

Comparison of GOME-2 UVA satellite data to ground-based UVA measurements in South Africa

D. Jean du Preez*^{1,2}, Alfio V. Parisi³, Danielle A. Millar⁴ Hassan Bencherif^{2,5} and
Caradee Y. Wright^{1,4}

¹ Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Pretoria,
South Africa,

² Laboratoire de l'Atmosphère et des Cyclones (LACy, UMR 8105 CNRS, Université de La
Réunion, Météo-France), Saint-Denis de La Réunion, France,

³ Faculty of Health, Engineering and Sciences, University of Southern Queensland,
Toowoomba, Australia,

⁴ Environment and Health Research Unit, South African Medical Research Council, Pretoria,
South Africa,

⁵ School of Chemistry and Physics, University of KwaZulu-Natal, Durban, South Africa

*Corresponding author e-mail: dupreez.dj@tuks.co.za (D. Jean du Preez)

ABSTRACT

Satellite estimates of surface ultraviolet A (UVA) (315-400 nm) from the Global Ozone Monitoring Experiment (GOME)-2 were compared to ground-based measurements at four stations in South Africa for 2015. The comparison of daily exposure and daily maximum irradiance was completed for all-sky and clear-sky conditions. There is a strong linear correlation between the satellite and ground-based data with a correlation coefficient (r) between 0.86 and 0.97 for all sky conditions. However, at three of the stations the satellite data is underestimated compared to ground-based data with a mean bias error (MBE) between -8.7% and -20.6%. A seasonal analysis indicated that there is a link between the bias in ground-based and GOME-2 UVA and cloud fraction. Factors such as aerosols, surface albedo, altitude and data resolution may contribute to the under-estimations found at the three sites. These results indicate that satellite estimates of surface UVA over South Africa do not exhibit the same behaviour as other stations around the world and therefore require further validation.

INTRODUCTION

The risks and benefits of exposure to solar ultraviolet radiation (UVR) for life on Earth have been known for many years (1) and include impacts on human health (2), paints and plastics (3), crops (4), plants, terrestrial and aquatic ecosystems (5) and biogeochemical cycles (6). For humans, personal solar UVR exposure has positive and negative effects, for example, eliciting a vitamin D response and playing a role in skin cancer carcinogenesis, respectively (2). The exposure to UVR can result in acute or chronic effects on the skin. Erythema, immune suppression and pigmentation are acute effects while chronic effects include photoaging and photocarcinogenesis (7).

Solar UVR is divided into three bands: UVA (315-400 nm), UVB (280-315 nm), and UVC (100-280 nm). Shorter UVR wavelengths (<320 nm) are more photo-biologically active than longer UVR wavelengths (8). As a result, although the longer UVR wavelengths penetrate the skin more deeply, the shorter wavelength UVR is more likely to initiate a carcinogenic response in the skin (9).

The important impacts of solar UVR and the need for long-term measurements have led to the establishment of ground-based monitoring stations around the world. These stations form part of global and local monitoring networks. Global networks such as the Network for the Detection of Atmospheric Composition Change (NDACC) (10) and World Ozone and Ultraviolet Radiation Data Centre (WOUDC) (11) which is part of the Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO) are examples of such networks.

Several countries in Europe (12, 13) have national networks while there are established networks in Australia (14) and South Africa (15). The disadvantages of ground-based measurements are the low spatial coverage, capital expense of acquiring instrumentation and expenses related to maintenance and calibration.

Instruments such as the Ozone Monitoring Instrument (OMI) (16, 17) on board the Aura satellite and the Global Ozone Monitoring Experiment-2 (GOME-2), on board the Meteorological Operational satellite program (MetOp-A and MetOp-B) (16, 18), provide surface estimates of UVA and UVB with a high spatial coverage. MetOp satellites are polar orbiting and provide estimates of surface daily UVA and UVB which are derived from the near-real time ozone column and Advanced Very High-Resolution Radiometer (AVHRR) reflectances. Although these surface UVR estimates based on satellite data account for the effect of cloud cover and aerosol optical depth to accurately determine clear-sky UVR, there is a tendency towards positive bias and consequent overestimation (16) of ground-based measurements. Improvements in cloud cover (19) estimates and including absorption by aerosols in the boundary layer (20) can improve the quality of satellite estimates.

Due to the potentially harmful effects of UVA radiation on human, plant and animal health, measurements of UVA are important to accurately determine adverse exposure risks (21), modelling to predict UVR exposure (22) and for public awareness campaigns related to negative human health impacts (12). Furthermore, ground-based measurements play an important role in the validation of satellite estimates. In Low- and Middle-Income Countries (LMICs) such as in countries in Africa, often networks and instruments for monitoring solar UVA are sparse, poorly

