Comparison of GOME-2 UVA Satellite Data to Ground-Based Spectroradiometer Measurements at a Sub-tropical Site

A.V. Parisi[1,*], N. Downs[1], J. Turner[1] & R. King[1]

[1]Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba. Australia

[*]Corresponding author: Ph: +61 7 4631 2226; Email: parisi@usq.edu.au

Abstract

The UVA (315-400 nm) daily exposures and maximum daily irradiances from the GOME-2 satellite have been compared over three years to the corresponding data from a ground-based spectroradiometer for a sub-tropical Southern Hemisphere site. This is one of the first such comparisons for the GOME-2 UVA waveband in the Southern Hemisphere. For the UVA daily exposures and the maximum daily irradiances, the comparisons were undertaken for all sky conditions and for cloud free conditions. Under cloud free conditions the R^2 of the fitted regression line for the comparisons was 0.93 for the exposures and the irradiances. The influence of cloud reduced the R^2 values to 0.86 and 0.70 for the daily exposures and maximum irradiances respectively. The relative root mean square error (rRMSE), mean absolute bias error (MABE) and mean bias error (MBE) for the maximum daily UVA irradiances on the cloud free days were 0.08, 6.59 ± 7.32% and -1.04 ± 9.83% respectively. Similarly, for the daily UVA exposures on the cloud free days, the rRMSE, MABE and MBE were 0.10, 5.19 ± 6.42% and -0.79 ± 8.24% respectively. For the all sky conditions, the corresponding values were 0.20, 15.23 ± 14.90% and -0.79 ± 8.24% for the maximum daily irradiances and 0.19, 14.17 ± 14.56% and -4.63 ± 20.60% for the daily exposures. In any studies on the influence of UVA on human health, this can complement ground-based measurements that provide the

higher temporal and spatial resolution available only at a limited number of surface monitoring sites.

1. INTRODUCTION

Solar UV radiation increases the risk of skin cancer and sun-related eye disorders and also has the potential to damage plants, animals and ecosystems. Research to reduce the damaging effects requires the long term monitoring of solar UV exposures. There are several ground-based UV monitoring networks (for example, see [1], [2], [3]). In addition to these, satellite platforms for the monitoring of solar UV radiation reaching the surface of the earth are necessary for the provision of temporal and spatial global coverage on a time repetitive basis and for the establishment of any global trends. Typical satellite based instruments include the Ozone Monitoring Instrument (OMI) providing evaluation of solar UV since the 15th July 2004 [4], [5] and the second Global Ozone Monitoring Experiment (GOME-2) spectrometer on the polar orbiting Metop-A and Metop-B (Meteorological Operational) satellites. These GOME-2 satellites were launched in October 2006 and September 2012 respectively [6]. Metop-B has taken over the prime service with data available from 1 March 2014. The GOME-2 instrument has been providing data on atmospheric ozone, aerosols, trace gases and UV radiation [7] with the data products provided on a 0.5^o x 0.5^o regular latitude-longitude grid [6]. Since June 2009, the data set provided has included the UVA (315-400 nm) daily exposures and UVA daily maximum irradiances. This UVA data are necessary in research on the health effects of UV radiation due to the damaging influence of UV radiation extending into the UVA waveband [8]. This UVA data from the respective satellites require validation against ground-based instrumentation sensitive to local surface conditions.

For the UV irradiances and exposures, the OMI data overestimates the ground-based erythemal irradiances and the erythemal exposures over low albedo sites not covered by snow, with the difference ranging from 14 to 34% [9]. A comparison with 18 reference spectral instruments found that for snow free sites the daily erythemal exposures were within ±20% of the corresponding surface measurement for 60 to 80% of the values [10]. Mateos et al., [11] intercompared the erythemal UV from OMI to the erythemal UV from 14 ground-based stations over five countries between 43° N and 64° S with stations having data at different periods over 2005 to 2011. The average differences were a maximum of 25% for all-sky cases. Considering only the cases of cloudless skies provided an agreement of 10 to 20%. The application of a correction factor based on the aerosol absorbing optical thickness provided an improvement in the agreement with the difference falling to less than 20% for 90% of the cases [11]. A validation report of offline erythemal UV products from GOME-2 against 15 ground-based stations for data between June 2007 and May 2008 have found a positive bias of 10-20% for daily erythema UV exposures [12], [13]. A smaller, but still positive bias was found for the daily maximum irradiances.

