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Comparison of UV irradiances from Aura/Ozone Monitoring Instrument (OMI) with Brewer measurements at El Arenosillo (Spain) – Part 1: Analysis of parameter influence

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Abstract

The main objective of this study is to compare the erythemal UV irradiance (UVER) and spectral UV irradiances (at 305, 310 and 324 nm) from Ozone Monitoring Instrument (OMI) onboard NASA EOS/Aura polar sun-synchronous satellite (launched in July 2004, local equator crossing time 01:45 p.m.) with ground-based measurements from the Brewer spectroradiometer #150 located at El Arenosillo (South of Spain). The analyzed period comprises more than four years, from October 2004 to December 2008. The effects of several factors (clouds, aerosols, ozone and the solar elevation) on OMI-Brewer comparisons were analyzed. The proxies used for each factor were: OMI Lambertian Equivalent Reflectivity (LER) at 360 nm (clouds), the Aerosol Optical Depth (AOD) at 440 nm measured from the ground-based Cimel sun-photometer (http://aeronet.gsfc.nasa.gov), OMI total column ozone, and solar elevation at OMI overpass time.

The comparison for all sky conditions reveals positive biases (OMI higher than Brewer) 12.3% for UVER, 14.2% for UV irradiance at 305 nm, 10.6% for 310 nm and 8.7% for 324 nm. The OMI-Brewer Root Mean Square Error (RMSE) is reduced when cloudy cases are removed from the analysis, (e.g., RMSE ∼20% for all sky conditions and RMSE smaller than 10% for cloud-free conditions). However, the biases remain and even become more significant for the cloud-free cases with respect to all sky conditions. The mentioned overestimation is clearly documented as due to aerosol extinction influence. The differences OMI-Brewer typically decrease with increasing the Solar Zenith Angle (SZA). The seasonal dependence of the OMI-Brewer difference for cloud-free conditions is driven by aerosol climatology.

To account for the aerosol effect, a first evaluation in order to compare with previous TOMS results (Anton et al., 2007) was performed. This comparison shows that the OMI bias is between +14% and +19% for UVER and spectral UV irradiances for moderately-high aerosol load (AOD>0.25). The OMI bias is decreased by a factor of 2 (the typical bias varies from +8% to +12%) under cloud-free and low aerosol load

conditions (AOD<0.1). More detailed analysis of absorbing aerosols influence on OMI bias at our station is presented in a companion paper (Cachorro et al., 2010).

1 Introduction

The study of ultraviolet (UV) solar radiation reaching the Earth‘s surface has achieved a notable interest in the last decades. This is due to concerns related to the well-known ozone depletion (WMO, 2006). Thus, it is of great importance to continue high accuracy UV radiation measurements at different locations. Satellite UV data complement ground-based measurements providing global daily maps with uniform geographical coverage from a single instrument. The continuous validation of satellite UV data with ground-based measurements from well-calibrated and well-maintained instruments is an essential task for assessing the quality and accuracy of satellite data and to identify local to regional specific sources of uncertainty (e.g., Arola et al., 2005; Tanskanen et al., 2007).

Ozone Monitoring Instrument (OMI) (Levelt et al., 2006), launched in July 2004, is the successor to the Total Ozone Mapping Spectrometer (TOMS) instruments. In the last decade, the UV irradiance products from TOMS has been extensively compared with ground measurements mostly using Brewer spectroradiometers (Kalliskota et al., 2000; McKenzie et al., 2001; Chubarova et al., 2002; Subburg et al., 2002; Fioletov et al., 2004; Cede et al., 2004; Meloni et al., 2005; Arola et al., 2005; Kazantzidis et al., 2006). These works revealed that the satellite UV data overestimate the ground-based measurements in many locations. The work of Antón et al. (2007) compared the erythemal UV irradiance (UVER) derived from TOMS with Brewer measurements at El Arenosillo (South Spain) under different sky conditions. This work showed that TOMS overestimates the UVER data by 12% during cloud-free days, and the bias increases with the aerosol load.

The first comprehensive validation of the OMI UV products can be found in Tanskanen et al. (2007), which shows good agreement between OMI-derived daily erythermal doses and the daily doses calculated from the ground-based spectral UV measurements from 18 reference stations in Europe, Canada, Japan, USA and Antarctic. However, for OMI the bias increased up to 50% for sites affected by absorbing aerosols or trace gases. In addition, Buchard et al. (2008) compared the UV irradiance products from OMI with ground-based measurements recorded at two French locations, showing that the bias is less than 15% for clear sky conditions. Ialongo et al. (2008) showed that OMI UV data overestimate ground-based UVER values measured from both Brewer spectroradiometer and YES broadband radiometer (biases about 20%) at Rome (Italy). Weihs et al. (2008) showed that OMI-Brewer differences can reach +50% under overcast conditions during a validation campaign in the region of Vienna (Austria). Kazadzis et al. (2009) compared UV irradiance products from OMI against ground-based Brewer measurements at Thessaloniki (Greece), showing that OMI overestimates UV spectral irradiances by 30%, 17% and 13% for 305 nm, 324 nm, and 380 nm, respectively.

Within this framework, this paper aims to compare UV irradiances derived from OMI (collection 3) with UV irradiances measured by the Brewer spectroradiometer #150 located at El Arenosillo. The period of study extends from October 2004 to December 2008. The effects of clouds and aerosols on the OMI-Brewer UV differences are analyzed in detail. El Arenosillo station is an ideal location for OMI validation studies because of its high number of cloud-free days per year and the moderate frequency of desert dust outbreaks from Africa (Toledano et al., 2007a).

The paper is organized as follows. The ground and satellite-based measurements are described in Sect. 2. Section 3 introduces the methodology. The results and discussion are presented in Sect. 4 and, finally, Sect. 5 summarizes main conclusions.