supported with both capacity and funding and thus obtaining reliable UVA data is difficult. In fact, there has been relatively limited work to compare ground-based UVA and satellite UVA in the Southern Hemisphere. Parisi et al. (23) assessed UVA daily exposures and daily maximum irradiances under all-sky and cloud-free conditions for 489 days between 8 June 2009 and 18 August 2012. Satellite data were obtained from GOME-2 and compared to ground-based spectro-radiometer data for a subtropical Southern Hemisphere site. Results of all-sky conditions showed a positive bias in the GOME-2 satellite data where satellite daily exposure data and daily UVA satellite maximum irradiance data overpredicted surface measurements (23). Jebar et al. (24) evaluated broadband UVA solar noon irradiances provided for a long-term data series over 12 years at a sub-tropical Southern Hemisphere site derived from the OMI satellite spectral UVA irradiances for sky conditions where clouds did not obscure the Sun, 'Sun not obscured', and where clouds obscured the sun 'Sun obscured'. An inverse relationship was found between the amount of cloud cover and the correlation of ground-based and satellite data in 'Sun not obscured' conditions. Amplified results were found for 'Sun obscured' conditions where there was a low correlation ($R^2 = 0.51$, $r = 0.71$) of the satellite-derived UVA irradiance model with an increasing amount of cloud, as compared to 'Sun not obscured' conditions. Overall, the study found that approximately 71% of the days in the 12-year period were accounted for by calibration of the satellite-derived UVA irradiances to surface measurements for most 'Sun not obscured' conditions (24).

These comparisons between ground-based and satellite UVA data are important because they give insight into the difficulties and differences between different datasets that one could use in photobiological and photochemical scientific research. Given the sparsity of ground-based UVA

and satellite UVA inter-comparisons, especially in Africa, the aim of this study was to compare GOME-2 broadband UVA satellite data to ground-based UVA measurements in South Africa. Daily exposure and daily maximum irradiance from GOME-2 were compared to ground-based UVA measurements at four sub-tropical sites in South Africa for all-sky and clear-sky conditions. These data form a basis for the typical regional adjustments to the UVA data from GOME-2 required to corroborate the satellite and ground-based data. We also make recommendations that ground-based networks in LIMCs need support if their data are to be used in, for example, epidemiological studies.

MATERIALS AND METHODS

Satellite data: UVA data for 2015 from GOME-2 were collected through the EUMETSAT Satellite Application Facility on Atmospheric Composition Monitoring (AC SAF) (<https://acsaf.org/>) website using the coordinates of each station. The GOME-2 UVA dataset uses a radiative transfer model to calculate clear-sky UVA values at 30-minute intervals (25). The AC SAF offline UVA data have a horizontal resolution of 0.5° , spectral range from 315 nm to 400nm and the satellite algorithm accounts for aerosols and surface albedo through established climatologies (17). Other factors affecting UVR, such as ozone and cloud optical depth, are accounted for through observations from other MetOp satellites (25). The daily exposure (J/m^2) and daily maximum irradiance (W/m^2) were used for the analysis. The daily exposure was determined through the trapezoidal rule summation of the 30-minute irradiance values (23).

Daily Cloud Fraction (CF) data for 2015 from the Atmospheric Infrared Sounder (AIRS) (<https://airs.jpl.nasa.gov/>) satellite were used to investigate the influence of changes in seasonal

cloud cover with changes on satellite UVA estimates (26). Daily CF data refers to the amount of sky covered by clouds where 0 indicates no clouds present and 1 indicates overcast conditions. From the daily CF data, monthly mean and 3 month-moving means were calculated.

Ground-based data: Satellite estimates of UVA were compared to ground-based measurements of UVA at four stations namely, Irene, De Aar, Upington and Stellenbosch in South Africa (Fig. 1) (Table 1). The stations are located between 119 m above sea level (ASL) and 1 523 m ASL in both urban and rural areas. A comparison of satellite and ground-based UV Index (UVI) observations in South Africa, showed that stations further north experienced higher UVI during winter and had a smaller annual range compared to stations further south (27).

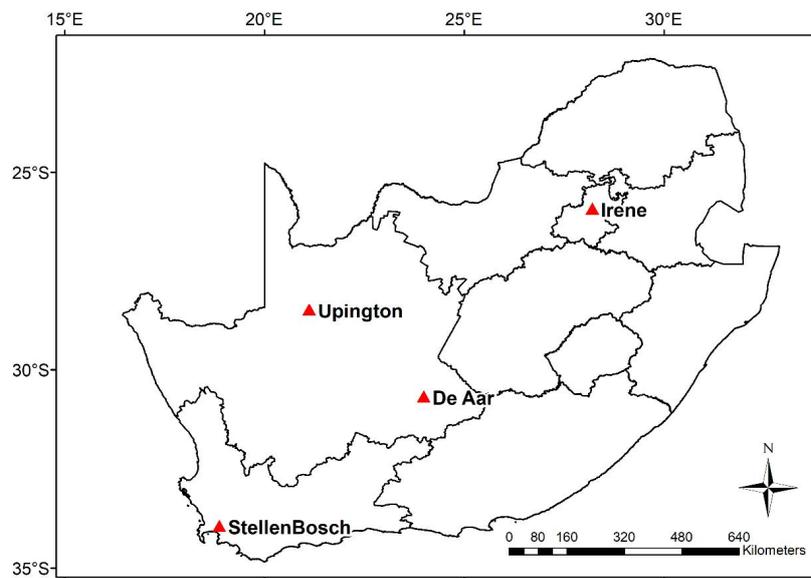


Figure 1. Map of South Africa indicating the location of the four stations used for the comparison of satellite and ground UVA data.

Table 1. Geographical description of stations used in this study.

