Comparison of ground-based and Total Ozone Mapping Spectrometer erythemal UV doses at the island of Lampedusa in the period 1998–2003: Role of tropospheric aerosols

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[1] The Total Ozone Mapping Spectrometer (TOMS) has the longest time series of globally distributed estimates of UV irradiance at the Earth's surface. The proper interpretation of TOMS estimated irradiances relies on well-calibrated and well-maintained spectrometers at the Earth's surface. In this study, daily erythemal irradiances measured by a Brewer spectrophotometer at the island of Lampedusa (35.5°N, 12.6°E), in the Mediterranean are compared with TOMS observations in the period January 1998 to August 2003. The comparison, also because of the peculiar conditions at Lampedusa, a very good site for ground-based validation of satellite observations, allows us to recognize how the space-borne observations are influenced by the presence of atmospheric aerosols. Two TOMS data sets, derived applying different algorithms to retrieve ozone and UV irradiance from the backscattered radiance, are used in this study: Version 7 (V7) and the recently developed version 8 (V8), which uses new climatologies for ozone and temperature profiles and accounts for the attenuation by tropospheric aerosols through the aerosol index (AI). As shown in previous studies performed with V7 TOMS data, satellite-derived erythemal doses systematically overestimate ground-based measurements, mainly because of uncorrected absorption by aerosols in the troposphere. The bias between the TOMS and Brewer doses for all-sky conditions is (9.4 ± 19.8)% for V7 and (7.3 ± 20.0)% for V8 and decreases to (5.6 ± 8.0)% for V7 and (3.4 ± 8.4)% for V8 for the cloud-free cases. The large standard deviations for all-sky conditions are due to nonhomogeneity in the cloud cover within the sensor field of view, while those for cloud-free days are caused by the large aerosol variability occurring at Lampedusa. The biases for cloud-free days have been related to differences in the TOMS AI UV attenuation algorithm and to the aerosol optical depth (AOD) at 415.6 nm measured with a Sun photometer at Lampedusa since 2001. The mean bias between the V7 TOMS and Brewer doses progressively increases with AI and AOD at 415.6 nm, from ± 3% for low AI and AOD up to 21% for $1.5 \leq AI < 2.5$ and $0.5 \leq AOD < 0.6$. The bias calculated with V8 data set varies between +6% for $0 \leq AI < 1$ and about −8% for $4 \leq AI < 5$, well within the respective uncertainties of the Brewer and TOMS measurements. TOMS V8 data show a smaller dependency on the aerosol absorption, indicating that the implemented corrections produce more reliable estimated doses. For very low aerosol loading (AOD at 415.6 nm below 0.2), the TOMS-to-Brewer erythemal dose ratio, both for V7 and V8, is approximately 1, indicating that the radiometric calibration of the Brewer instrument is consistent with the TOMS estimated irradiances from derived ozone and Rayleigh scattering attenuation.

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1. Introduction

[2] The amount of solar ultraviolet UVB (280–320 nm) radiation that reaches the Earth surface is moderated by atmospheric ozone absorption in addition to the effects of clouds and aerosols. An increase in UVB radiation is expected as a consequence of the ozone reductions at midlatitudes and high latitudes [e.g., *Bojkov et al.*, 1990], and the large decreases over Antarctica [*Farman et al.*,

Figure 1. Lampedusa Island (large circle) as seen from (left) Moderate Resolution Imaging Spectroradiometer (MODIS) and (right) the International Space Station in 2001 (picture ISS002-338-30). The small island of Linosa (small circle) is visible north of Lampedusa, and Malta (square) is visible to the northeast. Dust regularly blows over Lampedusa from Africa (Tunisia, Algeria, and Libya). See color version of this figure at back of this issue.

1985]. Owing to the observed local variability of UV irradiance caused by clouds and aerosols, the limited accuracy of the measurements of ultraviolet irradiance, and the relatively short time interval over which UV measurements are available, the detection of the long-term behavior of the ultraviolet irradiance at the surface of the Earth is still problematic for any particular ground site. Positive UVB trends over relatively long time intervals were, however, detected at several locations [e.g., *Blumthaler and Ambach*, 1990; *Correll et al.*, 1992; *Kerr and McElroy*, 1993; *Zerefos*, 2002].

[3] Ground-based instruments may provide high-quality measurements that require careful instrumental characterization and calibration. Owing to the high cost of instrumentation and its maintenance, ground-based networks for UV radiation measurements [e.g., *Scotto et al.*, 1988; *Bigelow et al.*, 1998; *Augustine et al.*, 2000; *Fioletov et al.*, 2001; *Schmalwieser and Schauberger*, 2001; *Cede et al.*, 2002; *Sabburg et al.*, 2002] have only a limited distribution over the Earth surface and are lacking in many areas, mainly oceanic regions. Ground-based observations, moreover, are generally representative of local atmospheric conditions and not necessarily conditions in the surrounding region.

[4] Satellites offer global coverage over extended periods and area, allowing the detection of regional or global changes. The use of a single instrument ensures that differences between measurements in different regions due to instrumental errors are minimal; however, continuous validation is necessary to guarantee that the temporal evolution derived from space is meaningful. The Total Ozone Mapping Spectrometer (TOMS) instrument provides the longest satellite series of UV measurements with a global coverage, started in 1978 on Nimbus 7 satellite and continuing with Earth Probe TOMS. The TOMS UV irradiance is derived from measurements of backscattered radiance converted into ozone, cloud reflectivity, and aerosol absorption using radiative transfer calculations [*Herman et al.*, 1999]. The sensitivity of TOMS to ozone amounts and aerosols near the surface is reduced, so that the ozone and aerosols extinction in the lower layers has to be assumed. This can lead to large differences with respect to ground-based measurements, especially in industrialized regions where pollution reaches high levels or in regions underneath aerosol plumes associated to dust storms or biomass burning.

[5] This paper presents the daily erythemal dose measured at Lampedusa Island (35.5°N, 12.6°E), Italy, from 1998 to 2003 by means of the double-monochromator Brewer spectrophotometer 123. The instrument is sited at the ENEA Station for Climate Observations. The position of Lampedusa is particularly interesting since the island is small (approximately 20 km^2) and isolated in the Mediterranean. A photograph taken from the International Space Station in 2001 (picture ISS002-338-30) is shown in Figure 1. The image approximate size is 120 $\times$ 80 km^2. There are no large islands or continental areas within a radius of about 120 km; as appears in Figure 1, Lampedusa represents just a small perturbation in the satellite field of view, almost totally occupied by the sea, thus the island is particularly suitable for validation of satellite observations. It must be also mentioned that cloudless sky is very often found at Lampedusa (mainly in the period May–September). The island is characterized by large variability of aerosol properties and optical depth. Part of the time it is reached by air masses from Europe, and part of the time it is exposed to air coming from Africa, especially in summer. African air masses often carry high amounts of desert aerosol, which significantly affect the UV radiation fluxes [*di Sarra et al.*, 2001, 2002; *Zerefos et al.*, 2002].

[6] In this study the erythemal doses, calculated from the ground-based measurements of UV irradiance weighted by the CIE action spectrum [*McKinlay and Diffey*, 1987], have been compared to the similar doses retrieved from the TOMS instrument. Previous validation papers [*Herman et al.*, 1999; *Kalliskota et al.*, 2000; *McKenzie et al.*, 2001] have shown that satellite-derived UV doses are significantly and systematically larger than ground-based measurements, even if the day-to-day variations are similar. These analyses have shown that the overestimate depends on atmospheric conditions and on ground albedo. Tropospheric aerosols and ozone have been shown to play a role in dose estimation from satellite measurements. *McKenzie et al.* [2001] have examined the differences between TOMS-estimated and

ground-based measurements of erythemal dose at Lauder, a clean air site in the Southern Hemisphere, and at three more polluted sites in the Northern Hemisphere. They concluded that, while the agreement is good for the pristine site, the satellite retrievals are overestimated for polluted sites caused by an inadequate account of extinction by aerosols and ozone in the troposphere.