2 Data

2.1 Satellite observations

The OMI satellite instrument is a contribution of the Netherlands' Agency for Aerospace Programs (NIVR) in collaboration with the Finnish Meteorological Institute (FMI). It is on board the NASA EOS/Aura platform launched in July 2004 (Schoeberl et al., 2006). This remote sensing UV spectrometer continues currently long-term ozone measurements by NASA Total Ozone Mapping Spectrometer (TOMS) instrument which was operative on board of two satellites: Nimbus-7 (1978–1993) and Earth Probe (EP) (1996–2005). The OMI instrument is a nadir viewing spectrometer that measures solar reflected and backscattered radiation 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 instrument has a 2600 km wide viewing swath and it is capable of daily global contiguous mapping.

The OMI surface UV algorithm (OMUVB) is based on the TOMS UV algorithm developed at NASA Goddard Space Flight Center (GSFC) (Krotkov et al., 1998, 2001). This algorithm estimates the surface UV irradiance from lookup tables (LUTs) obtained by a radiative transfer model using the OMI-derived total ozone, surface albedo and cloud information as input parameters for modelling (Tanskanen et al., 2006, 2007).

In this study OMI UV products are obtained using the new version of the OMI level 1 (radiance and irradiance) and level 2 (atmospheric data products) data set named collection 3. This new version takes advantage of a coherent calibration and revised dark current correction (see NASA DISC site http://disc.gsfc.nasa.gov/Aura/OMI/ for OMI level 2 data. and Aura Validation data Center site at http://avdc.gsfc.nasa.gov for the OMI station overpass data).

2.2 Ground-based data

The Brewer MK-III double monochromator spectrophotometer #150 measures global UV spectral irradiance between 290 and 363 nm with spectral resolution (FWHM) ~0.6 nm, and wavelength accuracy of 0.05 nm. A complete wavelength scan takes 4.5 min. The spectrophotometer is periodically calibrated by comparison with a quartz-halogen NIST-traceable standard lamp (1000 W DXW type). This lamp presents an uncertainty of 1.56% at 250 nm and 1.12% at 350 nm. This calibration transfer results in uncertainties of ±5% in the Brewer spectral irradiance measurements (Vilaplana, 2004). In addition, the Brewer #150 is inter-compared every two years against the transportable Quality Assurance of Spectral Ultraviolet Measurements in Europe (QASUME) reference spectroradiometer (Gröbner et al., 2005). All these calibration processes guarantee the ~5% accuracy of the Brewer UV spectral measurements used in this study. Finally, a cosine correction has been applied to the measurements using a technique described in the work of Antón et al. (2008).

To analyze the aerosol effect on the OMI UV bias, measurements from the automatic CIMEL sun- sky photometer were used. The instrument belongs to RIMA-PHOTONS networks as part of the NASA AERONET network (http://aeronet.gsfc.nasa.gov). The CIMEL sun photometer measures direct sun and sky radiation at four wavelength channels, 440, 670, 870 and 1020 nm (10 nm FWHM for the visible channels) (Holben et al., 1998). The automatic cloud screening algorithm is applied to the raw data resulted in level 1.5 products (Smirnov et al., 2000). Aerosol Optical Depth (AOD) and the Ångström coefficient (α) from the AERONET direct sun data were analyzed to characterize the aerosol load and type similarly to Cachorro et al. (2006, 2008) and Toledano et al. (2007b).

The ground-based instruments are located at the “El Arenosillo” Atmospheric Sounding Station (ESAt-El Arenosillo). This station belongs to the Earth Observation, Remote Sensing and Atmosphere Department, National Institute of Aerospace Technology of Spain (INTA). It is located in Mazagón, Huelva, Spain (37.1° N, 6.7° W, 20 m a.s.l.).

This site participates in the Global Ozone Observing System (GO3OS) of the Global Atmosphere Watch (GAW) program of World Meteorological Organization (WMO) as station #213. Data gathering, retrieval and reporting procedures at these stations are standardized by the WMO quality assurance procedures.

3 Methodology

The UV irradiance weighted with the erythemal action spectrum adopted by the Commission Internationale de l'Eclairage (CIE) (McKinlay and Diffey, 1987) (denoted as UVER) and absolute spectral UV irradiances (Watts/nm/m^2) (at 305 nm, 310 nm and 324 nm) were used for the comparison between OMI observations and Brewer measurements.

In this work, we used daily OMI pixels with centers from 0.1 km to 48 km from the site, being the average value 11.5 km. In addition, in this comparison we used the Brewer data between 12:30 and 14:30 local solar time close to the OMI overpass time at ∼13:45. The average time difference between the Brewer measurements and the OMI overpass is only 6 min. The OMI-Brewer data with time differences higher than 15 min (∼5% of all data) are removed in the comparison.

To select cloud–free conditions, the OMI Lambertian Equivalent Reflectivity (LER) at 360 nm was used. Thus, a day is considered cloud-free during OMI overpass when LER is lower than 10% (Kalliskota et al., 2000). The percentage of such cloud-free days is about 50% of the total amount of days at El Arenosillo station.

High aerosol events were identified according to the Aerosol Optical Depth (AOD) measured with CIMEL sun-photometer. Unfortunately, this instrument was not equipped with UV filters during the period of study, being the shortest channel used for the analysis was centered at 440 nm (FWHM =10 nm). In order to examine the effects of aerosols on the differences between satellite and ground-based near-noon CIE irradiances, AOD$_{440}$ was daily averaged between 12:30 and 14:30 true solar time on each day.

To investigate the effect of clouds and aerosols on the OMI bias, the following four datasets were analyzed:

- Dataset #1: All sky conditions.
- Dataset #2: All cloud-free cases (LER$<$10%).
- Dataset #3: Cloud-free cases with low aerosol load (LER$<$10% and $\text{AOD}_{440}<0.1$).
- Dataset #4: Cloud-free cases with moderate-high aerosol load (LER$<$10% and $\text{AOD}_{440}>0.25$).