	Irene	De Aar	Upington	Stellenbosch
Co-ordinates	25.91°S, 28.21°E	30.67°S, 23.99°E	28.48°S, 21.12°E	33.93°S, 18.87°E
Altitude (m)	1 523	1 284	848	119
Site characteristics	Polluted, large city in temperate climate region (28)	Unpolluted, located in a semi-desert region away from in large cities (29).	Unpolluted, located in an arid climate region away from in large cities (28).	Polluted, city in Mediterranean climate region (30).

The South African Weather Service (SAWS) and the Southern African Universities Radiometric Network (SAURAN) monitor surface UVA in South Africa. Data for 2015, from four stations and the two networks (SAWS: Irene, De Aar, Upington; and SAURAN: Stellenbosch) were used. At each station, a Kipp & Zonen UVS-AB-T UV radiometer was used. This specific radiometer measures both UVA and UVB and provides separate measurements of these radiation categories. The radiometer measures UVR between 315 nm and 400 nm, with a cosine response of less 2.5% between 0° and 70° solar zenith angle. The voltage output (Volts) from the radiometer is converted to irradiance (W/m^2) using the radiometric calibration factor. The irradiance is then corrected for spectral mismatch errors using conversion factors which are determined by the manufacturer based on modelled UV irradiances. The SAWS and SAURAN provided the 1-minute irradiance data in W/m^2 which had already been corrected for spectral mismatch errors. The three radiometers in the SAWS network were last calibrated by the manufacturer between December 2013 and February 2014 using Oriel Si-photodiode (Serial no.126) reference instrument. The reference used is traceable to the Van Swinden Laboratory (VSL) B.V., Netherlands. The radiometer at Stellenbosch was last

calibrated in October 2012. To our knowledge, none of the radiometers were taken to inter-comparison campaigns but the performance of the radiometers are consistent with other inter-comparisons (31). Previous inter-comparisons of Kipp & Zonen UVS-AB-T UV radiometers have shown that the instruments have an uncertainty of approximately 6% and long-term stability with 10% variation between calibrations every 2-years (32).

Analyses: To compare the satellite and ground-based UVA data, the 1-minute data from the ground-based stations were used to calculate the daily exposure and daily maximum irradiance values. This was only performed if there were a complete set of records for the corresponding day. The daily exposure was calculated using trapezoidal integration and the daily maximum irradiances were calculated from the data using 10-minute intervals. The GOME-2 data were quality controlled using the methods described in the Product User Manual (17).

The comparison was conducted for all-sky days and clear-sky days which were determined using a clear-sky determination method due to the lack of cloud observations at the study sites. The clear-sky determination method uses three steps to identify clear-sky days from surface UVR data (33). The third step requires a climatology of data and as a result only the first two steps were used as there was insufficient data to create a climatology at the stations.

The first step compared the linear correlation between the pre-solar noon and post-solar noon values, reversed. The second test determined if monotonic increases and decreases occurred in the morning and afternoon, respectively. Any day which has a correlation value of less than 0.8 or is not monotonic was deemed to be cloudy and was removed from the analysis (33).

The mean bias error (MBE) and mean absolute bias error (MABE) were calculated between the predicted and ground-based observations (23, 34). Indeed, a positive MBE value indicates that the GOME-2 data are higher than the ground-based observations, and *vice-versa*. A seasonal analysis should account for changes in cloud cover due to seasonal variability.

RESULTS

UVA time-series and cloud-cover analysis

The time-series for the 2015 GOME-2 data and the ground-based observations of the daily exposure (Fig. 2) and the daily maximum irradiance (Fig. 3) show an annual cycle. The maximums occurred during the austral summer and the minimums during the austral winter. The clear-sky data of both the daily exposure and daily maximum irradiance have less variability than compared to the data for all-sky conditions. This indicates that the clear-sky determination methods successfully removed cloud cover as an influencing factor.

The lowest daily exposure of $1.59 \times 10^5 \text{ J/m}^2$ and $0.27 \times 10^5 \text{ J/m}^2$ occurred at Stellenbosch for the GOME-2 and the ground-based data, respectively. The lowest and highest daily maximum irradiances occurred at Stellenbosch and De Aar, respectively. De Aar had a peak daily maximum irradiance of 63.3 W/m^2 and 85.01 W/m^2 for GOME-2 and ground-based data, respectively. Stellenbosch was the only station where the GOME-2 data were above the ground-based observations. Regardless of the season, Stellenbosch data shows a systematic shift between ground based and GOME-2 measurements. The under-estimations at Irene, De Aar and

Upington were visible under both sets of sky conditions. The factors contributing toward these findings are discussed below.