[7] Recently, a new version (version 8) of the algorithm for the conversion of the backscattered radiances into TOMS products (ozone, erythemal dose, reflectivity, AI) has been developed, correcting small errors present in the previous version (version 7). The new algorithm takes advantage of a new climatology for ozone and temperature profiles, includes a correction for the Sun glint and for the effect of aerosols in the troposphere based on the AI, and uses a better calibration procedure.

[8] The aim of this study is to examine the series of erythemal doses from Brewer measurements at the marine remote site of Lampedusa in relation to the TOMS-derived values, using both version 7 and 8 data products, in order to obtain the role of tropospheric aerosols in the estimation of the UV dose from backscattered radiance. The differences between TOMS versions 7 and 8 and the Brewer-derived erythemal doses will be discussed and the effects of the ozone retrieval correction on the estimated doses will be highlighted. To perform this analysis, the TOMS aerosol index and the aerosol optical depth measured at 415.6 nm by the MultiFilter Rotating Shadowband Radiometer (MFRSR) have been used in conjunction with the doses.

2. Ground-Based Measurements

[9] The Brewer spectrophotometer was originally designed to measure global (direct plus diffuse) UV irradiance and total columnar ozone. A description of the Brewer instrument is given by *Kerr et al.* [1985]. At Lampedusa a Brewer MK III, which uses a double monochromator, has been operational since 1998. Total ozone is measured with the instrument entrance optic oriented toward the Sun (direct Sun) or at the zenith (zenith sky). During a UV measurement, light enters the instrument through a Teflon diffuser enclosed in a quartz dome. The Brewer MKIII performs scans from 286.5 nm to 363 nm in 0.5 nm increments, with a spectral resolution of about 0.55 nm. The double monochromator Brewer performs reliable measurements down to 295 nm, because of high stray light suppression [*Bais et al.*, 1996]. The irradiance scale of the Brewer at Lampedusa is maintained by performing routine checks with 50 W lamps, and periodic calibrations with 1000 W FEL lamps, traceable to NIST, by means of a field calibrator [*Early et al.*, 1998]. The calibrations with the 1000 W lamp were performed once in 1999 and 2002, and are routinely carried out every approximately 50 days since May 2003. The instrumental responsivity was progressively corrected, referring the periodic checks with the 50 W lamps to the 1000 W lamp calibrations, during the period January 1998 to May 2003; the responsivity was determined directly from the 1000 W lamp calibrations afterward. The estimated uncertainties associated with the UV irradiance measurements are about ±5% at about 305 nm (close to the maximum of the spectral erythemal action spectrum) and are better toward longer wavelengths.

[10] The cosine error in the Brewer spectrometer contributes significantly to underestimations of the UV irradiance: *Fioletov et al.* [2002] estimate a 5–12% (on average 9%) correction, depending on both the specific Brewer instrument and particular conditions (e.g., noontime solar zenith angle). Thus the correction for the nonideal cosine response of the spectrometer must be considered. The angular response of the diffuser of the Brewer at Lampedusa was measured by the manufacturer in 1995. In May 2003 the diffuser was replaced; the angular response of the new diffuser was measured in May 2004 as part of the Quality Assurance of Spectral Ultraviolet Measurements in Europe (QASUME) project. The cosine correction to the global erythemal irradiance was estimated following *Bais et al.* [1998] for both diffusers and for angles between 12° and 84°. Radiative model calculations show that the correction function varies less than 1.5% from 305 to 360 nm; since the erythemal irradiance spectrum has its peak value around 310 nm, the correction at this wavelength was applied to the integrated spectrum. The cosine corrections depend essentially on the cosine response of the diffuser, and on the direct-to-global radiation ratio f. In its turn, f depends on the solar zenith angle, on total ozone (at short wavelengths), and on the aerosol optical depth. At Lampedusa (minimum SZA = 12°) at 310 nm the direct component is always smaller than 57% (aerosol-free case) of the global irradiance; consequently, the cosine correction for Brewer 123 is always between 2.5 and 5% (corresponding to totally diffuse radiation field) for the old diffuser, and between 5 and 10% for the new diffuser. The correction was implemented assuming average aerosol conditions (optical depth of 0.3 at 550 nm) and total ozone (320 DU) and considering the dependence on solar zenith angle. By neglecting changes of aerosol optical depth and total ozone, an uncertainty of $\sim$1% and $\sim$2% must be added for the measurements obtained with the old and new diffuser respectively.

[11] The time period of data considered in this study is from 1 January 1998 to 31 August 2003. Owing to several instrumental problems, few measurements are available during the first part of 1998. Measurements were interrupted during part of year 2001 to allow maintenance work in the laboratory.

[12] Daily doses were calculated from the spectral UV irradiance measurements and weighted by the CIE erythemal action spectrum; a correction for the changes of the Sun-Earth distance during the year was applied to normalize the data set to 1 AU. The number of measurements is a function of the length of the day, so it is minimum in winter and maximum in summer. An insufficient number of acquisitions during daytime can be a source of error in the dose calculation, so we considered days when at least seven measurements were available. This choice excludes most of the measurements performed in the winter months, when the number of the UV scans per day varies between 3 and 6. Days when the scans were concentrated only in the morning or in the afternoon, or lacking of spectra around solar noon, i.e., close to the satellite overpass, were discarded. The number of days for which the acceptance criteria were met is 945 for all-sky conditions.

[13] Effective cloud-free days were defined using the direct Sun ozone measurements, performed frequently by

the Brewer throughout the day. The standard deviation of the total ozone value retrieved from direct Sun observation is dependent on the presence of clouds along the Brewer-Sun line of sight. Clouds induce a fast variability of the measured signals, thus producing an enhanced standard deviation on the total ozone value, which is calculated in the measurement routine as the average of five successive observations. Thus we use the standard deviation of the total ozone as an indication of the presence of clouds. This method is obviously not deterministic, but allows a reasonable discrimination of the data when other information on cloudiness is not available. For the identification of effective cloud-free days the following criteria were adopted. First, the daily number of total ozone measurements, N_{tot}, was calculated; measurements at air mass (μ) larger than 4 have been disregarded. Second, N, the number of measurements with a standard deviation, σ, not greater than 2.5 DU, was determined. Only days with N larger than 8 were considered. Effective cloud-free days are identified as those characterized by a ratio N/N_{tot} higher than 2/3 and by a standard deviation of the daily average not greater than 2%. Applying these criteria, 489 days were classified as effectively cloud-free. *Sabburg et al.* [2002] used σ as an indicator for the presence of clouds in conjunction with TOMS reflectivity, while *Gröbner and Meleti* [2004] defined a cloud-screening procedure taking into account both σ and the standard deviation for the AOD derived from the Brewer measurements.