While comparisons with erythemally effective UV are important, there has been, to the authors' knowledge only one comparison at 67.37 °N of the GOME-2 UVA data with ground-based instrumentation [12], with no previous comparison in the Southern Hemisphere. The UVA wavelengths are not affected by the potential under prediction of ozone by satellite due to the minimal absorption by ozone in the UVA waveband. However, there is aerosol absorption in the UVA waveband. Therefore, it is hypothesised that the general positive bias in the erythemal satellite data also exists in the UVA waveband and a comparison for the UVA waveband is required. This will be investigated by comparing GOME-2 daily UVA exposures and daily UVA maximum irradiance over a period of three years with ground-based spectroradiometer data for a sub-tropical Southern-Hemisphere site for all sky conditions and for cloud free conditions.

2. MATERIALS AND METHODS

A. Satellite UVA Data

The GOME-2 UVA data over the sub-tropical Southern Hemisphere ground site of Toowoomba, Australia (27.6 ºS, 151.9 ºE, 693 m asl) were obtained through the O3M SAF (Ozone Monitoring and Atmospheric Chemistry Satellite Application Facility) [7] web site (http://o3msaf.fmi.fi/offline_access.html). The data is typically available between three and fifteen days after collection. Toowoomba is a relatively unpolluted, inland regional city located approximately 130 km from the Pacific Ocean with the surrounding areas being generally devoted to agriculture. The albedo of the surroundings are of the order of 2% for vegetation to less than 8% for soil to 16% for concrete [14].

The GOME-2 UV data set is developed by calculation of the clear sky UVA at half hourly intervals of each day with a radiative transfer model [6], and corrections are applied by the evaluation of input parameters from available satellite information. These include daily ozone information from the GOME-2 and aerosols and albedo obtained from climatological values. The cloud optical depth information is obtained from the Advanced Very High Resolution Radiometer (AVHRR/3) onboard the Metop satellites and the National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellites (POES) in the morning (equatorial overpass time of approximately 9:30 local time) and afternoon (approximately 14:30 local time) respectively [5], with interpolation of the cloud optical depths to other sunlit times. Trapezoidal integration of the half hourly irradiance values over each day provides the daily exposures and allows evaluation of the maximum daily irradiances. These UVA exposures and irradiances provided on the O3M SAF web site that have been evaluated using the above data sources are referred to in this paper as the GOME-2 UVA data.

Approximately three years of UVA exposures and irradiances for the period 8 June 2009 to 18 August 2012 were accessed covering the Toowoomba measurement site [7]. Over this site, annual maximum and minimum noon time solar zenith angles (SZA) are 41^o and 4.5^o respectively [15]. The retrieved GOME-2 data over this period provided a total of 874 days.

B. Ground-Based UVA Data

The ground-based daily UVA exposure and the maximum daily irradiance for the comparison with satellite data were measured with a spectroradiometer (model DTMc300, Bentham Instruments, Inc. UK) calibrated to the National Physical Laboratory, UK standard and located in a temperature stabilized enclosure on a rooftop site at the University of Southern Queensland, Toowoomba campus. This instrument automatically records the solar UV spectrum every ten-minutes in 0.5 nm increments from 280 to 400 nm [16], with the initialization of a scan and the data collection taking a total of approximately three minutes. The overall absolute irradiance accuracy of this data is of the order of ± 9% due to the temporal stability, cosine error, dark count variability and the traceability of the absolute irradiance of the calibration lamps [16]. The ± 9% accuracy was evaluated from the addition of the manufacturer provided errors and the average for the variation in the scans of a given UV source. Comparison to satellite data was made for the periods when the ground-based instrument was operational over the complete day (5:00 to 19:00 local time). The unweighted spectral data were summed from 315 to 400 nm and multiplied by the wavelength increment to provide the integrated spectral UVA irradiances in W/m^2 at ten-minute intervals. The maximum of the ten-minute UVA irradiances for each day was determined from this data. Trapezoidal integration of the irradiances over each ten-minute time period between spectral scans and summation over each day provided the total daily UVA exposure. A total of 664 days of ground-based spectroradiometer data were available for analysis in the period 8 June 2009 to 18 August 2012. From this a total of 489 matching days of ground-based UVA and GOME-2 satellite UVA data were available for comparison.