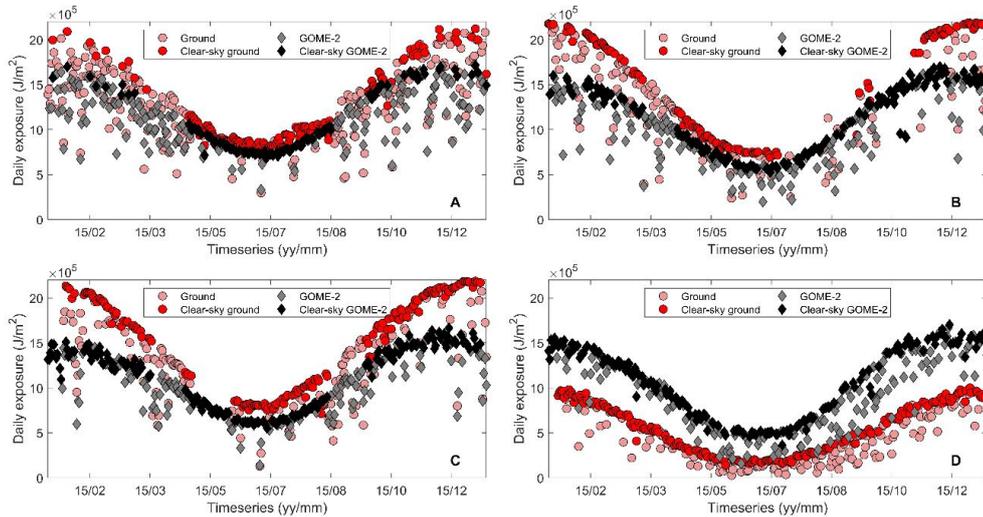


Figure 2. Time-series daily exposure at (A) Irene, (B) De Aar, (C) Upington and (D) Stellenbosch for 2015.

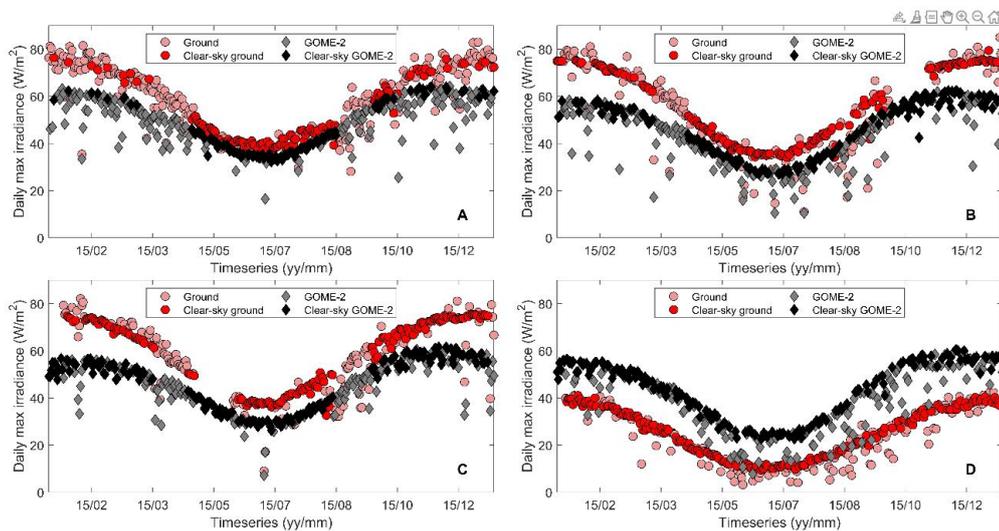


Figure 3. Time-series daily maximum irradiance at (A) Irene, (B) De Aar, (C) Upington and (D) Stellenbosch for 2015.

There are seasonal variations in CF (Fig 4) depending on the station. The highest monthly mean CF occurred at Stellenbosch (0.5) and the lowest at Upington (0.05). Irene reaches a maximum during the austral summer and a minimum during winter. The same can be seen De Aar and Upington with lower amplitudes. At Stellenbosch, the annual cycle differs, maximums occur during winter and minimum in summer.

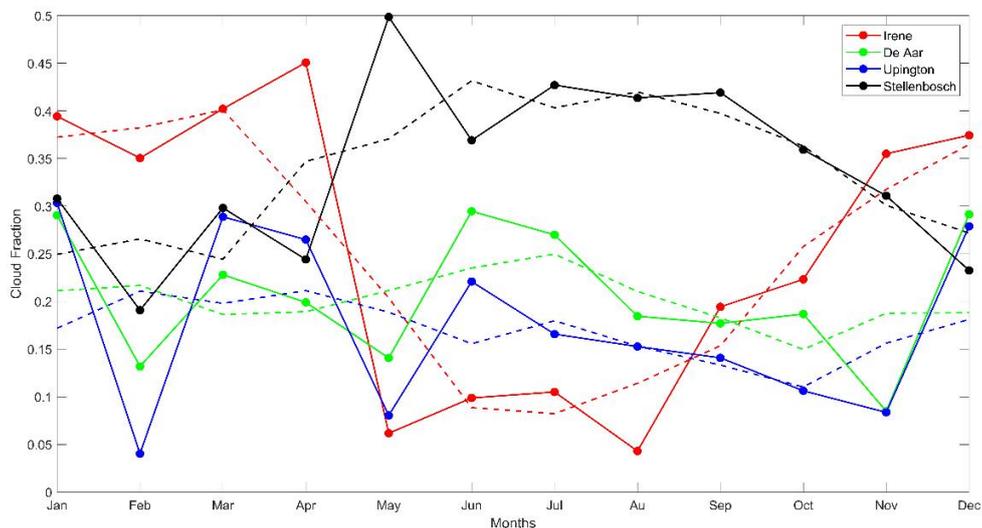


Figure 4. Monthly mean cloud fraction (CF) from AIRS observations for 2015 at Irene (red), De Aar (green), Upington (blue) and Stellenbosch (black). The smoothed seasonal values obtained by using a 3-month running average filter are superimposed for each site with dash lines.