[14] The AOD values have been derived from the measurements of the MFRSR, installed at Lampedusa in July 2001. The instrument measures the global and diffuse irradiance in six narrow bands centered at 415.6, 495.7, 614.6, 672.8, 868.7, 939.6 nm with 10 nm FWHM bandwidth, and in a broadband (300–1100 nm) channel; the direct radiation is derived as the difference between the global and the diffuse irradiances [*Harrison et al.*, 1994]. The instrument is calibrated by means of several Langley plots, performed in cloud-free half days characterized by small and stable aerosol amount. Low aerosol conditions are not usual at Lampedusa; however, because of the frequent cloud-free days, a relatively large number of useful calibrations are obtained (about 20 in the period July 2001 to September 2003 for the channel at 415.6 nm). The aerosol optical depth, AOD, at 415.6 nm is used for our purpose, since AOD in the UV is not available. The MFRSR acquires irradiances at fixed time intervals throughout the day; the frequency of measurements has changed from about one measurement every 30 minutes to one measurement per minute. On the basis of the evolution of global and diffuse irradiances it is possible to identify cloud-free days in a reliable manner. An experienced operator identified these days from a visual inspection of the data. This method produces a much more accurate determination of cloud-free periods than the one based on ozone observations. However, MFRSR data are available only after July 2001, and both definitions will be used in the analysis.

3. Satellite Data

[15] Erythemal dose values from the TOMS instrument on Earth Probe (EP) have been considered in this study. The TOMS UV daily dose over Lampedusa is estimated by a single measurement of six backscattered radiances at the time of the satellite overpass, around 1000 UT, and it represents an average of the atmospheric (particularly aerosol amount and cloud cover) and surface conditions over the area covered by the TOMS instrumental footprint, varying from approximately 26×26 km^2 at nadir to 60×33 km^2 at the maximum side-viewing scan angle [*Herman et al.*, 1999].

[16] Details of the retrieval algorithm are given by *Herman et al.* [1999] for Nimbus 7/TOMS. A similar procedure is applied to Earth Probe TOMS, except that 360 nm is used in place of the 380 nm reflectivity channel. In a first step, the clear-sky (cloud and aerosol free) irradiance is calculated by means of a radiative transfer model, and then a cloud correction factor is applied. This factor, which represents the ratio between cloudy-sky and clear-sky irradiance transmittance, is evaluated using the TOMS 360 nm irradiance and a plane-parallel radiative transfer model that assumes there is a homogeneous cloud layer between 700 and 500 hPa. Because the reflectivity of a cloud can be as high as that of snow (depending on age, depth and purity), snow cover can be misinterpreted as a cloud, thus causing an underestimation of the UV irradiance at the surface. The cloud correction factor is presumed to be valid throughout the day, thus large daily discrepancies between ground-based measurements and TOMS-derived erythemal doses can arise for cases with cloud cover variability during the day.

[17] Reflecting aerosols are taken into account in the cloud correction factor, while absorbing aerosols are included in the estimated UV irradiance using the TOMS aerosol index to obtain a correction factor based on an aerosol plume assumed as a thin layer at about 3 km height.

[18] According to *Herman et al.* [1999] the accuracy of the monthly erythemal dose estimated by TOMS is ±6% but increases to ±12% in Toronto, Canada, when absorbing aerosols (dust and smoke particles) were present. Studies of other Brewer sites have shown differences between 0 and 25% that appear to be associated with various forms of absorbing aerosols.

[19] The aerosol index (AI) expresses the alteration of the Rayleigh scattering wavelength dependence by absorbing aerosol with respect to a purely Rayleigh scattering atmosphere [see *Hsu et al.*, 1999], and is calculated using the 331 and 360 nm channels for EP/TOMS. The definition of the AI implies that positive values generally correspond to absorbing aerosol, while negative values to nonabsorbing aerosol; however, moderately absorbing aerosols that are near the Earth's surface cannot be differentiated from nonabsorbing aerosols [*Hsu et al.*, 1999]. This is thought to be the source of most of the differences between TOMS and ground-based measurements.

[20] In April 2001 TOMS calibration problems, which have been affecting ozone measurements after mid 2000, were discovered. Consequently, the erythemal dose and the AI after mid 2000 have both been affected. While TOMS measurements have undergone the new reprocessing, the daily version 7 data have been judged usable for most purposes, except for trend analysis.

[21] In this paper both versions 7 and 8 (V7 and V8) TOMS data have been used in order to assess how the comparison with the ground-based measurements improves with the most recent TOMS data set; moreover, previous comparisons refer to the V7 data.

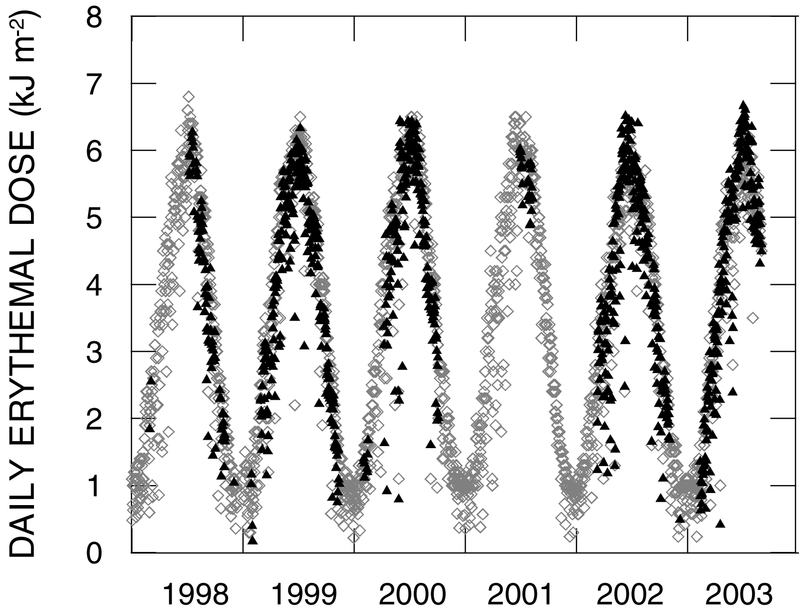

Figure 2. Time series (1998–2003) of erythemal dose measured at the surface by means of the Brewer spectrophotometer (triangles) and derived from version 8 TOMS observations (diamonds).

[22] The erythemal dose and the aerosol index given in a 1° latitude by 1.25° longitude grid have been linearly interpolated over Lampedusa (35.5°N, 12.6°E). The time series of TOMS satellite-derived dose measurements is continuous, apart occasional gaps of one or two days. From 13 December 1998 until 2 January 1999, a spacecraft anomaly occurred so that no scan data were acquired; analogous events stopped the instrument operation from 2 August to 12 August 2002 and from 15 May to 22 May 2003. The total number of TOMS daily dose values used in this study from January 1998 to August 2003 is 1983 for V7 and 1940 for V8.