The cloud free days over the site, defined as days during which the maximum daily cloud cover did not exceed two octas (or two eighths) cloud were determined through the use of an automated ground-based total sky imaging camera (model TSI440, Yankee Environmental Systems, PA, USA), with 62 days being cloud free out of a total of 489 days. This instrument is located on the same building roof and within five metres of the spectroradiometer. Both the instruments have an unobstructed hemispherical sky view. An image is collected by the sky camera every ten-minutes at the same time as the start of each spectroradiometer scan. The images were downloaded to a network connected computer where the TSI440 image analysis software calculates the fraction of cloud cover [17].

A linear regression line was fitted to the comparison of the GOME-2 UVA maximum daily irradiance data with the corresponding ground-based Bentham spectroradiometer data set for all sky conditions and the cloud free data separately. This was repeated for the daily UVA exposures. The relative root mean square error (*rRMSE*) was calculated between the GOME-2 and the corresponding Bentham spectroradiometer daily maximum irradiance and daily total exposures for both sky condition sets as follows:

$$rRMSE = \sqrt{\frac{1}{N}\sum_{1}^{N}\left(\frac{UVA_{Ground}-UVA_{Predicted}}{UVA_{Ground}}\right)^{2}} \quad (1)$$

where N is the number of data pairs of GOME-2 and Bentham spectroradiometer data, UVA_{Ground} is each ground-based Bentham spectroradiometer value and $UVA_{Predicted}$ is the corresponding UVA value predicted from the GOME-2 regression model. For both the UVA maximum daily irradiance data and the UVA exposure data the Mean Absolute Bias Error (MABE) was calculated as the average, absolute difference between observed ground values and predicted UVA values based on the corresponding regression scale factor. The Mean Bias Error (MBE) was also calculated to provide an indication of direction in over- or under-estimation as well as change in magnitude [18].

3. RESULTS AND DISCUSSION

The time series of three years of GOME-2 UVA daily exposures and the daily maximum irradiances are provided in Figure 1. The cyclical variation in the UVA daily exposures and the maximum irradiances for the day are due to SZA changes with season. For a given SZA, the most significant influence causing the variation from the expected annual cloud free envelope is the presence of cloud, the other is aerosols. The influence of atmospheric ozone levels is minimal in the UVA waveband compared to the UVB due to the significant drop in the ozone absorption cross section for UVA wavelengths compared to the UVB [19]. The maximum and minimum daily UVA exposures in the GOME-2 UVA data that were matched with the ground-based data were 1.8 MJ/m^2 and 0.248 MJ/m^2 respectively with a median of 1.05 MJ/m^2 and the corresponding ground-based daily UVA exposures were 1.5 MJ/m^2, 0.12 MJ/m^2 and 0.80 MJ/m^2 respectively. Similarly, maximum daily GOME-2 irradiances over each day in the 8 June 2009 and 18 August 2012 period ranged from 64.3 to 12.1 W/m^2 with a median of 46.7 W/m^2 and the corresponding ground-based values were 68.6, 7.5 W/m^2 and 43.0 W/m^2.

A. Cloud free comparison

A comparison of the GOME-2 maximum daily UVA irradiances compared to the corresponding ground-based values is provided in Figure 2 for the cloud free days. There are a total of 62 cloud free days compared to 489 days for all sky conditions. For all but one of these cloud free days the maximum daily UVA irradiance estimated from the GOME-2 satellite was higher than the same day ground-based estimate. The linear regression analysis indicated an average rate of change in ground measured data with satellite measured data (slope) of 0.95 (Table 1). The R^2 value of 0.93 indicates that 93% of the variability in ground-based UVA data was explained by the linear relationship between the two variables (Table 1). The rRMSE for these cases was 0.08 (Table 1) . The MABE % (± standard deviation) was 6.59 ± 7.32 and MBE % (± standard deviation) was -1.04 ± 9.83. In a similar manner, Figure 3 provides a comparison of the GOME-2 daily UVA exposures compared to the corresponding ground-based values for cloud free days. The GOME-2 satellite data showed a positive bias for all 489 days when compared to the same day's ground-based estimates. The average rate of change (slope) of the linear relationship between satellite and ground based UVA measurements for cloud free days only was 0.84 with an R^2 of 0.93 and a rRMSE of 0.10 (Table 1). The MABE % was 5.19 ± 6.42 and the MBE % was -0.79 ± 8.24.