The selection of these data sets is based on a previous analysis of TOMS irradiance data (e.g., Antón et al., 2007). Regression analysis was performed separately for each subset and statistics such as the Mean Bias Error (MBE) and the Mean Absolute Bias Error (MABE) were calculated. These statistics are obtained by the following expressions:

$$\text{MBE} = 100 \times \frac{1}{N}\sum_{i=1}^{N}\frac{\text{OMI}-\text{Brewer}}{\text{OMI}} \tag{1}$$

$$\text{MABE} = 100 \times \frac{1}{N}\sum_{i=1}^{N}\frac{|\text{OMI}-\text{Brewer}|}{\text{OMI}} \tag{2}$$

The uncertainty of MBE and MABE is characterized by the Standard Error (SE).

4 Results and discussion

4.1 All sky conditions

Initially the surface UV irradiance products from OMI were compared with simultaneous measurements performed by the Brewer spectroradiometer #150 for all sky conditions. The number of days analyzed is 1272 during the period of study: October 2004–December 2008 (80% of the total days).

The results of the correlation between OMI and Brewer UV data are presented in Table 1. The regression analysis shows positive OMI bias characterized by regression slopes of 1.13 (UVER), 1.15 (UV 305 nm), and 1.09 (UV 310 nm), and 1.02 (UV 324 nm), and with correlation coefficients higher than 0.90. The RMSE statistics (residual error of the fit) is between 20% and 23%, being larger for shorter wavelengths in agreement with the work of Kazadzis et al. (2009). As an example for this dataset, Figure 1a shows the scatter plot for UVER data. The scatter plots for the spectral UV irradiances at the three wavelengths (not shown) present a very similar behavior.

Table 2 shows the parameters obtained from the relative OMI-Brewer differences. The positive sign of the MBE means that all OMI UV products overestimate on average the ground-based measurements. This average overestimation is (12.27±0.50)% for UVER data and varies from (8.69±0.51)% for UV at 324 nm to (14.24±0.52)% for UV at 305 nm. In addition, the MABE parameter is between 13.6% for UV at 324 nm and 17.6% for UV at 305 nm. The uncertainty of this last parameter is lower than 0.5%, indicating the statistical significance of the values.

In this work, the OMI Lambertian Equivalent Reflectivity (LER) at 360 nm is used as proxy for analyzing the influence of cloudiness on the OMI-Brewer comparison. Using bins of size 5%, Fig. 2 shows the MBE as a function of LER. Error bars represent the Standard Errors (SE) of the bin that are plotted for UVER only for clarity. The figure shows little dependence of MBE on LER for low values of this proxy: MBE ~5%–13% for LER<30%. However, this parameter decreases with LER>30% (with increasing variability, note larger error bars) and for LER~50%, biases have both positive and negative values. The SE increase when LER increases, in agreement with previous TOMS studies (i.e., Kalliskota et al., 2000; Chubarova et al., 2002; Cede et al., 2004; Antón et al., 2007). Therefore, while the positive OMI-Brewer biases are seen over the whole LER range, the negative biases are also observed at LER ~50% (mostly cloudy conditions). However we must emphasize that at our site the frequency of days with

LER>50% (8%) is much lower than cloud-free days (55% of days with LER<10%).

This result is related to the fact that the OMI UV products are an average over a satellite pixel (13 by 24 km for nadir viewing and ~50km off-nadir viewing directions). Thus, variability of cloudiness within the satellite pixel can lead to a significant difference between ground-based (a single point) and OMI UV data (pixel) (Weihs et al., 2008). Defining a criterion to select cloud-free conditions only using satellite information is a difficult issue. According to Kalliskota et al. (2000), days with LER<10% could be considered cloud-free, being 719 cloud-free days at our site (~55% of all days). This percentage confirms the prevalence of cloudless situations over the El Arenosillo station. However, if Cimel AOD data are used to define cloud-free conditions at our station, then the cloud-free days represents a percentage of 68% of all days. Applying both OMI and AERONET cloud-screening reduces the percentage of cloud-free days to ~49% of all days. Therefore, the selection of cloudy or cloud-free situations using only OMI LER data presents an inherent uncertainty, as it allows sub-pixel clouds.

Previous OMI UV validation studies (e.g., Taskanen et al., 2007; Buchard et al., 2008; Ialongo et al., 2008) were performed at solar noon. Since the difference in atmospheric conditions (clouds, aerosols) between local noon and OMI overpass time (~01:45 p.m.) can affect such comparisons (Ialongo et al., 2008) here the OMI-Brewer comparisons were performed at the OMI overpass time.

4.2 Dataset #2: cloud-free conditions

For this data set the OMI versus Brewer correlation results for all OMI UV products are shown in Table 1. Figure 1b shows the correlation plot for UVER data (similar plots for the spectral UV wavelengths not shown). Compared with all sky conditions (Fig. 1a) the noise is considerably smaller and correlation is tighter. The statistical parameters show that agreement is excellent for all OMI products. The noise is also significantly lower for cloud-free days (RMSE lower than 10%) than for all sky conditions (RMSE higher than 20%), which is consistent with the assumption that clouds are the main source for the scatter between satellite and ground-based UV data. Table 2 presents the statistical parameters of the relative differences between satellite and ground-based data, showing that the biases remain and even become more significant for this cloud-free dataset #2. This finding is related to the absence of the cloudiness compensating effect occurred for dataset #1 (see Fig. 2).

Total Ozone Column (TOC) data retrieved from OMI-TOMS algorithm (Bhartia and Wellemeyer, 2002) were also compared with Brewer TOC measurements at El Arenosillo for this dataset (not shown). Although the correlation between satellite and ground-based TOC data is excellent (R^2~0.99), OMI total ozone data are on average 1.31% smaller than Brewer measurements. This result agrees with the work of Antón et al. (2009) which validated OMI ozone products with ground-based observations from network of Spanish Brewer spectrophotometers for the period 2005–2007. The slight underestimation of TOC values from OMI algorithm could potentially explain the overestimation found for the OMI UV products (especially for the shortest wavelengths), since the OMUVB algorithm uses the TOC values from OMI-TOMS as input. However, lack of correlation between OMI-Brewer TOC and UV differences implies that uncertainties in TOC can not explain the observed biases in UV.

Using AOD data from collocated CIMEL sun-photometer, we analyzed the OMI-Brewer bias (MBE) as a function of the extinction AOD for cloud-free days similarly to the previous analysis using TOMS UV data (e.g., Antón et al., 2008). Figure 3 (left) shows a weak relationship between the relative differences in UV and extinction AOD, with a correlation coefficient ~0.4.

