Validation of OMI UV satellite data using spectral and broadband surface based measurements at a Queensland site

A Jebar, M. A. [1], Parisi, A. V., [1,*] Downs. N.J[1] and Turner, J.[1]

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

[*]Corresponding author: parisi@usq.edu.au

Abstract

This research reconstructed and validated the broadband UVA irradiances derived from discrete spectral irradiance data retrieved from the Ozone Monitoring Instrument (OMI) satellite from 1 January to 31 December 2009. OMI data at solar noon was compared to ground based spectral irradiances at Toowoomba (27°36’ S 151°55’ E), Australia at 310, 324 and 380 nm for both cloud free and all sky conditions. There was a strong relationship between the ground based UV spectroradiometer data and satellite based measurements with an R^2 of 0.89 or better in each waveband for cloud free days. The data show an over-estimate of the satellite derived spectral irradiances compared to the ground based data. The models developed for the sub-tropical site data account for this over-estimation and are essential for any data correlation between satellite and ground based measurements. Additionally, this research has compared solar noon broadband UVA irradiances evaluated with a model and the discrete satellite spectral irradiances for the solar noon values of cloud free days to those measured with a ground based UVA radiometer. An R^2 of 0.86 was obtained confirming that for cloud free days the broadband UVA can be evaluated from the OMI satellite spectral irradiances.

Introduction

The UV radiation waveband has been divided into three regions according to the wavelengths; UVC (100-280 nm), UVB (280-320 nm) and UVA (320-400 nm) (1). UVA has a longer wavelength, less energy and it has lower biological effectiveness than short wavelength UV. The earth's surface is exposed to a significant quantity of solar UV radiation. The UV region makes up 8-9% of the available solar energy reaching the top of the atmosphere. Of this, UVA radiation makes up 6.3% and is transmitted to the earth's surface without absorption (although it is prone to scattering and attenuation). Because of its longer wavelength, UVA damage occurs to greater depths in biological systems including below the human epidermis skin (2). Regular exposure to small amounts of the UVA, leads to significant damage and cutaneous alterations in the epidermis (3). UVA is therefore a health concern and must be accounted for in research that investigates the relationship of UV exposure to chronic human disease.

The importance of the influence of UV radiation on the earth and the poor spatial coverage of ground-based observation stations have created a demand for satellite based instrumentation. Approaches that depend on satellite data are suitable alternatives because satellites have the capability to determine important parameters over a wide area and provide accurate calculations in evaluating levels of UV irradiance where surface instrumentation is not available (4, 5). This requires correlating the satellite data to ground based data to attain an improved evaluation of the UV derived from satellite measurements. There are several kinds of satellite instruments that monitor UV radiation at the earth's surface: TOMS (Total Ozone Mapping Spectrometer), GOME (Global Ozone Monitoring Experiment), MODIS (Moderate Resolution Imaging Spectrometer) and OMI (Ozone Monitoring Instrument) (6). This paper considers the data from OMI (Ozone monitoring Instrument) which is a generation of spectrometers placed in orbit by NASA on 14 July 2004.

OMI observes the upper layers of the atmosphere and covers the UV band and near visible irradiance (270-500 nm) with high spatial (13×24 km^2 at nadir) and spectral resolution (0.5 nm). OMI was developed to monitor ozone columns, clouds, surface UV and gases ($NO_2, SO_2, HCHO, BRO, OCID$). Thus, the primary objective of OMI is to monitor long-term changes in the UV (7, 8, 9, 10, 11, 12). The OMI UV algorithm is a derivative of the TOMS (Total Ozone Mapping Spectrometer) UV based algorithm as developed previously by NASA (11). This algorithm evaluates the surface irradiance under cloud free conditions (E_{clear}). E_{clear} is then multiplied by the factor C_T (which is equal to the derived cloud fraction divided by the non-absorbing aerosol transmittance factor) to estimate the terrestrial irradiance in the presence of cloud (13) where,

$$E_{cloud} = E_{clear} C_T. \quad (1)$$

OMI does not cover the boundary layer of the atmosphere which means that absorption of aerosols in the lower atmosphere is not accounted for by the OMI algorithm. Consequently, the OMI algorithm typically overestimates the surface UV irradiance. Some researchers, Arola et al. (14) have applied a post- correction to reduce this overestimation by taking into account aerosol absorption.

Mateos et al. (15) have estimated the differences between satellite and ground based daily terrestrial erythemal irradiance. This was achieved by comparing the OMI measurements to six Spanish, three Argentinean, two Italian, two Israeli, and one Australian ground station. The results have shown an overestimation of the satellite values where all these results were compared at low surface albedo conditions. This overestimation significantly depends on lower atmospheric cloud condition, ozone and aerosols. Spectral comparison at a Northern hemisphere site with high levels of aerosols has found a higher overestimation of the satellite values at the shorter wavelength of 305 nm compared to that at 324 nm and 380 nm (16). Buntoung and Webb (17) have compared the results of erythemal UV dose measurements between OMI and broadband instruments at four urban sites in Thailand.