A possible explanation for satellite over-estimation may include the presence of local particulates and absorbing aerosols, including smoke and other tropospheric pollutants. The low altitude and potentially finite spatial influence of local atmospheric contributions are difficult to measure on larger scales by remote satellite instrumentation. The high R^2 values and relatively low MABE values indicate that although the satellite measurement system tends to estimate higher UVA values for both irradiances and exposures than does the ground-based system, there is a relatively consistent linear relationship between the two data sets when cloud free days only are considered.

B. All sky conditions

The comparison for all sky cases is provided in Figures 4 and 5 for the maximum daily UVA irradiances and for the daily UVA exposures. The influence of cloud has reduced the R^2 values to 0.70 and 0.86 and increased the *rRMSE* to 0.20 and 0.19 for the maximum irradiances and the daily exposures respectively as is seen by the higher degree of scatter of the data points. The MABE % was 15.23 ± 14.90 and the MBE % was -0.79 ± 8.24 for maximum daily irradiances and 14.17 ± 15.56 and -4.63 ± 20.6 respectively for daily UVA exposures. The greater variation in the data sets reflected in these results is most likely due to the changes in cloud cover throughout the day affecting the ground-based measurements between the two daily satellite observation times. The GOME-2 data incorporates the cloud fraction in the morning from the Metop satellites and in the afternoon from the NOAA POES satellite. This satellite data is a spatial average of the 0.5° x 0.5° pixel size area over the Toowoomba ground measurement site whereas the spectroradiometer data are temporal averages over the measurement times, taking into account the variations in local cloud cover every ten-minutes. Any differences in the parameters of the cloud, such as fraction, type, proximity with respect to the sun during the period of the measurement of the UV spectrum at the ten-minute spectroradiometer measurement times or variations in the cloud parameters over the satellite measurement pixel size are not taken into account in the comparison of the satellite and ground site data sets.

The research considered the appropriateness of using GOME-2 UVA measures as substitutes for ground-based methods in areas of no ground-based coverage, for a 0.5° x 0.5° area surface similar to Toowoomba. In this context the regression analysis is used to determine how accurately GOME-2 data (independent variable – *x* axis) predicted UVA measures from ground-based methods (dependent variable –*y* axis). As hypothesized in the Introduction, there was a positive bias in the GOME-2 UVA satellite data due to aerosol absorption being present in the UVA waveband, with variability in the results due to the influence of clouds. This is comparable to the positive bias of GOME-2 erythemal UV data which is influenced by local tropospheric aerosol, ozone and cloud cover.

4. SUMMARY AND CONCLUSIONS

This research has compared the UVA daily exposures and the maximum daily irradiances from the GOME-2 satellite on a 5^{o} x 5^{o} grid to those from a ground-based spectroradiometer for a subtropical Southern Hemisphere site over 489 matching days in the period 8 June 2009 to 18 August 2012. For each data set a regression line has been obtained between the ground-based data and the satellite data for all sky conditions and for cloud free conditions. The *rRMSE* reduced by up to a factor of two when only the data for the cases of cloud free skies were considered. A positive bias in the GOME-2 satellite data results are presented in this research under all sky conditions, with daily UVA satellite maximum irradiance data and satellite daily exposure data over-predicting surface measurements. These results are comparable to the over-predictions of between 14 and 34% for OMI erythemally effective exposure data [9]. Similarly, the GOME-2 over-predicts the erythemal UV [12].

Acknowledgments

The GOME-2 data were provided by the O3M SAF project of the EUMETSAT.

References

[1] R.L. McKenzie, G. Bodeker, G. Scott, J. Slusser and K. Lantz, "Geographical differences in erythemally weighted UV measured at mid-latitude USDA sites," *Photochem. Photobiol. Sci.* vol.5, pp.343-352, 2006.

[2] P. Gies, R. Roy, J. Javorniczky, S. Hendersen, L. Lemus-Deschamps and C. Driscoll, "Global solar UV index: Australian measurements, forecasts and comparison with the UK," *Photochem. Photobiol*. vol.79, pp.32-39, 2004.

[3] J. Sabburg, J.E. Rives, R.S. Meltzer, T. Taylor, G. Schmalzle, S. Zheng, N. Huang, A. Wilson, and P.M. Undelhofen, "Comparisons of corrected daily integrated erythemal UVR data from the U.S. EPA/UGA network of Brewer spectroradiometers with model and TOMS-inferred data," *J. Geophys. Res*., 107(D23), 4676, doi:10.1029/2001JD001565, 2002.