Arola et al. (2005) previously studied TOMS surface UV bias at 324 nm as function of aerosol column Absorption Optical Depth (AAOD). They reported a significant correlation (about 0.8) higher than the one found in this study. Kazantzidis et al. (2006) made the same studies but with extinction AOD and they found a correlation greater than 0.65. Buchard et al. (2008) also analyzed relationship between the AOD and the OMI-surface UV bias, founding correlation coefficient is about 0.6, while Ialongo et al. (2008) found similar correlation (R^2~0.5) at SZA larger than 55 degrees.

Figure 3 (right) shows MBE as function of AOD, binning the data with a 0.1 AOD bins. Larger relative UV differences correspond to larger AOD. As seen from the figure the OMI UV bias increases with increase in AOD, in agreement with earlier findings. Therefore, under cloud-free conditions aerosol is the second major parameter affecting the bias in satellite derived UV irradiance. This can be explained by the fact that OMI UV algorithm does not properly account for the absorbing aerosols in the boundary layer (Krotkov et al., 2005; Taskanen et al., 2007; Arola et al., 2009). Spectrally the largest UV differences occur at the shortest wavelengths (Fig. 3, right) where the uncertainly in both satellite algorithm and Brewer instrument are higher (Kazantzidis et al., 2006).

4.3 Dataset #3: cloud-free conditions with low aerosol load

The number of pair of cases OMI-Brewer selected for this dataset is 304, representing the 23% of all days within the analyzed period. The atmospheric conditions corresponding to this dataset are more similar to the model assumptions used in the OMI algorithm and, therefore, a better agreement with ground-based measurements is expected.

Figure 1c shows the scatter plot between OMI and Brewer for UVER data. Similar plots were elaborated for spectral UV irradiances at 305, 310 and 324 nm (not shown). All scatter plots show positive OMI bias and an excellent correlation for the four cases (R^2~0.98) as illustrated in Table 1 which also shows statistical errors of the slope and the intercept. These results indicate that the differences between OMI and ground-based Brewer UV measurements are reduced to the measurements uncertainties (~5%) when the aerosol and cloud effects are removed. These results agree with early TOMS UV validation studies (Krotkov et al., 1998; Cede et al., 2004; Antón et al., 2007).

Table 1 shows that the RMSE values for this dataset are lower than results obtained for all sky conditions. Thus, for UVER comparison, the RMSE decreases from 20.7% (all sky conditions) down to 7.0% (cloud-free cases with low aerosol load). To summarize, the cloudiness and aerosols explain a percentage of RMSE variation of

65% for UVER, 62% for UV irradiance at 305 nm, 65% for UV irradiance at 310 nm and 69% for the UV irradiance at 324 nm.

Table 2 shows statistical parameters of the relative differences between Brewer and OMI UV products. It can be seen the significant decrease in the MBE and MABE parameters when cases with low aerosol load are selected. It is remarkable that the MBE and MABE values are similar for spectral UV irradiance at 310 nm and 324 nm, suggesting that the OMI-Brewer differences are not related to ozone absorption, in agreement to the explanation given in Sect. 4.2.

It should be noted that not all of this bias is due to the OMI algorithm, but also due to the Brewer measurement uncertainties related to the cosine response, absolute calibration, etc. Furthermore, note that also a 2–3% of bias is also due to the differences between the modelled OMI algorithm data and Brewer measurements under cloud-free conditions.

4.4 Dataset #4: cloud-free conditions with moderate-high aerosol load

The number of days selected for this dataset is 90, representing 7% of the whole cloud-free dataset. The cases with moderate-high aerosol optical depth have been analyzed according to the aerosol climatology in our area (Toledano, 2005; Cachorro et al., 2006; Toledano et al., 2007b).

Figure 1d shows the scatter plot of OMI versus Brewer UVER data. The UVER and spectral UV data (not shown) present a notable OMI overestimation, but the correlation remains significant (R^2 between 0.89 and 0.96, and RMSE values between 7.0% and 8.0%). Other informative parameters of the regression are shown in Tables 1 and 2.

It can be seen from the Table 2 for this dataset the MBE and MABE parameters more strongly depend on UV wavelength (as wavelength decreases, MABE increases). This wavelength dependence of OMI-Brewer bias for moderate-high aerosol load may be partially attributed to the aerosol influence over the Brewer spectral measurements. Aerosols can also increase effective absorption path for tropospheric ozone and other anthropogenic gases causing more effective UV reduction at shorter UV wavelengths (Bernard et al., 2003; Kaskaoutis et al., 2006; Badarinath et al., 2007).

If the statistical parameters obtained for the dataset #3 and #4 are compared (Tables 1 and 2), it can be seen that the RMSE, MBE and MABE parameters are significantly higher for the dataset #4 than for the dataset #3. Thus, for UVER comparison, the MBE is (+10.87±0.36)% for low aerosol loading cases, and (+18.22±0.58)% for high aerosol load. This overestimation is mainly due to the fact that current OMI surface UV algorithm assumes no absorbing aerosols in the boundary layer. This assumption produces two effects over OMI algorithm during high aerosol load conditions. Firstly, the obvious UV radiation overestimation due to the neglected aerosol absorption, and secondly, an underestimation of the effective Cloud Optical Depth (COD). This parameter is obtained by OMI measurements of the top-of-the-atmosphere radiance at 360 nm, which is reduced by the presence of absorbing aerosol in the troposphere. Since the obtained COD is used to determine the spectral transmission of UV irradiance relative to the clear sky conditions, the COD underestimation by OMI for high aerosol load conditions produces an additional overestimation in UV radiation products (Krotkov et al., 1998, 2001, 2002).

