free cases and cloudy cases. In Figure 6, the mean relative differences between ground-based and OMI total ozone column data generated by OMI-DOAS (Figure 6, top) and OMI-TOMS (Figure 6, bottom) algorithms are compared as a function of the OMI ground pixel SZA. It was seen that for OMI-TOMS the curves follow a similar pattern, showing an increase in underestimation as function of satellite SZA. Thus, the relative differences vary from almost 1.5% for small SZA to 2–3% for large SZA. Moreover, for the whole SZA range, the underestimation

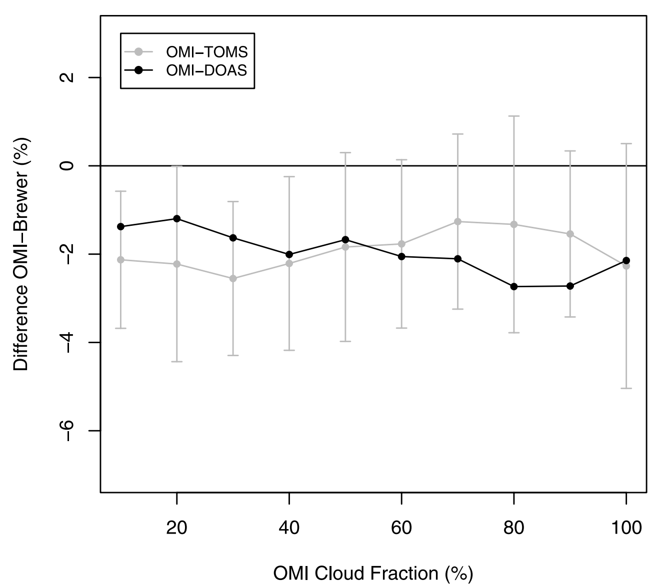

Figure 5. Differences between total ozone column data retrieved by OMI and Brewer total ozone column data as function of OMI cloud fraction (CF).

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