Satellite derived OMI measurements show an overestimation under cloud free conditions of the UV irradiance by 10-40% for urban sites. Ialongo et al. (18) have compared the differences of erythemal dose rates (EDRs) and erythemal daily doses (EDD) between OMI and ground-based instruments (Brewer and broadband radiometer measurements) that were located in Rome, Italy. Again, the results show OMI overestimation of the satellite derived measurements compared with the Brewer and radiometer UV measurements. However, no previous research has compared the broadband unweighted UVA (320-400 nm) data derived from the OMI to ground based instruments. The research in this paper will firstly compare the cloud free solar noon spectral irradiances at three wavelengths from OMI with ground based spectral spectroradiometer data. Using the spectral irradiances at these wavelengths we develop a method to evaluate the broadband UVA solar noon irradiances derived from OMI satellite spectral data for cloud free days and validate this against ground based broadband data obtained from a radiometer at a Southern Hemisphere sub-tropical site.

2- Methods

Ground Based Data

The time period of the data collected in this research is 12 months beginning 1 January and ending 31 December 2009. Data were collected at the University of Southern Queensland, Toowoomba, Australia (27°36' S 151°55' E, elevation 693 m). The ground-based UVA data of this study were recorded by two instruments located at this site on a building roof with a relatively unobstructed view of the sky. Firstly, the spectral solar UV was recorded with a calibrated UV spectroradiometer (model DTM 300, Bentham Instruments. UK). Parisi and Downs (19) have described the structure, installation and operation of the Bentham spectroradiometer installed at this site. The calibration of the spectroradiometer is traceable to the UK standard and the error of the spectroradiometer data is estimated as ±9%. The global UV spectra obtained from the Bentham spectroradiometer are recorded at 10 minute intervals, from 5:00 am to 7:00 pm daily with 0.5 nm increment scans taking less than two minutes to complete, beginning at 280 nm and ending at 400 nm. Secondly, the ground based broadband unweighted UVA data was recorded with a UVA Biometer which was calibrated yearly to the spectroradiometer (model 501A, Solar Light Inc, PA, USA). This instrument is temperature stabilized at 25 ^{o}C and records the broadband UVA exposures continuously every five minutes.

Ground-based cloud fraction data were obtained from a sky camera located at the same site. To identify the cloud conditions (cloudy or cloud free sky), this study has used a Total Sky Imager (model TSI440 Yankee Environmental Systems, PA, USA). This instrument is based on a CCD colour camera recording images of the sky reflected on a half-sphere dome, providing an approximate 160^{o} field of view (20). Image processing software running on a PC acquires images, processes the images to determine pixels that are either cloud or cloud free and determines if the solar disc is obscured (19, 21).

In this study the TSI-440 instrument has missing data from 17 March to 22 July 2009 and from 25 November to 31 December 2009 due to a failure of the instrument network (73 days). Consequently, the broadband erythemal UV Biometer data were used to determine if the noon time sky was clear on these days. Here, the erythemal UV exposures measured by a separate broadband Biometer (model 501, solar light Inc, PA, USA) recording in five minute daily intervals was employed to monitor noon time sky conditions. If the data monitored in this way formed part of a bell-shaped curve at noon, and met the mathematical criterion according to "The change in magnitude with time test" of Long and Ackerman (22) it was taken as a cloud free sky. Days which did not fit the criterion of Long and Ackerman were not counted as cloud free (Figure1a). Thus, if the curve was not smooth at noon, it was taken as cloudy (Figure1b).

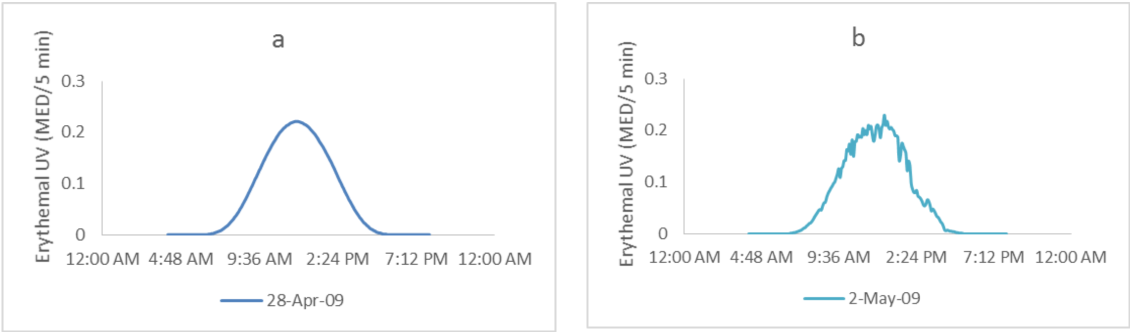


Figure 1. Time series of biometer erythemal UV irradiance for determining cloud condition at solar noon; (a) cloud free; (b) cloud affected.