Statistical comparison

The statistical analysis was performed over 2015 as well as for the four seasons. Both the daily exposure (Table 2) and daily maximum irradiance (Table 3) were analysed under all-sky and clear-sky conditions. Stellenbosch and De Aar had the highest and lowest data availability, respectively. Stellenbosch had the most clear-sky days in 2015.

For both the daily exposure and daily maximum irradiance, there was a strong linear relationship between the ground-based and GOME-2 data. Although there was a stronger linear relationship in the daily exposure compared to the daily maximum irradiance. On the determined clear-sky days, the linear relationship was stronger. A negative MBE at Irene, De Aar and Upington indicated that the GOME-2 data under-estimated surface UVA.

Table 2. Statistical comparison of daily exposure at Irene (A), De Aar (B), Upington (C) and Stellenbosch (D) for 2015 and each season. Clear-sky values are given in brackets.

	2015	DJF	MAM	JJA	SON
Irene					
N*	283 (110)	68 (11)	70 (24)	64 (56)	71 (19)
r	0.93 (0.98)	0.84 (0.85)	0.91 (0.99)	0.84 (0.80)	0.90 (0.88)
R-squared	0.87 (0.95)	0.70 (0.70)	0.82 (0.94)	0.66 (0.54)	0.78 (0.65)
MABE (%)	12.5 (11.3)	15.5 (18.3)	11.1 (18.9)	11.8 (56.4)	13.6 (18.9)
MBE (%)	-8.7 (-10.6)	-14.2 (-18.3)	-8.34 (-18.9)	-8.2 (-52.8)	-5.3 (15.7)
De Aar					
N	208 (105)	71 (37)	76 (34)	51 (13)	78 (21)

r	0.97 (0.98)	0.91 (0.71)	0.98 (0.99)	0.70 (0.84)	0.96 (0.90)
R-squared	0.94 (0.96)	0.83 (0.20)	0.94 (0.96)	0.46 (0.52)	0.88 (0.78)
MABE (%)	21.1 (22.6)	25.9 (28.1)	19.5 (16.6)	9.70 (7.9)	7.66 (11.5)
MBE (%)	-18.3 (-22.6)	-25.9 (-28.1)	-18.6 (-16.6)	-2.7 (-7.9)	-7.2 (-11.5)
Uppington					
N	266 (145)	73 (38)	33 (17)	76 (48)	78 (42)
r	0.95 (0.97)	0.89 (0.83)	0.91 (0.95)	0.75 (0.67)	0.90 (0.86)
R-squared	0.89 (0.94)	0.80 (0.50)	0.84 (0.88)	0.54 (0.30)	0.78 (0.71)
MABE (%)	22.9 (25.0)	28.5 (31.0)	18.3 (11.0)	24.8 (29.6)	23.8 (23.9)
MBE (%)	-20.6 (-24.7)	-28.5 (-31.0)	-17.9 (-11.0)	-19.3 (-28.3)	-19.8 (-23.9)
Stellenbosch					
N	304 (166)	71 (46)	29 (48)	75 (39)	77 (33)
r	0.96 (0.97)	0.85 (0.72)	0.95 (0.99)	0.95 (0.96)	0.95 (0.94)
R-squared	0.88 (0.89)	0.72 (0.50)	0.84 (0.88)	0.85 (0.89)	0.83 (0.81)
MABE (%)	130.2 (110.8)	66.2 (63.9)	152.8 (125.3)	206.5 (133.6)	131.9 (77.1)
MBE (%)	130.2 (110.8)	66.2 (63.9)	152.8 (125.3)	206.5 (133.6)	131.9 (77.1)

Table 3. Statistical comparison of daily maximum irradiance at Irene (A), De Aar (B), Upington (C) and Stellenbosch (D) for 2015 and each season. Clear-sky values are given in brackets.