4. Comparison Between Brewer and TOMS Erythemal Dose

[23] Figure 2 shows the comparison of the daily ground-based UV doses and the corresponding V8 TOMS-estimated doses from January 1998 (Brewer data start on March) to 31 August 2003. As previously discussed, because of

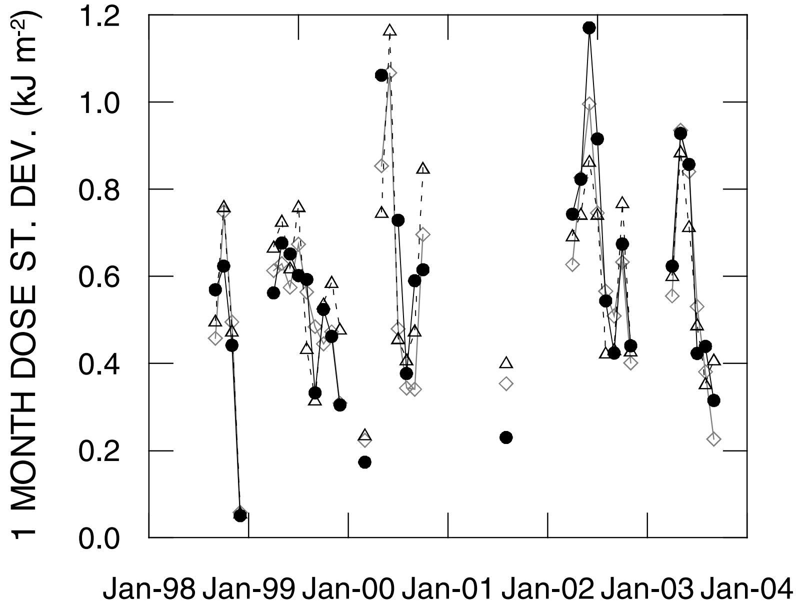

Figure 3. Time series (1998–2003) of the monthly standard deviation of the surface (circles) and satellite-derived version 7 (V7) (diamonds) and version 8 (V8) (triangles) daily erythemal dose, calculated for all-sky conditions.

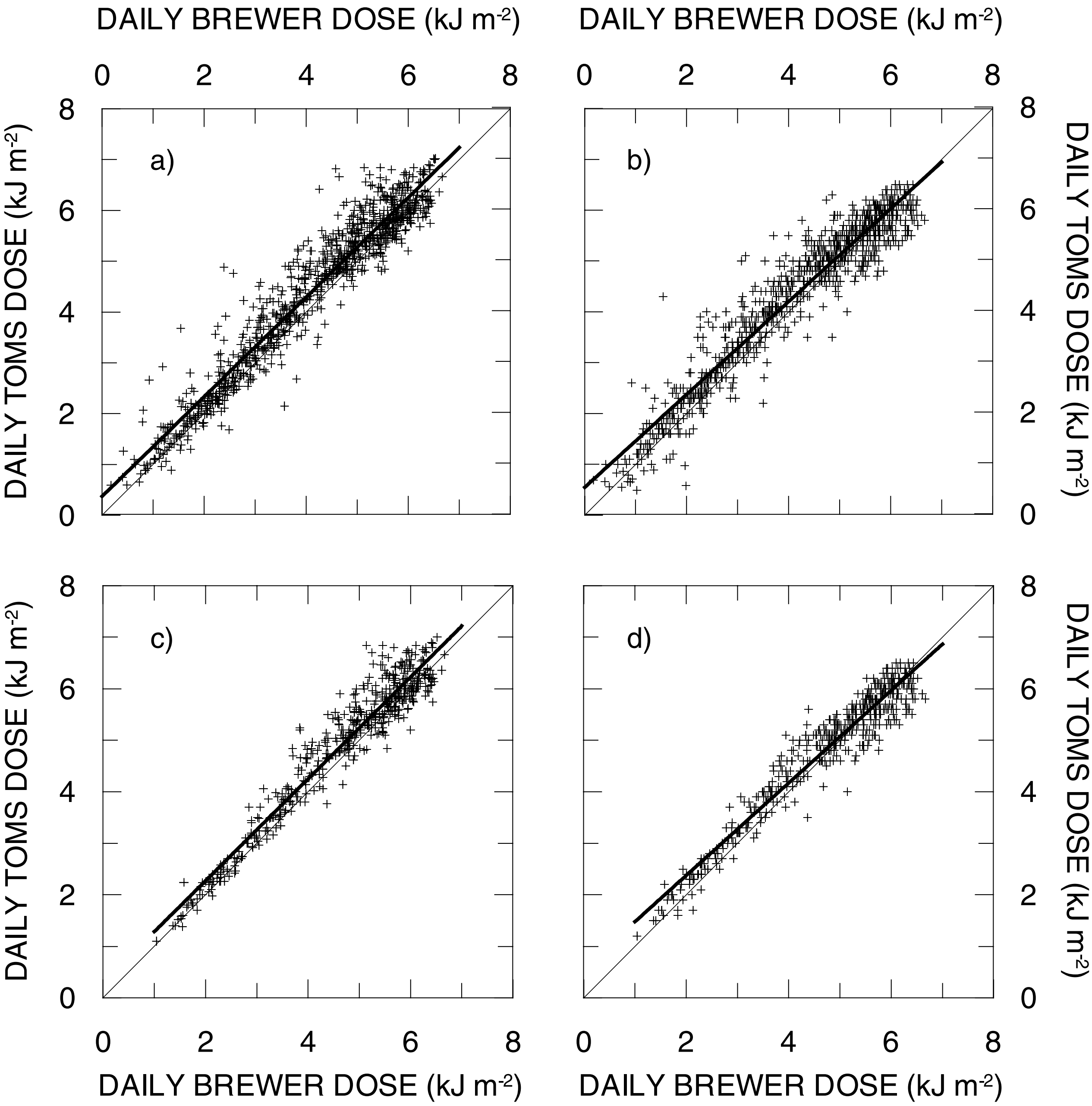

Figure 4. Scatterplot of satellite-derived versus the surface daily erythemal dose for (a) V7 and (b) V8 TOMS data and all-sky conditions and (c) V7 and (d) V8 TOMS data and effective cloud-free conditions. The regression lines are also shown. The thin line identifies the perfect correspondence between the two data sets.

several instrumental problems, few measurements are available during the first part of 1998, and observations are lacking during most of 2001. The evolution of the satellite-derived and ground-based erythemal doses is similar in Figure 2. The V7 TOMS doses are not shown in Figure 2. A more detailed discussion of the data follows and the differences with respect to the V8 data set will emerge in the analysis.

[24] The dispersion of the satellite-derived and ground-based measurements of UV dose was examined calculating the monthly standard deviation over the days when both Brewer and TOMS measurements are available. In Figure 3 a similar behavior of the two TOMS and the Brewer data sets for all-sky conditions is evident, with a linear correlation (R^2) of 0.84 and 0.76 for V7 and V8, respectively (significance level >99.99%).

[25] The scatterplots of the V7 and V8 TOMS daily dose versus the ground-based values are shown in Figures 4a and 4b for all-sky conditions and in Figures 4c and 4d for effective cloud-free days, respectively, while the statistics for the regression lines are reported in Tables 1 and 2. From Figure 4 it is clear how the restriction to cloud-free days eliminates outlying data and the lowest daily doses; the lowest doses lay on the 1-to-1 line, while the slopes of the regression lines are mainly determined by the intermediate to high dose values, measured in spring and summer. The

Table 1. Linear Regression Analysis Between Brewer and TOMS Estimates for All-Sky Conditions[a]

R^2	Slope	Intercept, kJ/m^2
	V7 TOMS	
0.922	0.980 ± 0.009	+0.372 ± 0.042
0.915	1.059 ± 0.003	0
	V8 TOMS	
0.912	0.915 ± 0.009	+0.544 ± 0.042
0.896	1.030 ± 0.004	0

[a]The square of the correlation coefficient (R^2) is given both for the best fit line and for the regression line constrained to pass through the origin. The number of cases is 935. The significance level is >99.99%.

slopes reported in Tables 1 and 2, obtained forcing the intercept to pass through the origin, show that TOMS data generally overestimate the daily doses, as evidenced by previous studies. The overestimation is larger for V7 data set than for V8 and for all-sky conditions: In the effective cloud-free cases the correspondence between Brewer and V8 TOMS doses is very close to the 1-to-1 line.