OMI Data

OMI satellite data was retrieved from the Giovanni website which is provided by NASA (http: //giovanni. gsfc. nasa.gov/giovanni/). The Giovanni website provides the OMI spectral UV irradiances at solar noon from October 2004 until the current day. In this study, the OMI spectral irradiance data was collected for the three UV wavelengths of 310 nm, 324 nm and 380 nm. The satellite data was collected from 1 January 2009 to 31 December 2009 and corresponds to the OMI satellite solar noon time derived spectral irradiance. To make a comparison between satellite data (OMI) and ground based Bentham spectroradiometer data, cloud free days were selected by using information from the TSI images when the amount of cloud was determined as 2 okta (25% sky coverage) or less (n=71) As explained previously, erythemally effective Biometer data was used for the days with missing data from the TSI. Therefore, the total number of days in the 1 January to 31 December period classified as cloud free was 71 (19.5% of the total number of days in the study period)

Derivation of Satellite Broadband UVA Irradiance

This research has made a comparison of the solar noon broadband UVA irradiances evaluated from the satellite spectral data with the broadband UVA irradiance measured with the ground based UVA Biometer. The satellite UVA irradiances were evaluated from the satellite spectral irradiances at 310, 324 and 380 nm for cloud free days. The trapezoidal rule was applied between 310, 324 and 380 nm, with the spectral irradiance at 380 nm extended out to 400 nm (23, 24) to develop a model for the evaluation of the broadband UVA (W/m^2) from 320 to 400 nm as follows:

$$\mathrm{UVA_{irrad}} = 0.57\ \mathrm{S_{310}} + 31.429\ \mathrm{S_{324}} + 48\ \mathrm{S_{380}} \qquad (2)$$

where S_{310}, S_{324} and S_{380} are the spectral UV irradiance ($W/m^2/nm$) at the respective satellite wavelengths. This formula approximates the irradiance limits for summation from 320 to 400 nm to provide the broadband UVA.

3-Results and Discussion

Spectral Data

The time series of the cloud free spectral irradiances for the satellite data are shown in Figure 2 for wavelengths: 310, 324 and 380 nm. This figure shows that the signal increases from 310 to 380 nm because the measured UV irradiance increases with wavelength in the UVA spectrum.

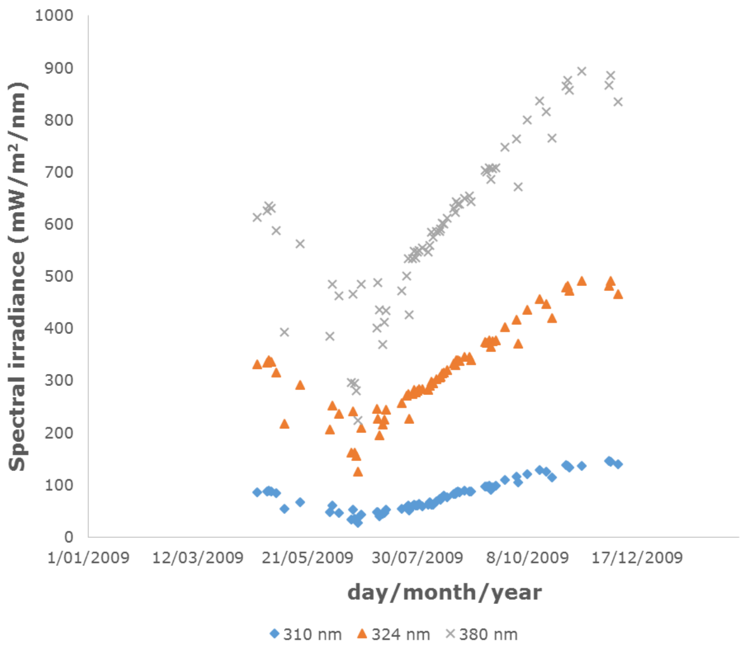
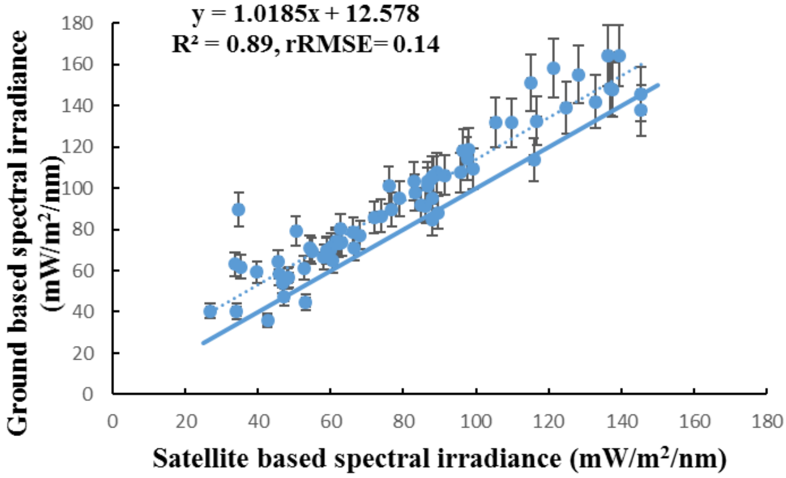