Our results agree with the study of Weihs et al. (2008) who reported an increase in the ratio of OMI UVER data to the ground measured UVER as a function of AOD at 368 nm. This ratio increased from 1.05 (AOD =0.15) to 1.35 (AOD =0.6). Several studies (e.g., Krotkov et al., 2004, 2005; Arola et al., 2005; Kazadzis et al., 2009) have suggested off-line corrections for absorbing aerosols if the AAOT (Absorbing Aerosol Optical Thickness) is known or can be estimated at the site. In this sense, Arola et al. (2009) have recently proposed a correction for absorbing aerosols by using global monthly aerosol climatology and applying the parameterization suggested by Krotkov et al. (2005). The problem is that currently, there are no standard methods for measuring AAOT (or aerosol Single-Scattering Albedo, SSA) in the UV wavelengths even from the ground. Such measurements are currently available only at few sites (Krotkov et al., 2005; Arola et al., 2007). AAOT or SSA values can be obtained in AERONET aerosol stations but they are determined only in visible-infrared wavelengths (shortest 440 nm) and with a high associated uncertainty. Otherwise, new satellite aerosol absorption product from the OMI (Torres et al., 2007), if proved sensitive to boundary-layer aerosol, could be used for operational improvement in the future version of the OMI surface UV algorithm. This is currently the subject of ongoing research.

Therefore taking into account currently available aerosol information at our site we need (a) to evaluate the absorbing aerosols optical thickness at our site and (b) to analyze its influence in OMI bias. This is an extensive work which has been carried out in a companion paper (Cachorro et al., 2010).

4.5 Seasonal dependence

Buchard et al. (2008) analyzed the dependence of the relative differences between OMI UV data and ground-based measurements on SZA, showing larger discrepancies for SZA higher than 65°. Kazadzis et al. (2009) showed no statistically significant dependence on SZA for the OMI-Brewer relative UV differences at Thessalonica. Thus, this dependence is also analyzed in this study. In Fig. 4 the relative differences (MBE) between ground-based and OMI UVER data are compared as a function of the OMI ground pixel SZA for all sky conditions. The data are binned with a 4.25° SZA bins. Figure 5 shows similar binned data including all OMI data sets with error bars representing standard errors.

For dataset #1 (all sky data), Figs. 4 and 5a show a small bias dependence (about 8%) on SZA, with the bias decreasing with SZA, from about 17% to 9%. For dataset #2 and #3 (Fig. 5b and c), this dependence is reduced and no dependence is seen for dataset #4 (Fig. 5d). Although only UVER is shown, this evaluation was also performed for the other spectral UV products and we observe that 324 nm wavelength compares best.

The UV bias time series as function of month (Fig. 6) reveal a notable seasonal dependence for the dataset #1, with amplitude about 10%, increasing from 10% in winter to almost 20% in summer. This seasonal amplitude is reduced by a factor of 2 when cloud-free and low aerosol load cases are selected (dataset #3), showing two peaks as observed in a previous TOMS-Brewer comparison (Anton et al., 2007). These two peaks in March–April and summer are consistent with AOD climatology at our station and roughly correspond to the periods with frequent desert dust intrusions (Toledano et al., 2007a, b). This indicates that clouds and aerosols together with SZA greatly affect the seasonal dependence found in this work for all sky conditions.

5 Conclusions

This study focuses on the comparison between OMI and Brewer surface UV products at El Arenosillo station (South of Spain) for the period October 2004–December 2008 where we studied the influence of several factors: clouds, aerosols, ozone, solar elevation and aerosols. Our results confirm that OMI surface UV data overestimate the Brewer measurements with bias between 8% and 14% for all sky conditions. We found no significant changes when cloud-free conditions are selected.

The relationship between the OMI-Brewer differences and the OMI LER showed a slight dependence with OMI LER, with notable bias for larger values. Thus, the cloudiness is the main factor that introduces scatter in the satellite-ground-based correlation for all sky conditions. This study shows that the OMI-TOMS total ozone column used as input in the OMI UV algorithm has no affect on the relative differences between OMI and Brewer UV products.

The relative differences between OMI and Brewer UV products show a modest decrease with SZA for all sky conditions except days with high aerosol loading, when the bias is near constant. This fact causes a pronounced seasonal dependence of the bias with the largest differences occurring during summer. The amplitude of this seasonal dependence is notably reduced when cloud-free and low aerosol loads conditions are selected, but each data set shows its own features. Thus, for instance, cloud-free conditions (dataset #2) and low aerosol load (dataset #3) clearly shows the modulation given by the aerosol climatology in this area.

The influence of aerosols is broadly observed when cloud-free case is considered in our station. According to the recent OMI UV validation results of Taskanen et al. (2008), our comparisons fall within "the middle of the range" of other ground UV stations. However, new measurements of aerosol absorption (i.e. Single Scattering Albedo, SSA) must be conducted to improve the estimated OMI UV values. A more detailed analysis of aerosol optical properties at our site has been carried out in a companion paper (Cachorro et al., 2010).

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Table 1. Results of linear regression analysis between OMI and Brewer UV products for all sky conditions (dataset #1), cloud-free conditions (dataset #2), cloud-free cases with low aerosol load (dataset #3), and cloud-free cases with moderate-high aerosol load (dataset #4). The parameters are the following: the slope of the regression, the Standard Error (SE) of the slope, the Y intercept, the SE of the Y intercept, the correlation coefficients (R^2), and the Root Mean Square Errors (RMSE).