[26] *Herman et al.* [1999] found that weekly averaged UV irradiance measured by a Brewer spectroradiometer at Toronto is systematically 20% smaller than the TOMS estimates during the summer; nonetheless, taking into account the major sources of uncertainty, including aerosol absorption, of the two data sets, the ground-based measurements are in close agreement with those from space.

[27] From the analysis of the SUV-100 double monochromator measurements at San Diego in the period 31 October 1992 to 6 May 1993, *Kalliskota et al.* [2000] estimated that TOMS-derived CIE dose were higher than the ground-based measurements by 25%. The intercomparisons carried out by *McKenzie et al.* [2001] from the beginning of EP TOMS activity until 2000 produced similar results, with differences on the daily erythemal dose of 20–30% for the two European sites of Thessaloniki and Garmisch-Partenkirchen and about 15% for Toronto. *DeLuisi et al.* [2003] compared the TOMS UV irradiances with the observations taken from 1996 to 1999 at five U.S. stations equipped with the broadband UVB-1 instrument or Solar Light UV Biometer. Their results for all-sky conditions show biases of (17.0 ± 30.2)% for Bondville (Illinois), (10.6 ± 27.9)% for Boulder (Colorado), (0.44 ± 51.1)% for Fort Peck (Montana), (20.5 ± 21.5)% for Goodwin Creek (Mississippi), and (24.5 ± 29.3)% for Bismarck (North Dakota). The corresponding biases for cloud-free sky are (19.2 ± 5.5)% for Bondville, (15.6 ± 4.3)% for Boulder, (17.1 ± 5.2)% for Fort Peck, (18.1 ± 4.1)% for Goodwin Creek, and (17.9 ± 4.9)% for Bismarck.

[28] *Sabburg et al.* [2002] have compared the daily erythemal doses of four Brewer MKIV spectroradiometers of the U.S. Environmental Protection Agency (Boulder, Rocky Mountain, Gaithersburg, and Research Triangle Park) with the TOMS-derived data in the period 1996–2000, after accurate corrections for stray light, cosine errors, temperature dependence, temporal variations of the instrumental response. They estimated the percentage bias between the surface and the satellite data as 100(Brewer-TOMS)/TOMS and obtained that the Brewer doses for cloudless days were underestimated by biases between −1.4 and −12.5% with an average of −5% for the four sites, the lowest absolute value being that of Rocky Mountain site, about 2900 m above sea level, experiencing very low AODs during the year (0.09 in spring-summer and 0.05 in fall-autumn at 340 nm).

[29] We calculated the bias as 100(TOMS-Brewer)/Brewer and we found that the mean bias between the two data sets for all-sky conditions is (9.4 ± 19.8)% for V7 and (7.3 ± 20.0)% for V8, where the standard deviation is calculated on the sample of daily data. The large value of the standard deviation is attributable mainly to the non-homogeneity in the cloud cover and to the large satellite footprint. The differences in the mean bias between V7 and V8 TOMS data will be discussed in terms of aerosol absorption in the next paragraph.

[30] In effective cloud-free cases the bias is (5.6 ± 8.0)% for V7 and (3.4 ± 8.4)% for V8. A strong reduction of the standard deviation of the bias is evident, because of a higher homogeneity of the scene seen by the space-borne sensor for cloud-free cases. These mean bias values are sensibly lower than those reported by previous comparisons [*Herman et al.*, 1999; *Kalliskota et al.*, 2000; *McKenzie et al.*, 2001; *DeLuisi et al.*, 2003] and may be reasonably due to the fact that the surface characteristics within the satellite field of view are homogeneous at Lampedusa (see Figure 1).

[31] The standard deviation for all-sky conditions is lower or very close to those found by *DeLuisi et al.* [2003]; however, for effective cloud-free cases it is higher and may be reasonably explained with the large aerosol variability occurring at Lampedusa. The different methods applied to identify cloud-free periods may also play a role.

[32] It is worth noting that, calculating the bias with the expression used by *Sabburg et al.* [2002], our result for effective cloudless days is −(4.8 ± 6.9)% with V7 and −(2.7 ± 8.0)% with V8.

[33] As previously mentioned, effective cloud-free days have been selected according to the Brewer direct Sun ozone measurements. We have associated with each effective cloud-free day the V7 and V8 TOMS reflectivity at 360 nm and we have found that for most of the days the albedo is lower than 10%, with values larger than 15% representing 3.9% and 6% of the cases for V7 and V8, respectively (Figure 5). These cases do not necessarily represent the situation over the site of Lampedusa, because they are the result of an average over the TOMS field of view. The surface reflectivity determined by TOMS is about 4–6% over land and slightly higher over water. There is frequently a small amount of ground nonabsorbing haze that may add a few percent to the cloud-free reflectivity, so

Table 2. Linear Regression Analysis Between Brewer and TOMS Estimates for Effective Cloud-Free Conditions[a]

R^2	Slope	Intercept, kJ/m^2
	V7 TOMS	
0.929	0.989 ± 0.012	+0.296 ± 0.061
0.926	1.047 ± 0.004	0
	V8 TOMS	
0.930	0.898 ± 0.011	+0.580 ± 0.056
0.914	1.012 ± 0.003	0

[a]The square of the correlation coefficient (R^2) is given both for the best fit line and for the regression line constrained to pass through the origin. The number of cases is 487. The significance level is >99.99%.

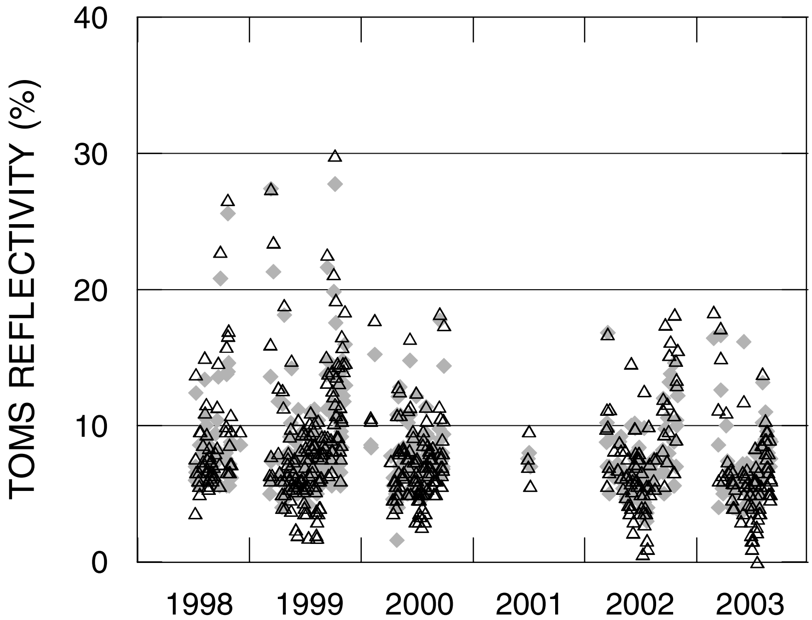

Figure 5. Time series (1998–2003) of V7 (diamonds) and V8 (triangles) TOMS reflectivity for effective cloud-free days.

the reflectivity value of 10% can be reasonably representative for the albedo on a cloud-free scene. Considering only days with TOMS reflectivity lower than 10% (406 cases for V7 and 374 for V8), we obtain a bias of (6.0 ± 7.8)% for V7 and (3.0 ± 7.8)% for V8. Thus, by applying the identification of cloud-free days by means of the Brewer ozone measurements we obtain substantially the same results as derived by screening the TOMS reflectivity values below 10%. In the papers by *Herman et al.* [1999] and *Kalliskota et al.* [2000] cloud-free days are those for which the TOMS reflectivity is lower 10%, while *McKenzie et al.* [2001] fixed to 20% the reflectance threshold value.