[4] A. Tanskanen, N. Krotkov, J. Herman and A. Arola, "Surface ultraviolet irradiance from OMI," *IEEE Trans. Geoscience and Remote Sensing*, vol. 44, pp. 1267-1271, 2006.

[5] I. Ialongo, A. Arola, J. Kujanpaa and J. Tamminen, "Use of satellite erythemal UV products in analysing the global UV changes," *Atmos. Chem. Phys*., vol. 11, pp. 9649-9658, 2011.

[6] J. Kujanpää and N. Kalakoski, "Operational surface UV radiation product from GOME-2 and AVHRR/3," *Atmos. Meas. Tech.,* vol. 8, pp. 4399-4414, 2015.

[7] O3M SAF (Ozone Monitoring and Atmospheric Chemistry Satellite Application Facility). 2015. Access information of offline products. [Online]. Available: http://o3msaf.fmi.fi/offline_access.html

[8] N. S. Agar, G. M. Halliday, R. Barnetson, H. N. Ananthaswamy, M. Wheeler and A. M. Jones, "The basal layer in human squamous tumors harbours more UVA than UVB

fingerprint mutations: A role for UVA in human skin carcinogenesis," *Proc. Nat. Acad. Sci.*, vol. 101, pp. 4954-4959, 2004.

[9] V. Buchard, C. Brogniez, F. Auriol, B. Bonnel, J. Lenoble, A. Tanskanen, B. Bojkov and P. Veeflink, "Comparison of OMI ozone and UV irradiance data with ground-based measurements at two French sites," *Atmos. Chem. Phys*., vol. 8, pp. 4517-4528, 2008.

[10] A. Tanskanen, A. Lindfors, A. Määttä, N. Krotkov, J. Herman, J. Kaurola, T. Koskela, V. Lakkala, V. Fioletov, G. Bernhard, R. McKenzie, Y. Kondo, M. O'Neill, H. Slaper, P. den Outer, A. F. Bais and J. Tamminen, "Validation of daily erythemal doses from Ozone Monitoring Instrument with ground-based UV measurement data," *J. Geophys. Res.*, vol. 112, D24S44, doi:10.1029/2007JD008830, 2007.

[11] D. Mateos, J. Bilbao, A. Kudish, A. V. Parisi, G. Carbajal, A. di Sarra, R. Román and A. de Miguel, "Validation of OMI satellite erythemal daily dose retrievals using ground-based measurements from fourteen stations," *Remote Sens. Environ.*, vol. 128, pp. 1-10, 2013.

[12] N. Kalakoski, (2009). O3M SAF Validation Report. [Online]. Available: http://o3msaf.fmi.fi/docs/vr/Validation_Report_OUV_Feb_2009.pdf

[13] F. Jėgou, S. Godin-Beckman, M.P. Corrêa, C. Brogniez, F. Auriol, V. H. Peuch, M. Haeffelin, A. Pazmino, P. Saiag, F. Goutail, & E. Mahė, "Validity of satellite measurements used for the monitoring of UV radiation risk on health," *Atmos. Chem. Phys.*, vol. 11, pp. 13 377-13 394, 2011.

[14] U. Feister, & R. Grewe, "Spectral albedo measurements in the UV and visible region over different types of surfaces," *Photochem. Photobiol.* vol.62, no.4, pp.736-744, 1995.

[15] Geoscience Australia, (2015). Compute Sun and Moon Azimuth & Elevation. [Online]. Available: http://www.ga.gov.au/geodesy/astro/smpos.jsp

[16] A. V. Parisi and N. Downs, “Cloud cover and eye damaging solar UV exposures,” *Int. J. Biomet*., vol. 49, pp. 130-136, 2004.

[17] J. M. Sabburg and C. N. Long, “Improved sky imaging for studies of enhanced UV irradiance,” *Atmos. Chem. Phys*., vol. 4, pp. 2543-2552, 2004.

[18] M. Anton, D. Loyola, M. Lopez, J. M. Vilaplana, M. Banon, W. Zimmer and A. Serrano, “Comparison of GOME-2/MetOp total ozone data with Brewer spectroradiometer data over the Iberian Peninsula,” *Ann. Geophys.,* vol. 27, pp. 1377-1386, 2009.

[19] V. Gorshelev, A. Serdynchenko, M. Weber, W. Chehade and J. P. Burrows, “High spectral resolution ozone absorption cross-sections – Part 1: Measurements, data analysis and comparison with previous measurements around 293 K,” *Atmos. Meas. Tech*., vol. 7, pp. 609-624, 2014.