Figure 2. Time series of cloud free spectral irradiance at 310, 324 and 380 nm for cloud free days for the OMI satellite data from 1 January 2009 to 31 December 2009.

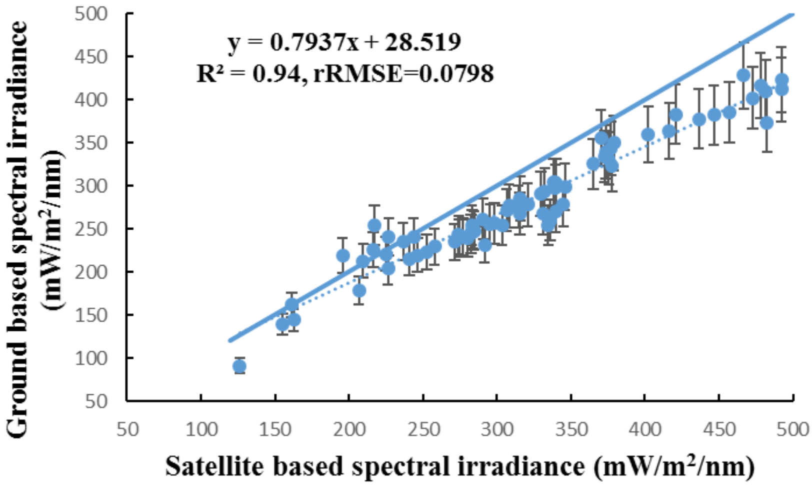
The linear regression of ground-based to satellite derived spectral irradiance on cloud free days is shown in Figure 3. The OMI data is a spatial average over a 1º×1º grid and the ground based data is at a given point. Additionally, the OMI overpass time is not at noon and is based on the data collected at the overpass time to calculate the values for solar noon, showing the need to provide calibrations as in this paper to ground based data. The error bars correspond to the ±9% error associated with the ground based measurements (19). The average of the aerosol levels from the Giovanni web site on these cloud free days from the MODIS instrument on the Aqua and Tera satellites is 0.04 showing the relatively low aerosol level over the site. The error at 310 nm due to the OMI evaluation of the ozone levels is expected to be minimal as the mean relative difference between OMI and ground based Dobson spectrophotometer ozone data for Brisbane (within 150 km of the site in this research) is within -1% (25). The satellite measured spectral irradiance comparisons to the ground based measurements show a clear correlation for the wavelengths of 310, 324 and 380 nm. There is a good comparison between satellite and ground based spectral irradiance measurements on cloud free days for the three discrete wavelengths with R^2 of 0.89 or better in each waveband (Figure 3). The R^2 value of 0.89 occurs for 310 nm where the magnitude of the spectral irradiance is the lowest. Sensitivity to ozone variations and instrument noise affect the sensitivity of the instrument at 310 nm, thereby increasing the uncertainty of the comparison at 310 nm.

(a)



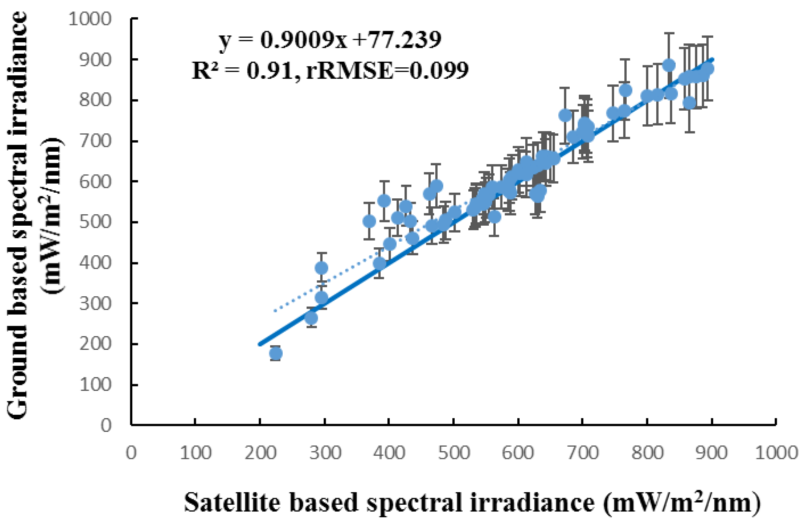
y = 1.0185x + 12.578
R² = 0.89, rRMSE= 0.14
Ground based spectral irradiance (mW/m²/nm)
Satellite based spectral irradiance (mW/m²/nm)