dataset #1

	Slope	SE (Slope)	Y intercept (mW/m^2)	SE (Y intercept) (mW/m^2)	R^2	RMSE (%)
UVER	1.13	0.01	2.51	0.96	0.94	20.7
UV 305	1.15	0.01	0.91	0.24	0.95	23.2
UV 310	1.09	0.01	2.11	0.51	0.94	21.1
UV 324	1.02	0.01	20.08	2.66	0.90	19.8

dataset #2

	Slope	SE (Slope)	Y intercept (mW/m^2)	SE (Y intercept) (mW/m^2)	R^2	RMSE (%)
UVER	1.17	0.01	−0.94	0.97	0.98	7.3
UV 305	1.17	0.01	0.27	0.25	0.98	8.9
UV 310	1.13	0.01	0.37	0.50	0.97	7.7
UV 324	1.09	0.01	7.13	2.51	0.96	6.6

dataset #3

	Slope	SE (Slope)	Y intercept (mW/m^2)	SE(Y intercept) (mW/m^2)	R^2	RMSE (%)
UVER	1.14	0.01	−0.79	1.14	0.98	7.0
UV 305	1.14	0.01	0.26	0.29	0.98	8.9
UV 310	1.11	0.01	0.10	0.58	0.98	7.3
UV 324	1.08	0.01	4.53	3.14	0.97	7.3

dataset #4

	Slope	SE (Slope)	Y intercept (mW/m^2)	SE(Y intercept) (mW/m^2)	R^2	RMSE (%)
UVER	1.19	0.03	5.38	4.84	0.95	7.2
UV 305	1.21	0.03	1.33	1.18	0.96	8.0
UV 310	1.13	0.03	5.27	2.53	0.94	7.7
UV 324	1.02	0.04	46.42	12.44	0.89	7.0

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Table 2. Statistical parameters of relative differences between OMI and Brewer UV products irradiances for all sky conditions (dataset #1), cloud-free conditions (dataset #2), cloud-free cases with low aerosol load (dataset #3), and cloud-free cases with moderate-high aerosol load (dataset #4). The parameters are the following: the number of data (N), the Mean Bias Error (MBE), the Standard Error (SE) of the MBE, the Mean Absolute Bias Error (MABE), and the SE of the MABE.

	dataset #1				
	N	MBE (%)	SE (MBE) (%)	MABE (%)	SE (MABE) (%)
UVER	1272	+12.27	0.50	15.96	0.41
UV 305	1272	+14.24	0.52	17.61	0.42
UV 310	1272	+10.64	0.51	14.94	0.42
UV 324	1272	+8.69	0.51	13.62	0.41
	dataset #2				
	N	MBE (%)	SE (MBE) (%)	MABE (%)	SE (MABE) (%)
UVER	703	+13.01	0.24	13.13	0.23
UV 305	703	+14.46	0.26	14.66	0.25
UV 310	703	+11.37	0.25	11.59	0.23
UV 324	703	+10.02	0.22	10.26	0.20
	dataset #3				
	N	MBE (%)	SE (MBE) (%)	MABE (%)	SE (MABE) (%)
UVER	304	+10.87	0.36	11.13	0.33
UV 305	304	+12.18	0.41	12.59	0.37
UV 310	304	+9.22	0.37	9.66	0.33
UV 324	304	+8.43	0.33	8.83	0.30
	dataset #4				
	N	MBE (%)	SE (MBE) (%)	MABE (%)	SE (MABE) (%)
UVER	94	+18.22	0.58	18.22	0.58
UV 305	94	+19.28	0.61	19.28	0.61
UV 310	94	+16.54	0.61	16.54	0.61
UV 324	95	+14.52	0.60	14.52	0.60

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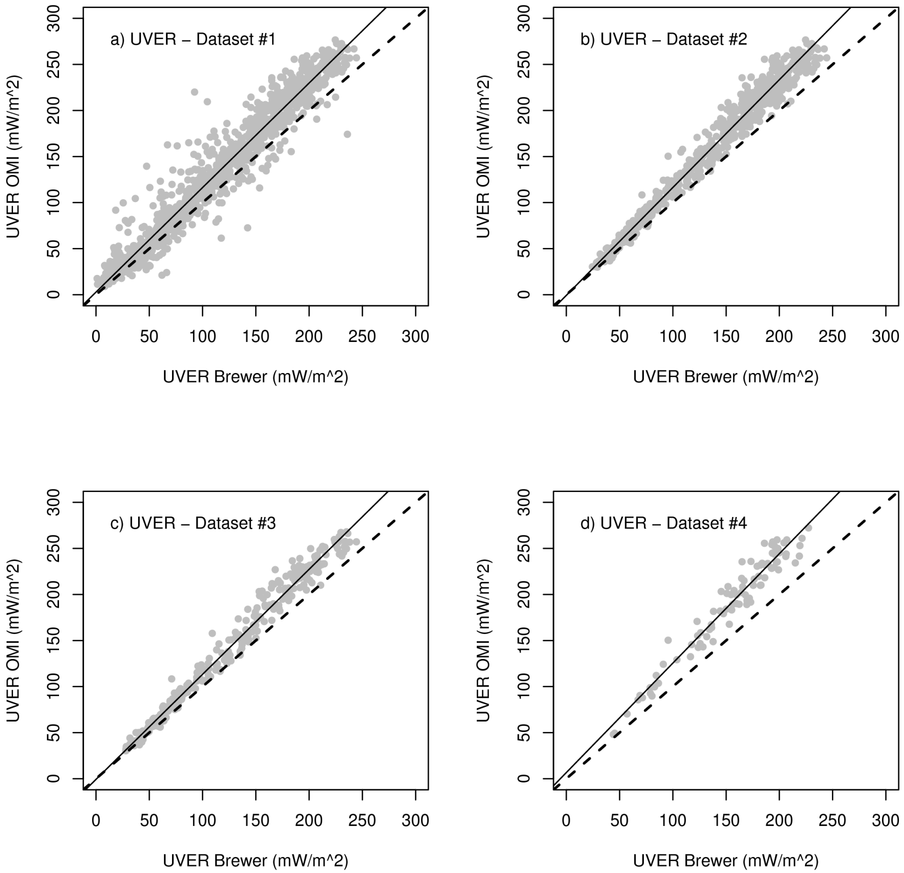

Fig. 1. **(a)** Correlation between OMI and Brewer UV products for all-sky conditions (dataset #1) for the UV irradiance weighted by the CIE spectrum (UVER); **(b)** for cloud-free sky condition or dataset #2; **(c)** dataset #3 and **(d)** dataset #4. The solid line is the least square linear regression line, and the dashed line symbolizes the ideal correlation of unit slope.