Table 1 – The parameters for the comparison of the GOME-2 and ground-based UVA data for maximum UVA irradiance and daily UVA exposure data. The first two rows are for the cloud free cases and the last two rows are for the all sky conditions data.

	N	R^2	Relative RMSE	Equation
Max UVA irradiances: cloud free	62	0.93	0.08	y = 0.95x – 4.16
Daily UVA exposures: cloud free	62	0.93	0.10	y = 0.84x – 1,525
Max UVA irradiances	489	0.70	0.20	y = 0.86x + 2.07
Daily UVA exposures	489	0.86	0.19	y = 0.83x – 63,770

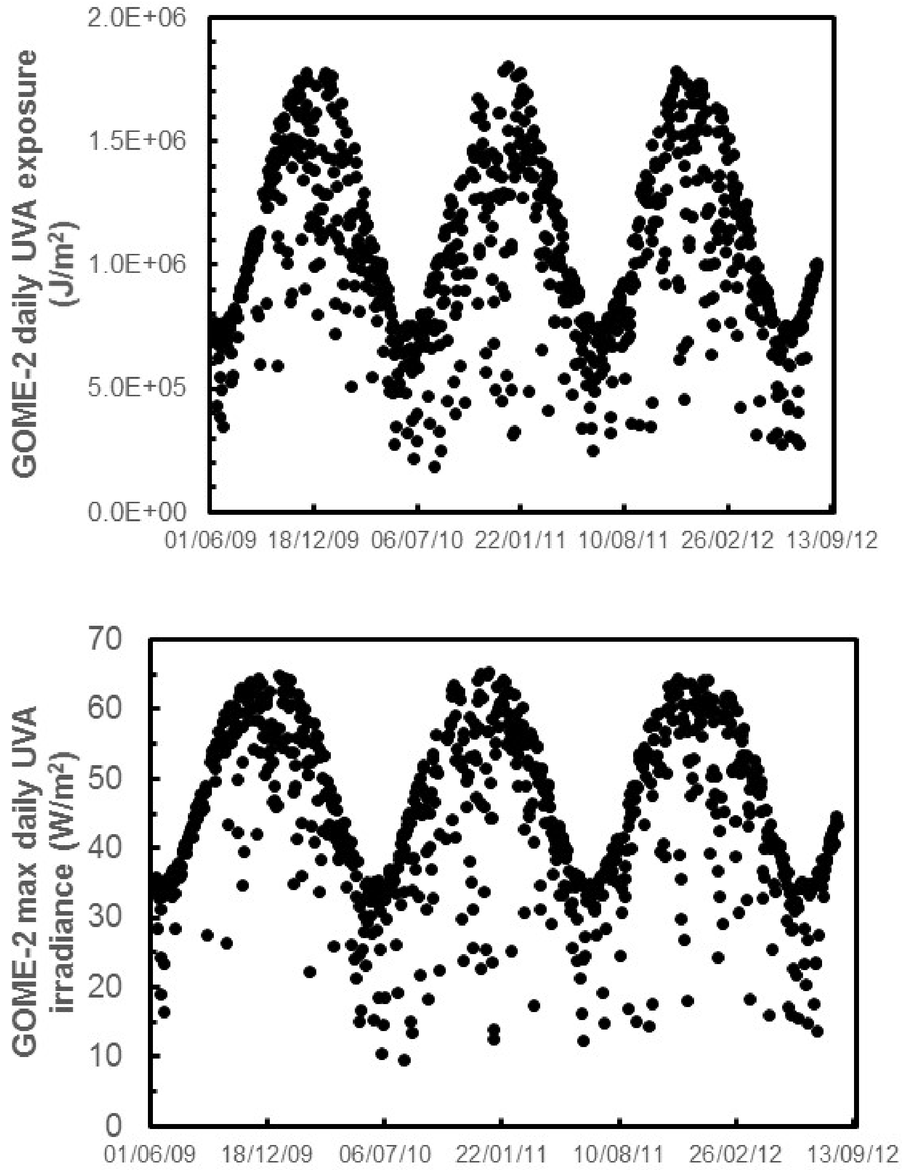

Figure 1 – Time series of the GOME-2 UVA total daily exposure (top graph) and UVA maximum daily irradiance (bottom graph). The *x*-axis dates are in the form of dd/mm/yy.