(b)



y = 0.7937x + 28.519
R² = 0.94, rRMSE=0.0798
Ground based spectral irradiance (mW/m²/nm)
Satellite based spectral irradiance (mW/m²/nm)

(c)



y = 0.9009x +77.239
R² = 0.91, rRMSE=0.099
Ground based spectral irradiance (mW/m²/nm)
Satellite based spectral irradiance (mW/m²/nm)

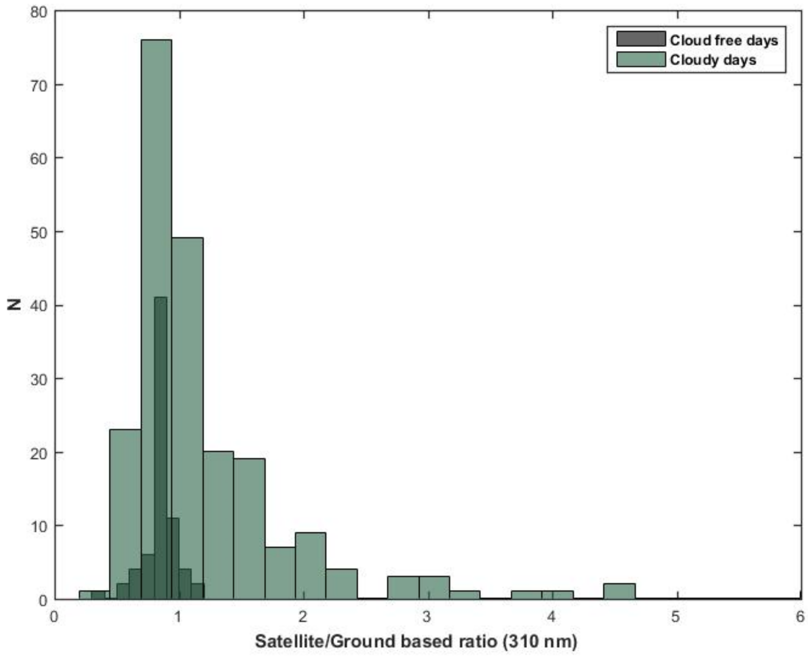
Figure 3. Cloudy free days OMI and Bentham spectral irradiance comparison for (a) 310 nm, (b) 324 nm, (c) 380 nm (n=71 cloud free days)**.** The error bars correspond to the ±9% error associated with the Bentham spectroradiometer data. The solid line in each graph is the 1:1 line.

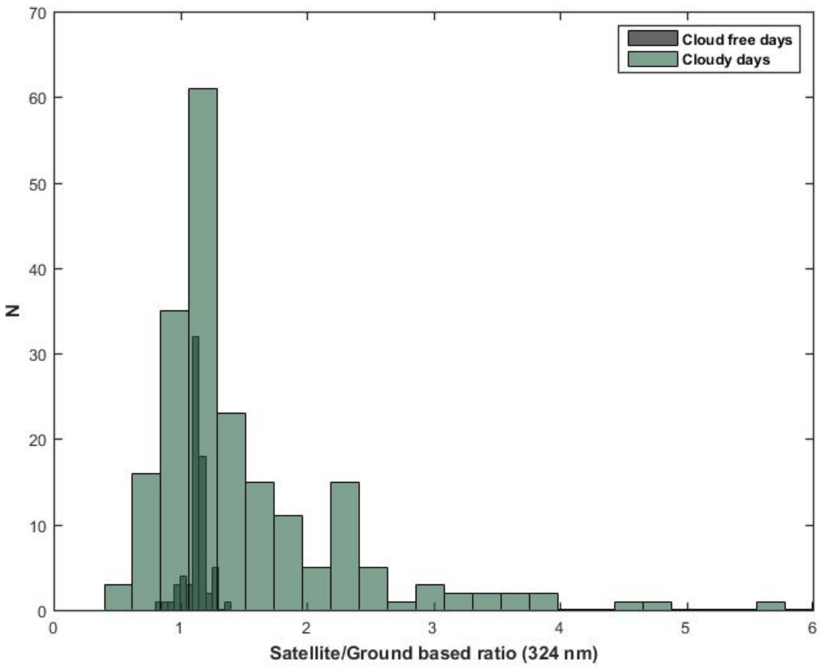
The distribution of satellite to ground based measured spectral irradiance is plotted in Figure 4 for cloud free and all sky conditions. Figure 4 illustrates that most of the spectral irradiances from the OMI satellite exceed measured ground based data as noted previously by other researchers for the shorter wavelength erythemal UV and UVB comparisons (15). Median, first quartile and third quartile statistics are given in Table 1 for the same distribution plotted in Figure 4.