[34] *Herman et al.* [1999] have shown that the comparison of weekly and monthly averages of the daily doses produces a better agreement between ground-based and satellite observations; since the TOMS dose is estimated on the base of a single measurement occurring near local noon for each Earth location, it can not take into account the rapid changes in clouds and aerosol amount that ground-based acquisitions can catch. We considered the weekly averages of the daily TOMS and Brewer doses, selecting only weeks with 3 or more days of measurements: The bias decreases to (6.4 ± 7.9)% for all-sky conditions and to (2.8 ± 6.8)% for effective cloud-free conditions. The standard deviations for all-sky conditions are sensibly lower for the weekly averages, but the mean biases are only slightly lower than those obtained for the daily doses: This proves that the observed biases reflect actual differences between the TOMS and the Brewer doses. Similar conclusions were reached by *Kalliskota et al.* [2000].

5. Aerosol Effect on the Retrieved TOMS Doses

[35] In order to study how aerosols influence the relationship between satellite-derived and ground-based measurements of UV dose, the analysis was carried out dividing days with different aerosol index; the mean TOMS/Brewer dose ratio was calculated for each class. In our study the comparison with the V7 TOMS erythemal dose and AI covers the period 1998–2000: The interruption of the Brewer measurements during most of year 2001 and the TOMS calibration problem afterward prevent a meaningful comparison after year 2000. On the other hand, the V8 TOMS product for the entire time interval of the Brewer measurements is used in the comparison.

[36] The AI definition has changed in the V8, because of the choice of slightly different wavelengths, so that the V8 AI values are larger than the V7 values: At Lampedusa the V7 AI ranges between −1.5 and 2.5 in the 1998–2000 period, while V8 AI values change in the interval 0–5 from 1998 to 2003. For V7 data, four cases were identified; the results are reported in Table 3, and evidently show that the bias increases with the AI from 3 to 21%.

[37] Day-to-day variability of TOMS and Brewer erythemal dose have been examined for the period of the Photochemical Activity and Ultraviolet Radiation modulat-

Table 3. Mean and Standard Deviation of the Bias Between V7 and V8 TOMS-Derived and Ground-Measured Daily Erythemal Dose for Various Classes of Aerosol Index (AI) Values[a]

	N	Bias, %
	V7 AI	
$-1.5 \leq AI < -0.5$	23	3.0 ± 1.0
$-0.5 \leq AI < 0.5$	179	5.5 ± 0.5
$0.5 \leq AI < 1.5$	46	13.1 ± 1.3
$1.5 \leq AI < 2.5$	10	21.0 ± 2.9
	V8 AI	
$0 \leq AI < 1$	243	6.3 ± 0.5
$1 \leq AI < 2$	92	2.8 ± 0.9
$2 \leq AI < 3$	44	−3.4 ± 1.3
$3 \leq AI < 4$	11	−6.4 ± 1.7
$4 \leq AI < 5$	3	−7.9 ± 1.1

[a]Time period is from 1 January 1998 to 31 December 2000 for V7 and from 1 January 1998 to 31 August 2003 for V8.

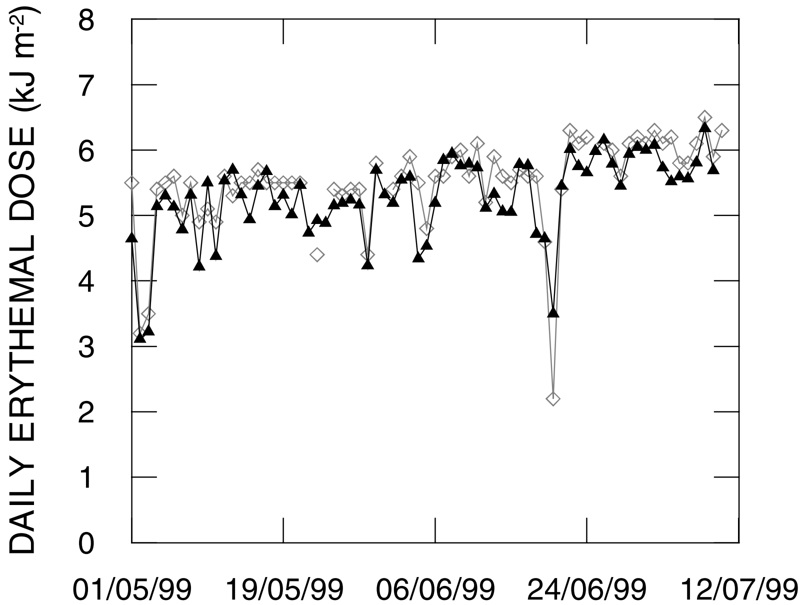

Figure 6. Time series of the erythemal dose measured at the surface (triangles) and derived from V8 TOMS observations (diamonds) during the Photochemical Activity and Ultraviolet Radiation modulating factors (PAUR II) campaign (1 May to 10 July, 1999).

ing factors (PAUR II) campaign [*Zerefos et al.*, 2002] from 1 May to 10 July 1999 when a large daily number of Brewer spectra were measured. Figure 6 shows the comparison of the ground-based with the V8 TOMS daily dose for all-sky conditions: V7 and V8 TOMS values are higher that the Brewer ones by (7.8 ± 1.0)% and (3.8 ± 1.0)%, respectively. During the campaign a variety of aerosol conditions occurred, with desert dust coming from the Sahara, producing large optical depths and enhanced aerosol amounts reaching up to 8 km altitude, and aerosol from Europe or North Atlantic, with low-to-moderate optical depths [*di Sarra et al.*, 2002].

[38] The agreement has been examined by grouping days according to the different paths followed by the air masses reaching Lampedusa [*di Sarra et al.*, 2001] and taking into account the aerosol index values: The results are reported in Table 4. Class a includes all the isentropic trajectories that did not pass over Africa (thus arriving from Europe or North Atlantic), class d includes those that spent several days over Africa (thus carrying Saharan dust), and classes b and c represent the intermediate situations, with trajectories that marginally overpass Africa. As expected, the UV absorbing desert dust produces the largest bias and the highest AI for V7 data among the various classes; when using the V8 TOMS doses the bias is always smaller than 6% and shows a smaller dependency on the different aerosol classes.

[39] The differences in the bias using the two TOMS data set can be explained with the aerosol-ozone correction which has been introduced in V8 algorithm. If there are unaccounted absorbing aerosols in a TOMS cloud-free scene, the calculated reflectivity is decreased from its proper value. In addition to the effect on scene reflectivity, absorbing aerosols reduce the apparent amount of retrieved ozone by reducing the spectral contrast caused by the ozone absorption cross section [*Torres and Bhartia*, 1999]. They show how the error in the estimate of the satellite-derived total ozone is related to the TOMS aerosol index values, with larger ozone underestimations for high AI (approximately a 1% error in retrieved ozone amount for each AI of aerosol), depending on the aerosol type, optical depth and aerosol layer height. For example desert dust, characterized by high AI values (up to 5–6), can produce errors as large as 10%, while carbonaceous aerosols from biomass burning produce smaller errors. Since at midlatitudes a 1% decrease in ozone amount produces about 1% increase in erythemal irradiance, the presence of TOMS-detected absorbing aerosols will determine an increase in erythemal irradiance just because of the ozone error. An additional erythemal irradiance and dose overestimate will occur from the portion of TOMS undetected aerosol.