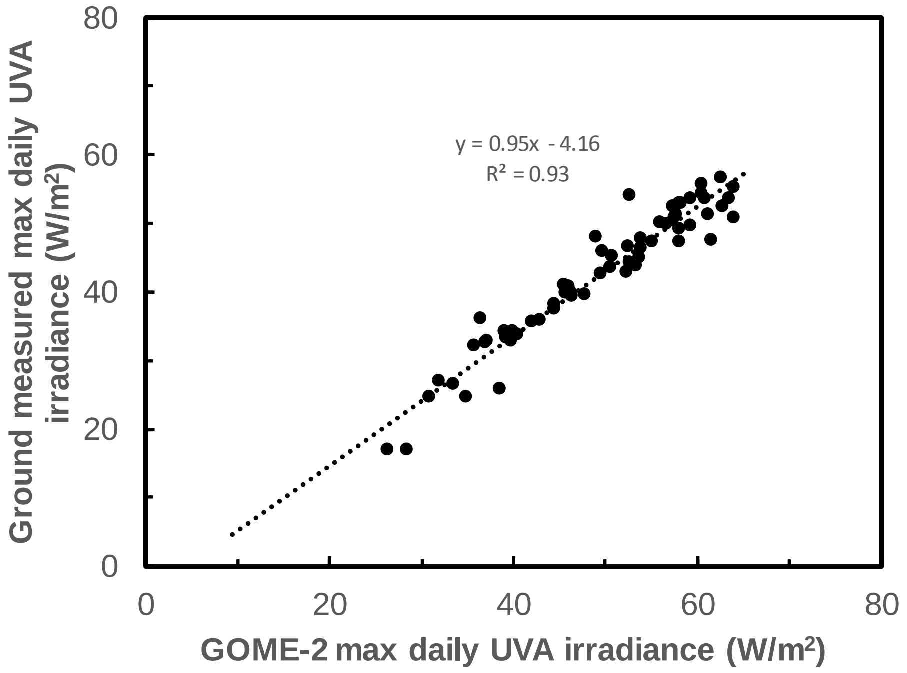

Figure 2 – Comparison of the GOME-2 UVA daily maximum irradiances with the respective ground-based spectroradiometer data for skies with less than two octa cloud (cloud free).

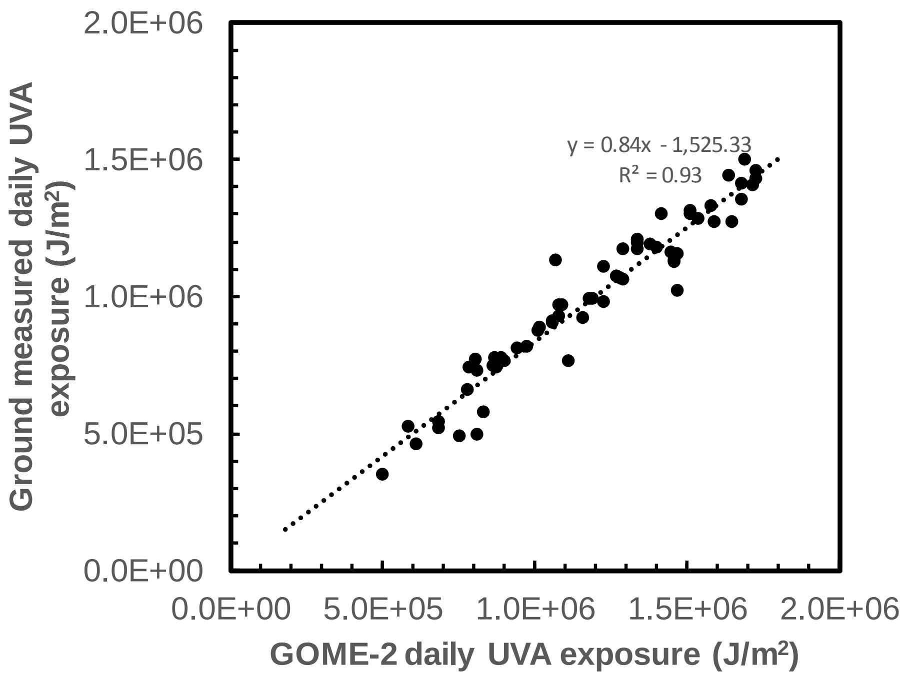

Figure 3 - Comparison of the GOME-2 UVA daily exposures with the respective ground-based spectroradiometer data for skies with less than two octa cloud (cloud free).