Those ratios above 1 confirm that some satellite measurements over predict the UVA irradiance for most sky conditions, which displays a similar trend to shorter wavelength comparisons as seen in the literature. Also seen in the Figure, the cloudy days have a much wider range of values with the median ratio generally being higher than one.

Table 1: The first quartile (Q1), median and third quartile (Q3) for cloudy and cloud free days at 310, 324 and 380 nm.

	Q1	Median	Q3
Cloud free days (310 nm)	0.82	0.85	0.89
Cloud free days (324 nm)	1.11	1.13	1.16
Cloud free days (380 nm)	0.95	0.98	1.00
Cloudy days (310 nm)	0.83	0.99	1.34
Cloudy days (324 nm)	1.06	1.22	1.76
Cloudy days (380 nm)	0.90	1.07	1.66


Cloud free days
Cloudy days
N
Satellite/Ground based ratio (310 nm)


Cloud free days
Cloudy days
N
Satellite/Ground based ratio (324 nm)

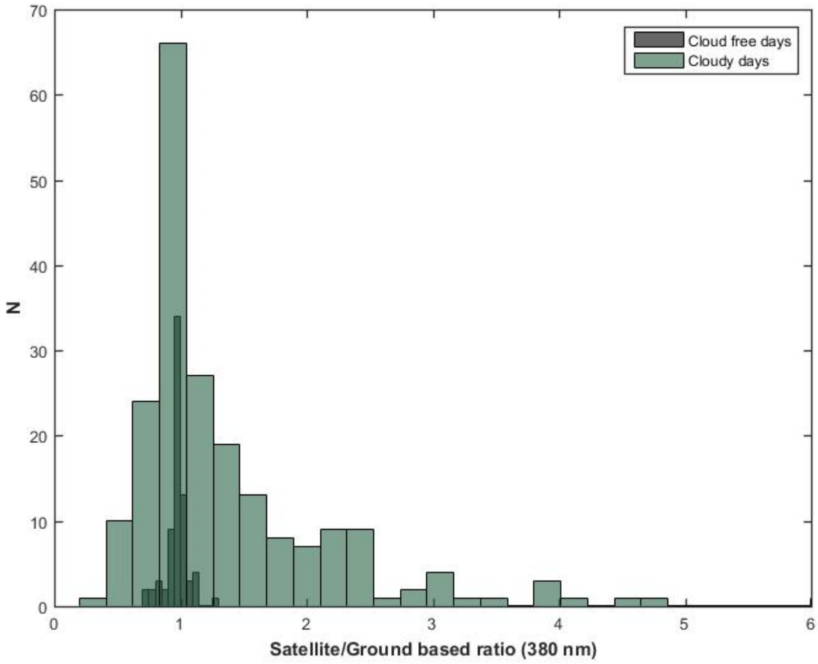


Figure 4. Histograms of the ratio of the satellite (OMI) to ground-based (Bentham) UV measurements for each of 310, 324 and 380 nm. Darker bars correspond to the measurements of cloud free days of 71 cloud free days and lighter bars correspond to 221 cloudy day's measurements. N is the number of values. For each graph there are 2 or less values above the value of 6.

Broadband UVA

Broadband UVA irradiances which are derived from the OMI data have been reconstructed and validated under cloud free days using a mathematical model (Equation 2). Figure 5 shows the UVA irradiances (W/m^2) modelled from the satellite spectral irradiances (W/m^2/nm) at 310, 324 and 380 nm for solar noon data measured on cloud free days in the period 1 January to 31 December 2009. The error bars represent the ±10% error associated with the ground based data. There is a reasonable agreement between the solar noon UVA broadband irradiance from the measured ground-based UVA Biometer instrument and the modelled UVA irradiance derived from satellite with an R^2 of 0.86. The figure shows the satellite UVA evaluation is approximately 30% higher which can be accounted for by calibration to ground based instruments and in turn used for health applications where ground based data are not available. The spectroradiometer measurements at 310, 324, 380 nm were used in equation (2) to calculate the UVA and compared to the Biometer UVA, the R^2 was 0.89 and the rRMSE was 0.082.