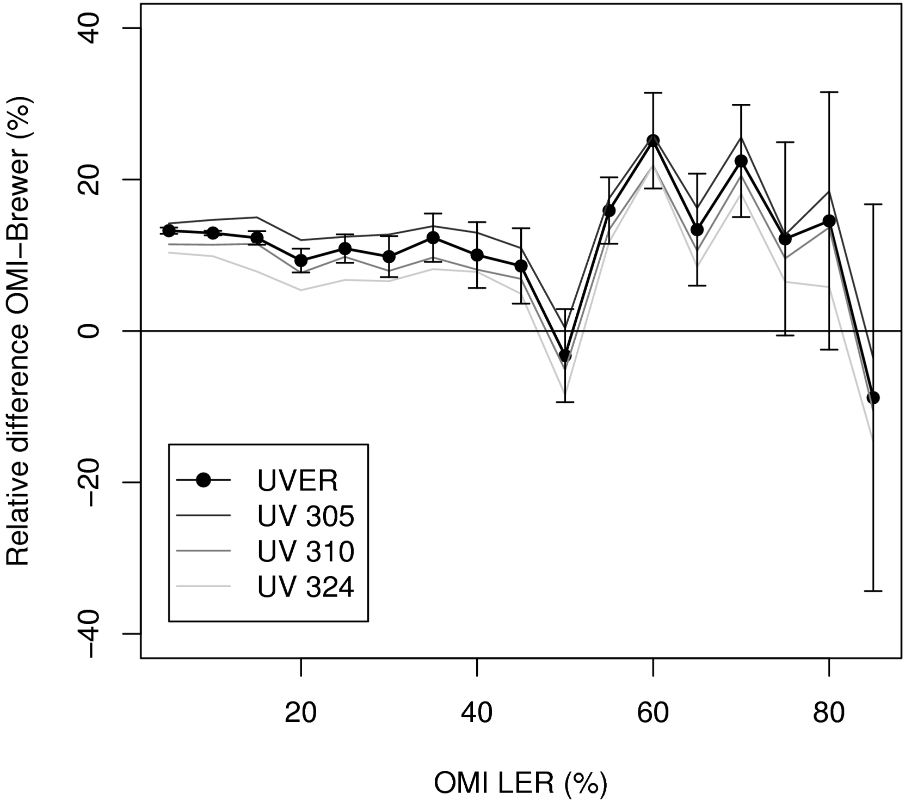

Fig. 2. Dependence of the relative difference between OMI and Brewer UV products with respect to the OMI Lambertian Equivalent Reflectivity (LER) at 360 nm for all sky conditions (dataset #1) taking binned data. The size of the bins is 5%.

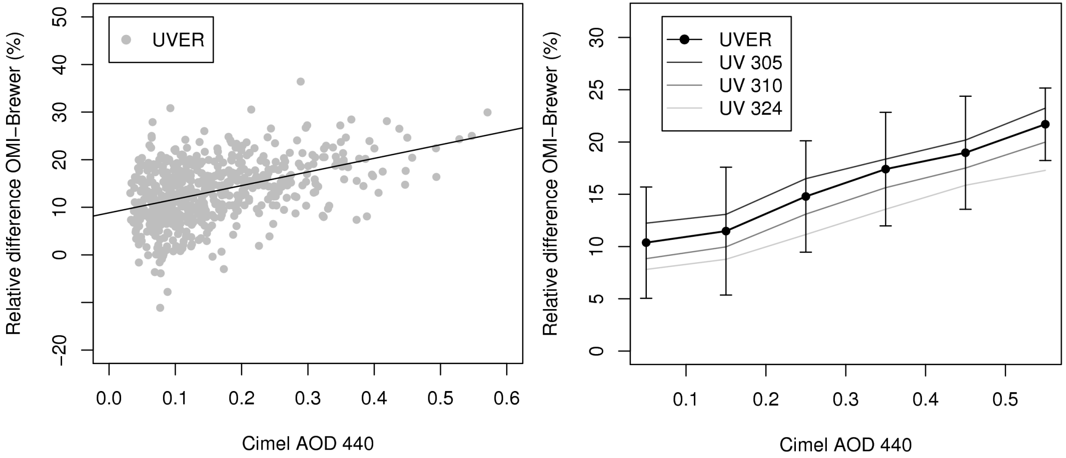

Fig. 3. Left: Dependence of the relative difference between OMI and Brewer UVER data with respect to the aerosol optical depth (AOD) at 440 nm measured from the Cimel photometer at El Arenosillo station for cloud-free conditions (dataset #2). Right: the same as before but taking binned data for the four UV OMI products. The data are binned with a 0.1 AOD bins.

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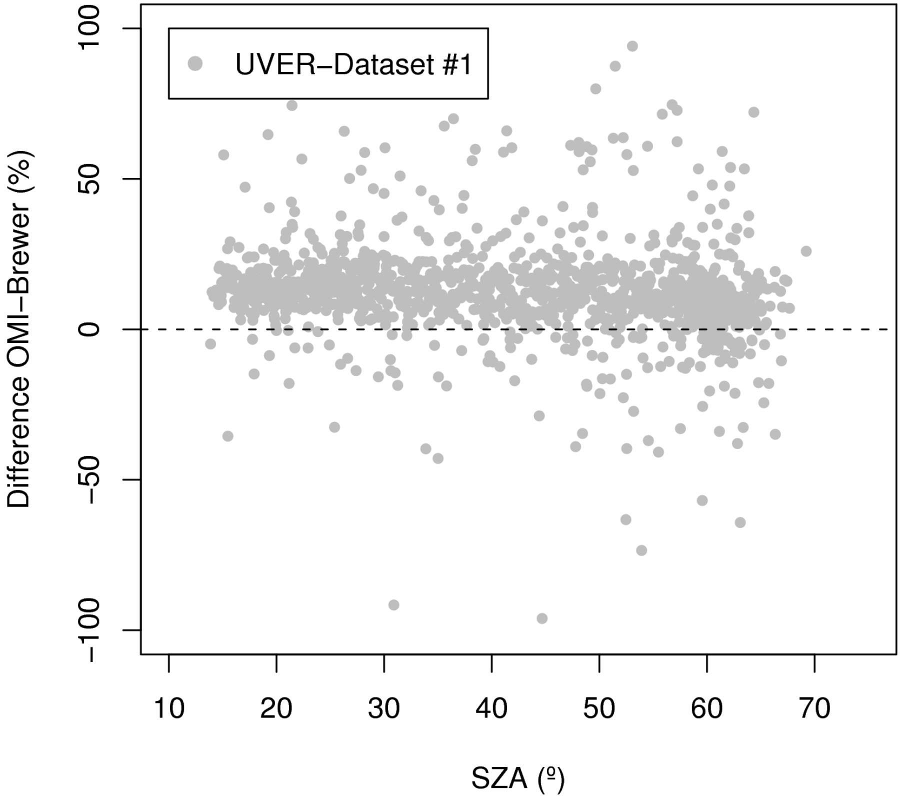