[40] We have examined the percent difference between the Brewer and V7 TOMS daily average total ozone as a function of the daily average AOD derived from the MFRSR measurements at 415.6 nm in the period 14 July 2001 to 31 August 2003 (Figure 7). In order to reduce possible errors, we focus only on the cases for which the sky was cloud-free throughout the day according to the MFRSR irradiance measurements: The number of cloud-free days for which the MFRSR AOD is available is 60. The range of variability

Table 4. Mean and Standard Deviation of the Bias Between TOMS-Derived and Ground-Measured Daily Erythemal Dose for Days of the PAUR II Campaign Grouped in Classes According to the Air Mass Isentropic Trajectory[a]

	V7 TOMS		V8 TOMS	
Class	AI	Bias, %	AI	Bias, %
a	0.1 ± 0.1	2.0 ± 2.2	0.4 ± 0.2	2.4 ± 2.4
b and c	0.4 ± 0.1	6.5 ± 2.5	1.0 ± 0.2	4.2 ± 2.1
d	1.1 ± 0.1	11.8 ± 1.3	1.9 ± 0.2	5.1 ± 1.8

[a]The mean values and the standard deviation of the TOMS aerosol index are also reported. PAUR II is the Photochemical Activity and Ultraviolet Radiation modulating factors campaign.

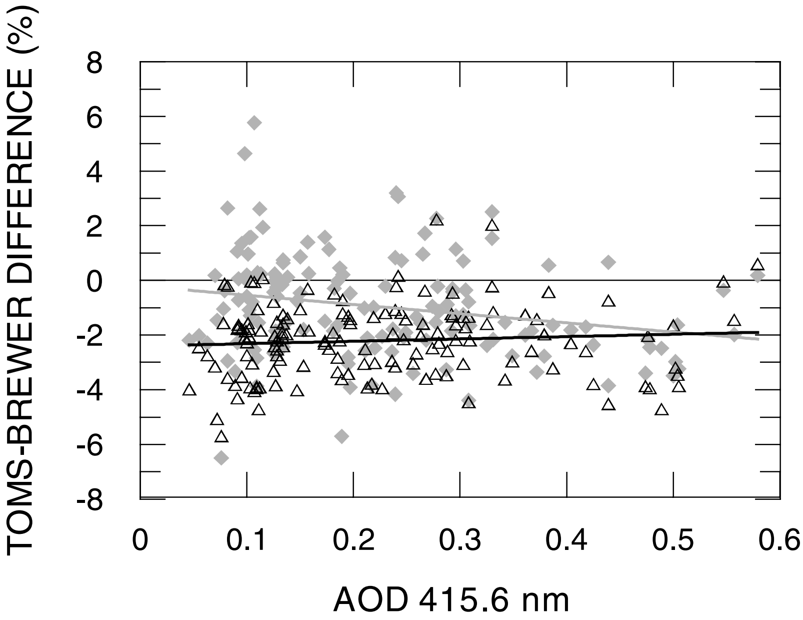

Figure 7. Percent difference of the TOMS V7 (diamonds) and V8 (triangles) and the Brewer daily average total ozone as a function of the daily average MultiFilter Rotating Shadowband Radiometer aerosol optical depth (AOD) at 415.6 nm for the cloud-free days in the period 14 July 2001 to 31 August 2003. The regression lines are also shown.

for the AOD in these cases is 0.078–0.551. The regression slope shows that the TOMS ozone is underestimated for values of the AOD larger than 0.3, and the discrepancies with Brewer measurements can be as large as 3% for AODs around 0.47–0.50. When the V8 TOMS ozone is used, the difference with the Brewer daily average tends to be independent on the AOD and remains around −2%.

[41] The aerosol index has been used to derive a correction to the estimated ozone amounts [*Torres and Bhartia*, 1999] so that the retrieval has an aerosol induced ozone error of less than 1%. The residual error in ozone would lead to an error in the TOMS erythemal irradiance and dose of less than 1%. Since there is also an aerosol correction in the reflectivity based on the aerosol index, the main effect would be in the fraction of aerosol absorption that is not detected by TOMS. If we take into account the V8 TOMS erythemal dose and AI values, the bias significantly changes, as reported in Table 3: As the AI varies from the lowest values (0–1) to the highest (4–5), the bias passes from positive (6.4 ± 0.5)% to negative −(7.9 ± 1.1)% values. According to *Herman et al.* [1999] the accuracy of the V7 TOMS doses is within ±6% under nonabsorbing aerosol conditions and within ±12% with dust and smoke aerosols; our results show that under varying aerosol conditions (both absorbing and nonabsorbing par-

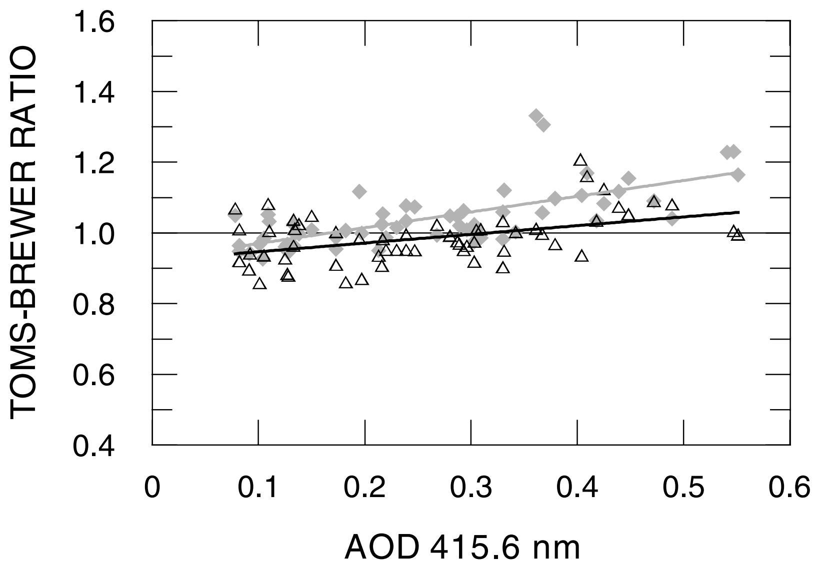

Figure 8. Ratio of V7 (diamonds) and V8 (triangles) satellite-derived to surface daily erythemal dose as a function of the daily average AOD at 415.6 nm for the cloud-free days in the period 14 July 2001 to 31 August 2003. The regression lines are also shown.

Table 5. Mean and Standard Deviation of the Bias Between TOMS-Derived and Ground-Measured Daily Erythemal Dose for Various Classes of AOD Values[a]

AOD	N	V7 TOMS Bias, %	V8 TOMS Bias, %
$0.0 \leq$ AOD < 0.1	5	−3.1 ± 2.1	−3.2 ± 3.2
$0.1 \leq$ AOD < 0.2	18	0.6 ± 1.2	−4.2 ± 1.8
$0.2 \leq$ AOD < 0.3	14	2.8 ± 1.0	−3.5 ± 0.8
$0.3 \leq$ AOD < 0.4	12	7.9 ± 3.5	−2.0 ± 1.3
$0.4 \leq$ AOD < 0.5	8	9.9 ± 1.7	8.5 ± 2.6
$0.5 \leq$ AOD < 0.6	3	20.7 ± 2.2	0.1 ± 0.5

[a]AOD is aerosol optical depth. The period refers from 14 July 2001 to 31 August 2003.

ticles), TOMS data provide a good estimate of erythemal dose at the surface.