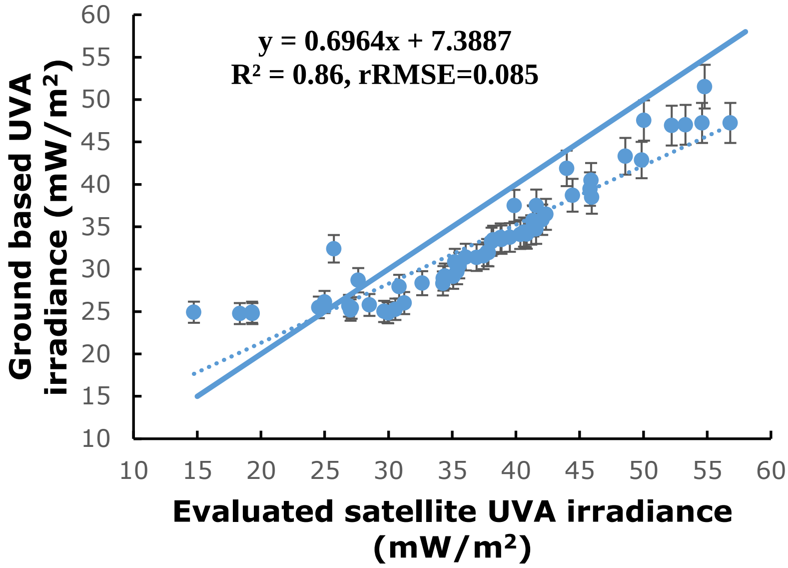


Figure 5. Comparison of the broadband UVA irradiances evaluated from OMI spectral data and the UVA irradiance from the ground based measurements were derived from Equation 2 to use the OMI spectral irradiances. The error bars are the ±10% error associated with the ground based data and the solid line is the 1:1 line.

Conclusion

The cloud free solar noon spectral irradiances from OMI have been compared with a ground based spectral spectroradiometer data at three wavelengths (310, 324, 380 nm) for a sub-tropical Southern Hemisphere site. These comparisons show a clear correlation for these wavelengths and with an R^2 of 0.89 or better in each waveband. These comparisons include the ±9% absolute error in the spectroradiometer ground based data and the errors in the spatial averaging of the satellite pixel data. In this paper, the ratio of the spectral irradiances from satellite compared to the ground based measurements has showed that for the cloud free cases at 324 nm, the median is higher than one. The corresponding median at 310 is less than one and it is very close to one at 380 nm. For the cloudy days the ratios have a much wider range of values with the median ratio being higher than one for 324 and 380 nm and very close to one for 310 nm. The observed spread in the cloud affected data is largely due to the temporal nature of local cloud cover and differences between the satellite overpass time and solar noon and the spatial averaging of the satellite data over the satellite pixel. The models developed account for this over-estimation at the sub-tropical research site and are essential for any data correlation between satellite and ground based measurements. Additionally, this research has developed a method to evaluate and validate the broadband UVA solar noon irradiances derived from OMI satellite spectral data at 310, 324, 380 nm for cloud free days against ground based broadband data taken from a UVA Biometer. There is reasonable agreement between the modelled UVA irradiance derived from OMI and the solar noon UVA broadband irradiance from the UVA Biometer with an $R^2$of 0.86.

Acknowledgements

We acknowledge the OMI mission scientists and associated NASA personnel for the production of the data used in this research effort.

References

1. Parisi, A. V., J. Sabburg and M. G. Kimlin (2004) Scattered and filtered solar UV measurements. Springer Science & Business Media.
2. Stamnes, K. and J. J. Stamnes (2008) Transport of Solar Radiation through the Atmosphere: Aspects Relevant for Health. 9-22.