	2015	DJF	MAM	JJA	SON
Irene					
N*	287 (111)	69 (11)	73 (25)	73 (56)	72 (19)
r	0.86 (0.97)	0.52 (-0.06)	0.83 (0.96)	0.70 (0.76)	0.60 (0.85)
R-squared	0.74 (0.94)	-0.06 (**)	0.69 (0.91)	-0.09 (0.38)	0.27 (0.63)
MABE (%)	9.4 (5.7)	15.9 (12.4)	8.9 (11.5)	5.2 (23.3)	9.2 (10.7)
MBE (%)	-8.9 (-5.5)	-15.9 (-12.5)	-8.9 (-11.5)	-4.7 (-22.3)	-7.9 (-9.5)
De Aar					
N	276 (137)	74 (37)	77 (34)	76 (39)	49 (27)
r	0.93 (0.98)	0.68 (0.55)	0.93 (0.98)	0.80 (0.91)	0.87 (0.91)
R-squared	0.87 (0.96)	**(**)	0.86 (0.96)	0.58 (0.76)	0.75 (0.83)
MABE (%)	12.3 (11.2)	19.5 (17.3)	11.3 (7.4)	7.4 (8.3)	7.5 (8.3)
MBE (%)	-11.9 (-11.2)	-19.5 (-17.3)	-11.3 (-7.4)	-6.6 (-8.3)	-6.9 (-8.3)
Upington					
N	267 (145)	65 (38)	51 (17)	76 (48)	75 (42)
r	0.90 (0.96)	0.65 (0.61)	0.83 (0.92)	0.70 (0.60)	0.82 (0.70)
R-squared	0.83 (0.92)	0.01 (**)	0.67 (0.83)	0.39 (0.14)	0.67 (0.48)
MABE (%)	13.04 (12.9)	19.9 (18.3)	11.1 (6.1)	9.3 (11.4)	13.3 (13.5)
MBE (%)	-12.7 (-12.8)	-19.9 (-18.3)	-11.1 (-6.1)	-8.5 (-10.9)	-12.7 (-13.5)
Stellenbosch					
N	308 (167)	72 (46)	79 (49)	78 (39)	79 (33)
r	0.92 (0.96)	0.26 (0.45)	0.91 (0.97)	0.89 (0.95)	0.78 (0.89)
R-squared	0.83 (0.85)	**(**)	0.81 (0.84)	0.79 (0.85)	0.60 (0.70)
MABE (%)	16.4 (17.7)	14.9 (16.6)	18.3 (18.8)	14.1 (12.5)	22.6 (16.3)
MBE (%)	16.3 (17.7)	14.0 (16.6)	18.3 (18.8)	14.1 (12.5)	22.4 (16.3)

The linear relationship between the ground-based UVA and GOME-2 is lower compared to the linear relationship over the entire period but increases using the determined clear-sky days.

The March, April, and May (MAM) season as well as the September, October, and November (SON) season have the strongest linear relationship at Irene, De Aar and Upington

for both daily exposure and daily maximum irradiance. The strongest linear relationship occurs at Stellenbosch during the MAM, SON and June, July, August (JJA) season).

DISCUSSION

During 2015, both the daily exposure and daily maximum irradiance showed a clear annual cycle under both sky conditions. Maximum and minimum annual values occurred during the austral summer and winter, respectively. The annual cycle of the daily dose and daily maximum irradiance was similar to other comparisons for sites in the Southern Hemisphere (24, 23).

From previous comparison studies (24, 35, 17, 23, 36) it was found that GOME-2 data would over-estimate surface UVA. We found that at Irene, De Aar and Upington the GOME-2 data underestimated surface UVA measurements. The continuous under-estimation occurred throughout the time-series for both the daily exposure and daily maximum irradiance. The under-estimation of GOME-2 satellite data have been recorded at high latitude sites such as Palmer (64.77° S, 64.05° W) and McMurdo (77.83° S, 166.67° E). At these locations, factors such as surface albedo play an important role and the under-estimations have a seasonal dependence (35).

The statistical results in Table 2 and Table 3 showed that the correlation coefficient (r), MABE and MBE at all four stations were similar to previous comparison studies (35, 23, 36) however, the MBE values indicated an under-estimation at Irene, De Aar and Upington. The extent of these under-estimations at the three stations were approximately the same as the over-estimations found at other locations. The over-estimation found at Stellenbosch for the daily

exposure with a MABE and MBE value of 130.2% was slightly higher than that found in other comparisons (35, 23) but the over-estimation of daily maximum irradiance was similar to other comparisons (36).

In Figures 2 and 3, there is evidence of a seasonal variability in the difference between the GOME-2 data and the ground-based observations. The largest bias occurred during the austral summer months (DJF) at Irene, De Aar and Upington. At these three stations, the smallest bias was seen during SON season. At Stellenbosch, the seasonality is different, the largest bias occurred during the austral winter months (JJA) and the smallest bias in the DJF season.

The differences between satellite and ground-based UVA (Fig.2 and Fig. 3) are higher during the austral summer for Irene, De Aar and Upington when the annual cycle is at a maximum for CF. This suggests that cloud cover is an important parameter and should be considered for satellite inversion processes to retrieve UVA exposure and maximum irradiance.

The under-estimation of satellite UVA data found in this study at South African sites may be attributed to several factors related to the satellite algorithm and to the location of stations. The GOME-2 data has a relatively coarse spatial resolution of 0.5° . An established climatology of aerosols and surface albedo was used in the satellite algorithm and therefore the effect of aerosols and albedo were not determined from observations. The algorithm calculates the surface UVA for a horizontal plane, changes in terrain height and altitude within the grid box can affect the satellite estimate (25, 35). Altitude has an effect on UVR at the surface (37). Stellenbosch is located at 118 m ASL whereas the other stations are above 800 m ASL.

Several study limitations were present. While data for additional years were available, calibration was not conducted regularly hence the data available for the year closest to the last calibration were used. The short dataset does allow for a thorough analysis and the precise dates for last calibration of ground-based network instrumentation were not available. Thus, a longer period of data could not be used as the accuracy of the data cannot be guaranteed. Further support to ground-based networks should be a priority for national meteorological services. Given challenges with ground-based data, photobiologists, photochemists and others who research the effects of UVA on biological systems should work hand-in-hand with ground-based network managers to understand data limitations.