[42] The TOMS/Brewer dose ratio have been related to the daily average AOD derived from the MFRSR measurements at 415.6 nm in the period 14 July 2001 to 31 August 2003. In Figure 8 the V7 TOMS/Brewer dose ratio is plotted as a function of the AOD at 415.6 nm: The correlation (R^2) is 0.47, with a significance level >99.99%. The regression line for the V7 data set clearly indicates that the ratio increases for increasing AOD. The growth rate for the ratio is 0.44 ± 0.06 for a unit AOD at 415.6 nm. *McKenzie et al.* [2001] found a rate of 0.60 for a unit AOD at 340 nm, considering the daily erythemal doses of Lauder (New Zealand), Thessaloniki (Greece) and Toronto (Canada). For the smallest AOD values, corresponding to a very clean atmosphere, the ratio is around 1, increasing rapidly to 1.08 for AOD around 0.35, i.e., for the average aerosol loading at Lampedusa. To highlight this feature, we have divided the AOD into six classes, and we have calculated the TOMS-Brewer bias for each class: Table 5 shows the results. Situations of high AODs are very often associated to Saharan dust outbreaks, causing, as already mentioned, strong absorption in the UV due to low single scattering albedo of dust aerosols [*Meloni et al.*, 2003]; the bias between V7 TOMS and Brewer erythemal dose can reach values as high as 25%. If the V8 TOMS data are used, the correlation (R^2) is lower (0.20) and the growth rate decreases to 0.25 ± 0.07 for a unit AOD at 415.6 nm; the ratio for AOD around 0.35 is about 1. From Table 5 a clear dependence of the V8 TOMS/Brewer ratio on the AOD is not discernable.

[43] Under clear-sky conditions, the aerosol optical depth and single-scattering albedo (i.e., the portion of aerosol absorption) can be derived [*Torres et al.*, 2002]. The comparison of the TOMS-derived with the ground-based measurements of AOD from AERONET sunphotometer shows that the agreement is within 30% in presence of UV-absorbing aerosols and within 20% for nonabsorbing aerosols. Use of AOD and single scattering albedo values to correct the ozone amount and account for aerosol absorption of UV radiation substantially reduces the difference between TOMS UV irradiance estimates and Brewer measurements.

6. Conclusions

[44] In order to properly take advantage of the long time series of globally distributed surface UV observations performed from the TOMS sensor, validations with measurements from well-calibrated and well-maintained ground-based spectrometers are necessary. Since the presence of absorbing aerosols is the main source of differences between ground-based measurements of irradiance and TOMS estimations, it is also desirable to have colocated instruments for detecting aerosol optical depth. The performance of the Brewer 123, operative at Lampedusa Island, in the Mediterranean, since 1998, is continuously checked in order to obtain accurate measurements of total ozone and UV spectra. Since 2001 the AOD at 415.6 nm is derived from measurements with a MFRSR Sun photometer. Lampedusa is often exposed to Saharan dust events, characterized by relatively large values of UV absorbing particles [e.g., *di Sarra et al.*, 2001, 2002; *Meloni et al.*, 2003]. Thus, at Lampedusa the comparison of the ground-based and satellite-derived daily erythemal doses is feasible and the role of the tropospheric aerosols can be examined. Moreover, the small dimensions of the island and its position in the Mediterranean, far from continental areas, make Lampedusa a very good site for the retrieval and validation of satellite data.

[45] The main results of this paper are as follows:

[46] 1. Persistent large differences between V7 TOMS and Brewer erythemal doses were observed. The differences reach 25% for conditions of heavy aerosol loading. The mean bias between the Brewer and the V7 TOMS data sets for cloud-free conditions is (5.6 ± 8.0)%. We show that the bias depends on the aerosol loading: It increases with AI and AOD at 415.6 nm, from ± 3% for low AI and AOD, up to 21% for $1.5 \leq$ AI < 2.5, and $0.5 \leq$ AOD < 0.6. These differences arise from an uncorrected ozone error caused by the presence of aerosols and from the fraction of aerosols that are not detected by TOMS.

[47] 2. The uncorrected ozone error was investigated by comparing the total ozone measured by the Brewer with V7 and V8 TOMS ozone in relation to the AOD at 415.6 nm. The Brewer-V7 TOMS differences are nearly zero for AOD < 0.2 and increase for larger AODs. In V8 TOMS data a correction of the aerosol effect on the ozone retrieval (and the erythemal UV) was implemented. The percent differences between the Brewer and the V8 TOMS-derived total ozone are substantially independent on the AOD, showing that the correction for the aerosol absorption sensibly improves the satellite estimates.

[48] 3. The mean bias between V8 TOMS and Brewer erythemal doses is (3.4 ± 8.4)% for cloud-free conditions; it varies between +6% for $0 \leq$ AI < 1 and about −8% for $4 \leq$ AI < 5. That is, it remains within the respective uncertainties of the Brewer and TOMS measurements.

[49] 4. For very low aerosol loading (AOD at 415.6 nm below 0.2), the ratios of both V7 and V8 TOMS/Brewer erythemal dose are approximately 1, indicating that the radiometric calibration of the Brewer instrument is consistent with the TOMS estimated irradiances from derived ozone and Rayleigh scattering attenuation.

[50] 5. The correction of the TOMS aerosol error appears to account for most of the observed differences in erythemal doses, the remaining differences probably being due to a not accurate detection of the aerosol near the surface.

[51] **Acknowledgments.** This research was funded by the Ministero per l'Ambiente e la Tutela del Territorio of Italy. The image of Lampedusa from the International Space Station is courtesy of Earth Sciences and

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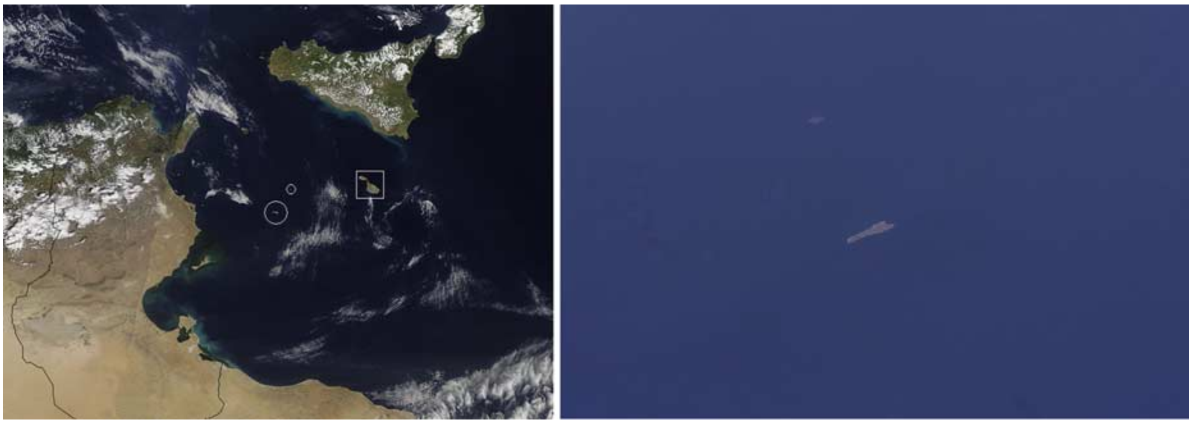

Figure 1. Lampedusa Island (large circle) as seen from (left) Moderate Resolution Imaging Spectroradiometer (MODIS) and (right) the International Space Station in 2001 (picture ISS002-338-30). The small island of Linosa (small circle) is visible north of Lampedusa, and Malta (square) is visible to the northeast. Dust regularly blows over Lampedusa from Africa (Tunisia, Algeria, and Libya).