3. Lavker, R. M., G. F. Gerberick, D. Veres, C. J. Irwin and K. H. Kaidbey (1995) Cumulative effects from repeated exposures to suberythemal doses of UVB and UVA in human skin. Journal of the American Academy of Dermatology 32, 53-62.
4. Soulen, P. F. and J. E. Frederick (1999) Estimating biologically active UV irradiance from satellite radiance measurements: A sensitivity study. Journal of Geophysical Research: Atmospheres 104, 4117-4126.
5. Paulescu, M., E. Paulescu, P. Gravila and V. Badescu (2012) Weather modeling and forecasting of PV systems operation. Springer Science & Business Media.
6. Bais, A., R. McKenzie, G. Bernhard, P. Aucamp, M. Ilyas, S. Madronich and K. Tourpali (2015) Ozone depletion and climate change: Impacts on UV radiation. Photochemical & Photobiological Sciences 14, 19-52.
7. Bernhard, G., A. Arola, A. Dahlback, V. Fioletov, A. Heikkilä, B. Johnsen, T. Koskela, K. Lakkala, T. Svendby and J. Tamminen (2015) Comparison of OMI UV observations with ground-based measurements at high northern latitudes. Atmospheric Chemistry and Physics 15, 7391-7412.
8. Pitkänen, M., A. Arola, K. Lakkala, T. Koskela and A. Lindfors (2015) Comparing OMI UV index to ground-based measurements at two Finnish sites with focus on cloud-free and overcast conditions. Atmospheric Measurement Techniques Discussions 8, 487-516.
9. Torres, O., A. Tanskanen, B. Veihelmann, C. Ahn, R. Braak, P. K. Bhartia, P. Veefkind and P. Levelt (2007) Aerosols and surface UV products from Ozone Monitoring Instrument observations: An overview. Journal of Geophysical Research: Atmospheres 112.
10. Veefkind, J. P., J. F. de Haan, E. J. Brinksma, M. Kroon and P. F. Levelt (2006) Total ozone from the Ozone Monitoring Instrument (OMI) using the DOAS technique. IEEE Transactions on Geoscience and Remote Sensing 44, 1239-1244.
11. Ialongo, I., V. Buchard, C. Brogniez, G. Casale and A. Siani (2010) Aerosol Single Scattering Albedo retrieval in the UV range: an application to OMI satellite validation. Atmospheric Chemistry and Physics 10, 331-340.
12. Jégou, F., S. Godin-Beekmann, M. Corrêa, C. Brogniez, F. Auriol, V. Peuch, M. Haeffelin, A. Pazmino, P. Saiag and F. Goutail (2011) Validity of satellite measurements used for the monitoring of UV radiation risk on health. Atmospheric Chemistry and Physics 11, 13377-13394.
13. Tanskanen, A., N. A. Krotkov, J. R. Herman and A. Arola (2006) Surface ultraviolet irradiance from OMI. IEEE transactions on Geoscience and Remote Sensing 44, 1267-1271.
14. Arola, A., S. Kazadzis, A. Lindfors, N. Krotkov, J. Kujanpää, J. Tamminen, A. Bais, A. Di Sarra, J. Villaplana and C. Brogniez (2009) A new approach to correct for absorbing aerosols in OMI UV. *Geophysical Research Letters* **36**.
15. Mateos, D., J. Bilbao, A. Kudish, A. V. Parisi, G. Carbajal, A. Di Sarra, R. Román and A. De Miguel (2013) Validation of OMI satellite erythemal daily

dose retrievals using ground-based measurements from fourteen stations. Remote Sensing of Environment 128, 1-10.

16. Kazadzis, S., A. Bais, A. Arola, N. Krotkov, N. Kouremeti and C. Meleti (2009) Ozone Monitoring Instrument spectral UV irradiance products: comparison with ground based measurements at an urban environment. *Atmospheric Chemistry and Physics* **9,** 585-594.

17. Buntoung, S. and A. Webb (2010) Comparison of erythemal UV irradiances from Ozone Monitoring Instrument (OMI) and ground-based data at four Thai stations. Journal of Geophysical Research: Atmospheres 115.
18. Ialongo, I., G. Casale and A. Siani (2008) Comparison of total ozone and erythemal UV data from OMI with ground-based measurements at Rome station. Atmospheric Chemistry and Physics 8, 3283-3289.
19. Parisi, A. V. and N. Downs (2004) Cloud cover and horizontal plane eye damaging solar UV exposures. International Journal of Biometeorology 49, 130-136.
20. Sabburg, J. and C. N. Long (2004) Improved sky imaging for studies of enhanced UV irradiance. Atmospheric Chemistry and Physics 4, 2543-2552.
21. Yankee Environmental Systems (2006). TSI-440 Total Sky Imager. Available at: http://www.yesinc.com/products/data/tsi440/index.html. Accessed on 1 September 2016
22. Long, C. N. and T. P. Ackerman (2000) Identification of clear skies from broadband pyranometer measurements and calculation of downwelling shortwave cloud effects. Journal of Geophysical Research: Atmospheres 105, 15609-15626.
23. Anav, A., C. Rafanelli, I. Di Menno and M. Di Menno (2004) An algorithm to evaluate solar irradiance and effective dose rates using spectral UV irradiance at four selected wavelengths. Radiation Protection Dosimetry 111, 239-250.
24. Igoe, D. and A. V. Parisi (2014) Broadband Direct UVA irradiance measurement for clear skies evaluated using a smartphone. Radiation Protection Dosimetry, ncu344.
25. Balis, D., M. Kroon. M.E. Koukouli. E.J. Brinksma. G. Labow. J.P. Veefkind and R.D. McPeters (2007) Validation of Ozone Monitoring Instrument total ozone column measurements using Brewer and Dobson spectrophotometer ground-based observations. Journal of Geophysical Research 112, D24546, doi:10,1029/2007JD008796.