Fig. 4. Dependence of the relative difference between OMI and Brewer for UVER with respect to OMI Solar Zenith Angle (SZA). The data are binned with a 4.25° bins.

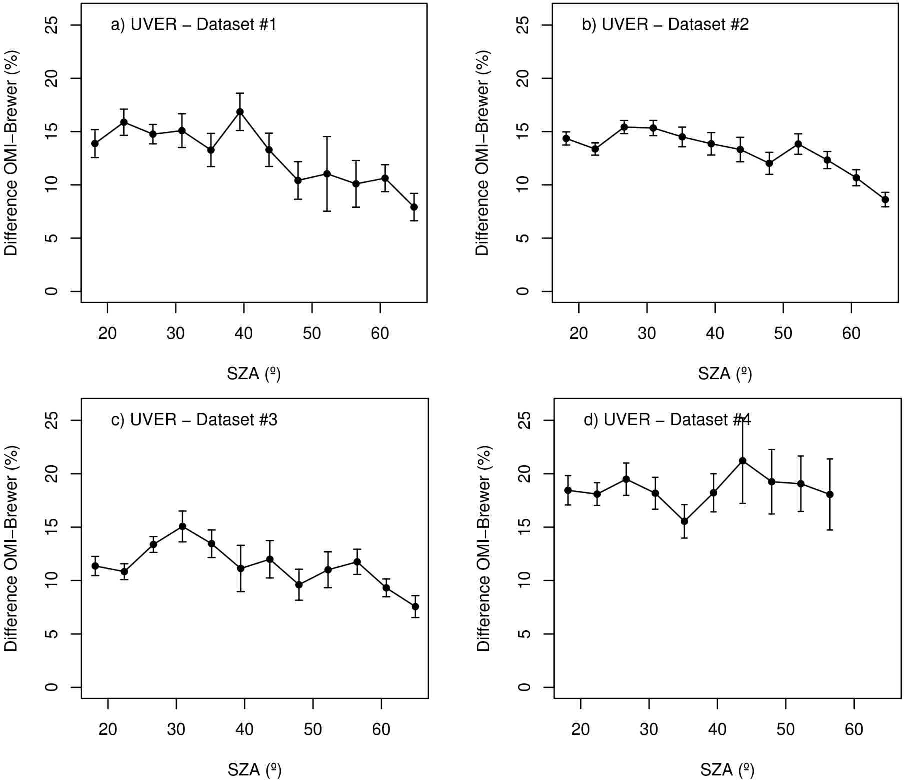

Fig. 5. The same as Fig. 4 but taking binned data for **(a)** all sky conditions (dataset #1); **(b)** for cloud-free sky condition or dataset #2; **(c)** dataset #3 and **(d)** dataset #4. The data are binned with a 4.25° bins.

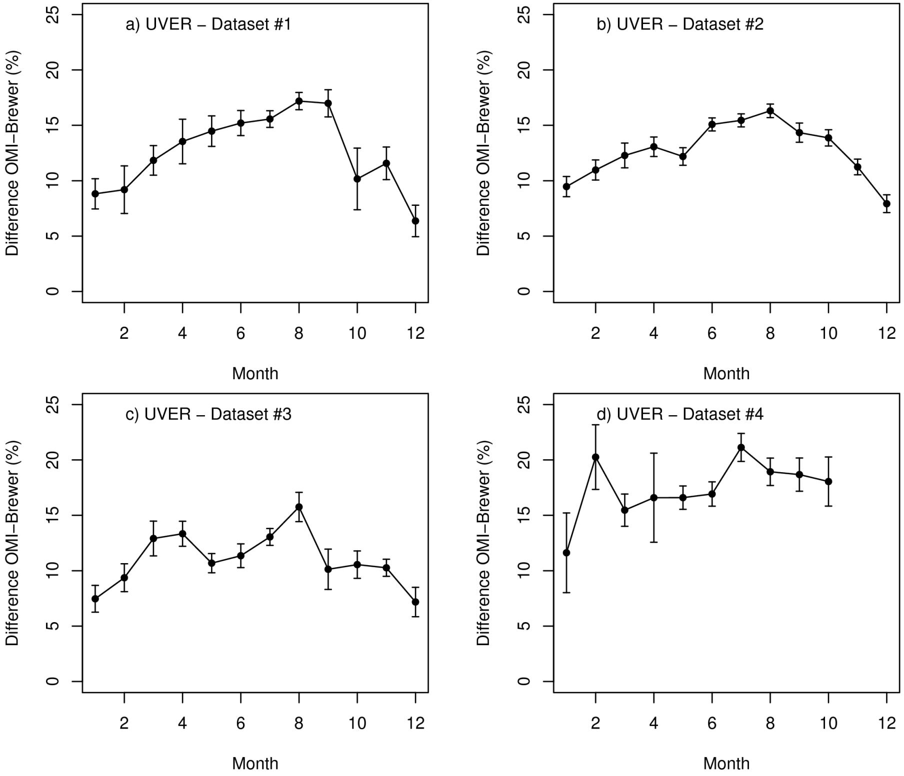

Fig. 6. Monthly evolution of the relative difference between OMI and Brewer UVER data for **(a)** all sky conditions (dataset #1); **(b)** for cloud-free sky condition or dataset #2 (up right); **(c)** dataset #3 and **(d)** dataset #4.