CONCLUSION

The broadband UVA irradiances from GOME-2 satellite data and ground-based radiometer data for 2015 at four sites in South Africa have been described for all-sky and clear-sky conditions. The comparison between the datasets of daily exposure and daily maximum irradiances showed that there exists a strong linear relationship between the satellite data and ground-based observations. At Irene, De Aar and Upington the satellite data were found to under-estimate surface UVA. At Stellenbosch, an over-estimation of satellite UVA was found which is consistent with comparisons around the world (35, 23). The identified under-estimations may be as a result of resolution of the satellite data, assumptions of aerosols and albedo in the satellite algorithm and the effect of altitude and terrain changes. A seasonal analysis showed that the largest biases occurred during summer months at Irene, De Aar and Upington when CF was

highest. Regular calibration is essential for a comprehensive analysis across multiple years to further compare satellite and ground-based observations.

ACKNOWLEDGMENTS:

This work is undertaken in the framework of the French South-African International Research Project ARSAIO (Atmospheric Research in Southern Africa and Indian Ocean). We thank the EUMETSAT Satellite Application Facility on Atmospheric Composition Monitoring (AC SAF) for providing the satellite data and the South African Weather Service (SAWS) and Southern African Universities Radiometric Network (SAURAN) for the ground-based data used in this paper. Caradee Y. Wright receives research funding from the South African Medical Research Council and the National Research Foundation (NRF, South Africa). D. Jean du Preez received a Doctoral scholarship from the University of Pretoria and a bursary from the French Embassy in South Africa.

REFERENCES

1. Diffey, B. (1991) Solar ultraviolet radiation effects on biological systems. *Physics in medicine & biology* **36**, 299.
2. Lucas, R. M., S. Yazar, A. R. Young, M. Norval, F. R. de Gruijl, Y. Takizawa, L. E. Rhodes, C. A. Sinclair and R. E. Neale (2019) Human health in relation to exposure to solar ultraviolet radiation under changing stratospheric ozone and climate. *Photochemical & Photobiological Sciences* **18**, 641-680.
3. Yousif, E. and R. Haddad (2013) Photodegradation and photostabilization of polymers, especially polystyrene. *SpringerPlus* **2**, 398.
4. Derebe, A. D., A. Gobena Roro, B. Tessfaye Asfaw, W. Worku Ayele and A. K. Hvoslef-Eide (2019) Effects of solar UV-B radiation exclusion on physiology, growth and yields of taro (*Colocasia esculenta* (L.)) at different altitudes in tropical environments of Southern Ethiopia. *Scientia Horticulturae* **256**, 108563.
5. Ballaré, C. L. and A. T. Austin (2017) UV radiation and terrestrial ecosystems: Emerging perspectives. *UV-B Radiation and Plant Life: Molecular Biology to Ecology*. Oxfordshire, CABI International, 23-38.

6. Sulzberger, B., A. T. Austin, R. M. Cory, R. G. Zepp and N. D. Paul (2019) Solar UV radiation in a changing world: roles of cryosphere–land–water–atmosphere interfaces in global biogeochemical cycles. *Photochemical & Photobiological Sciences* **18**, 747-774.
7. Young, A. R., J. Claveau and A. B. Rossi (2017) Ultraviolet radiation and the skin: Photobiology and sunscreen photoprotection. *Journal of the American Academy of Dermatology* **76**, S100-S109.
8. Lucas, R., T. McMichael, W. Smith, B. K. Armstrong, A. Prüss-Üstün and O. World Health (2006) Solar ultraviolet radiation : global burden of disease from solar ultraviolet radiation / Robyn Lucas ... [et al.] ; editors, Annette Prüss-Üstün ... [et al.]. World Health Organization, Geneva.
9. Diffey, B. L. (2002) Sources and measurement of ultraviolet radiation. *Methods* **28**, 4-13.
10. NDACC Network for the Detection of Atmospheric Composition Change. Available at: <http://www.ndaccdemo.org/>. Accessed on 28 April 2020.
11. WOUDC (World Ozone and Ultraviolet Radiation Data Centre) Available at: <https://woudc.org/home.php>. Accessed on 28 April 2020.
12. Schmalwieser, A. W., J. Gröbner, M. Blumthaler, B. Klotz, H. De Backer, D. Bolsée, R. Werner, D. Tomsic, L. Metelka, P. Eriksen, N. Jepsen, M. Aun, A. Heikkilä, T. Duprat, H. Sandmann, T. Weiss, A. Bais, Z. Toth, A.-M. Siani, L. Vaccaro, H. Diémoz, D. Grifoni, G. Zipoli, G. Lorenzetto, B. H. Petkov, A. G. di Sarra, F. Massen, C. Yousif, A. A. Aculinin, P. den Outer, T. Svendby, A. Dahlback, B. Johnsen, J. Biszczuk-Jakubowska, J. Krzyscin, D. Henriques, N. Chubarova, P. Kolarž, Z. Mijatovic, D. Groselj, A. Pribulova, J. R. M. Gonzales, J. Bilbao, J. M. V. Guerrero, A. Serrano, S. Andersson, L. Vuilleumier, A. Webb and J. O'Hagan (2017) UV Index monitoring in Europe. *Photochemical & Photobiological Sciences* **16**, 1349-1370.
13. Schmalwieser, A. W. and G. Schaubberger (2001) A monitoring network for erythemally-effective solar ultraviolet radiation in Austria: determination of the measuring sites and visualisation of the spatial distribution. *Theoretical and Applied Climatology* **69**, 221-229.
14. ARPANSA Ultraviolet Radiation Monitoring'. Available at: <https://www.arpansa.gov.au/our-services/monitoring/ultraviolet-radiation-monitoring> .
15. Mmathapelo, M. and Y. W. Caradee (2015) Real-time measurement of outdoor worker's exposure to solar ultraviolet radiation in Pretoria, South Africa. *S. Afr. J. Sci* **111**.
16. Kahn, R. A. (2015) Satellites and satellite remote sensing: Aerosol Measurements. In *Encyclopedia of Atmospheric Sciences (Second Edition)*. (Edited by G. R. North, J. Pyle and F. Zhang), pp. 51-66. Academic Press, Oxford.
17. Kujanpää, J. (2013) Product User Manual: Offline UV (OUV) Products, SAF/O3M/FMI/PUM/001.
18. EUMETSAT (2015) GOME-2 Factsheet. Available at: https://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=PDF_GOME_FACTSHEET&RevisionSelectionMethod=LatestReleased&Rendition=Web. Accessed on 14 December 2019.
19. Jégou, F., S. Godin-Beekman, M. P. Corrêa, C. Brogniez, F. Auriol, V. H. Peuch, M. Haeffelin, A. Pazmino, P. Saiag, F. Goutail and E. Mahé (2011) Validity of satellite measurements used for the monitoring of UV radiation risk on health. *Atmos. Chem. Phys.* **11**, 13377-13394.
20. Arola, A., S. Kazadzis, A. Lindfors, N. Krotkov, J. Kujanpää, J. Tamminen, A. Bais, A. di Sarra, J. M. Villaplana, C. Brogniez, A. M. Siani, M. Janouch, P. Weihs, A. Webb, T. Koskela,