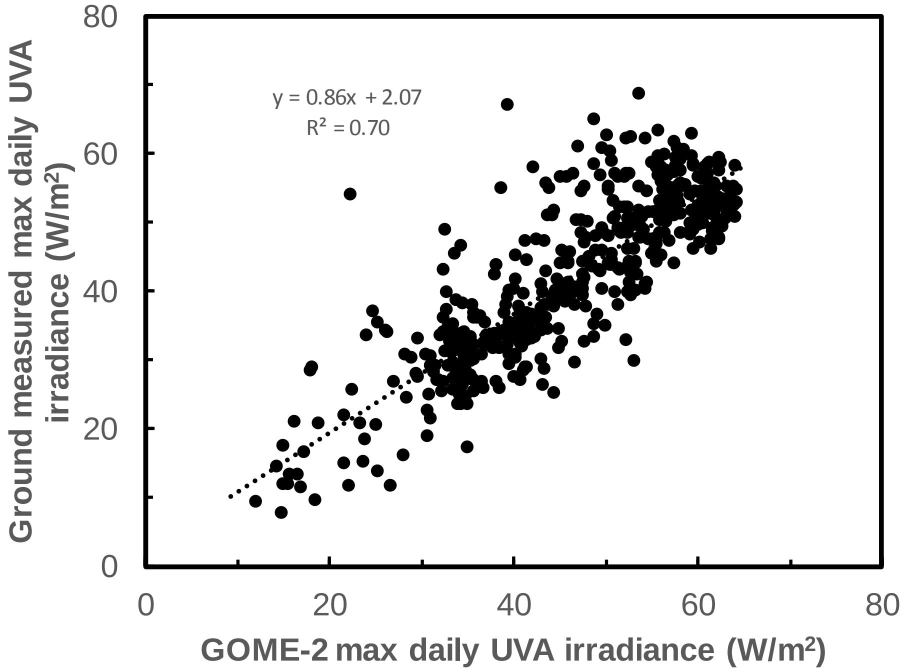

Figure 4 - Comparison of the GOME-2 UVA daily maximum irradiances with the respective ground-based spectroradiometer data for all cloud conditions.

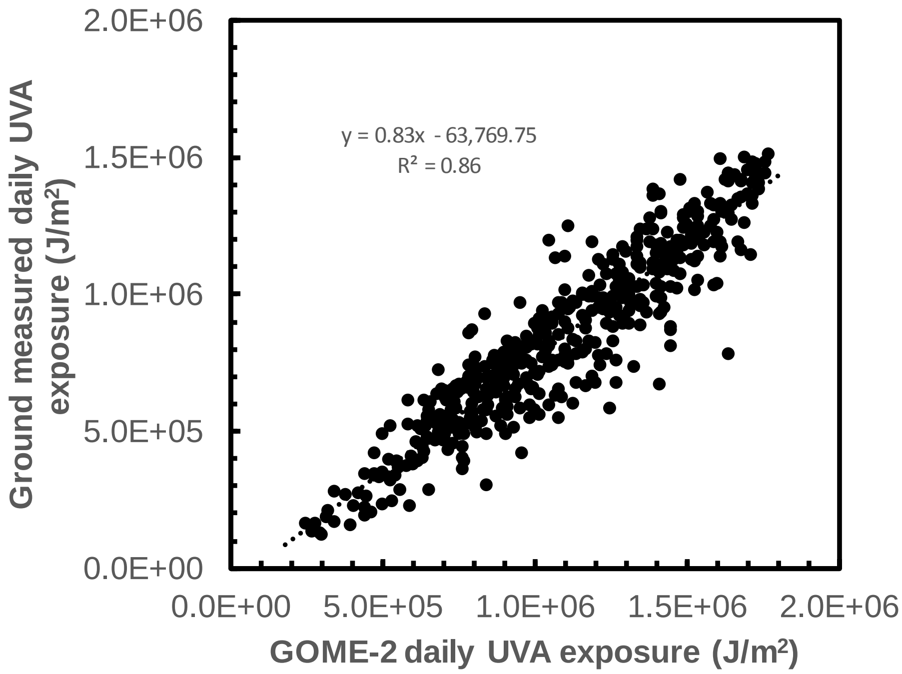

Figure 5 - Comparison of the GOME-2 UVA daily exposures with the respective ground-based spectroradiometer data for all cloud conditions.