- N. Kouremeti, D. Meloni, V. Buchard, F. Auriol, I. Ialongo, M. Staneck, S. Simic, A. Smedley and S. Kinne (2009) A new approach to correct for absorbing aerosols in OMI UV. *Geophys. Res. Lett* **36**.
21. Watson, M., D. M. Holman and M. Maguire-Eisen (2016) Ultraviolet Radiation Exposure and Its Impact on Skin Cancer Risk. *Seminars in Oncology Nursing* **32**, 241-254.
22. Vernez, D., A. Milon, L. Vuilleumier, J.-L. Bulliard, A. Koechlin, M. Boniol and J. F. Doré (2015) A general model to predict individual exposure to solar UV by using ambient irradiance data. *Journal of Exposure Science & Environmental Epidemiology* **25**, 113-118.
23. Parisi, A. V., N. Downs, J. Turner and R. King (2017) Comparison of GOME-2 UVA satellite data to ground-based spectroradiometer measurements at a subtropical site. *IEEE Geosci. Remote Sens. Lett.* **55**, 3145-3149.
24. Jebar, M. A. A., A. V. Parisi, N. J. Downs and J. F. Turner (2018) Evaluated UVA Irradiances over a Twelve-year Period at a Subtropical Site from Ozone Monitoring Instrument Data Including the Influence of Cloud. *Photochem. Photobiol* **94**, 1281-1288.
25. Kujanpää, J. and N. Kalakoski (2015) Operational surface UV radiation product from GOME-2 and AVHRR/3 data. *Atmos. Meas. Tech.* **8**, 4399-4414.
26. Teixeira, A. S. T. J. (2013) AIRS/Aqua L3 Monthly Standard Physical Retrieval (AIRS-only) 1 degree x 1 degree V006, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC).
27. Cadet, J.-M., H. Bencherif, T. Portafaix, K. Lamy, K. Ncongwane, G. J. R. Coetzee and C. Y. Wright (2017) Comparison of Ground-Based and Satellite-Derived Solar UV Index Levels at Six South African Sites. *Int. J. Environ. Res. Public Health* **14**, 1384.
28. Mabasa, B., J. Botai and L. Ntsangwane (2018) Update on the re-establishment of the South African Weather Service (SAWS) radiometric network in all six climatological regions and the quality of the data.
29. Esterhuyse, D. (2007) Horizon at station De Aar. PANGAEA.
30. Brooks, M. J., S. Du Clou, W. L. Van Niekerk, P. Gauché, C. Leonard, M. J. Mouzouris, R. Meyer, N. Van der Westhuizen, E. E. Van Dyk and F. J. Vorster (2015) SAURAN: A new resource for solar radiometric data in Southern Africa. *J. energy South. Afr.* **26**, 2-10.
31. Diémoz, H., A. Siani, G. Casale, A. Di Sarra, B. Serpillo, B. Petkov, S. Scaglione, A. Bonino, S. Facta and F. Fedele (2011) First national intercomparison of solar ultraviolet radiometers in Italy. *Atmos. Meas. Tech.* **4**, 1689.
32. Schmalwieser, A. W., B. Klotz, M. Schwarzmann, D. J. Baumgartner, J. Schreder, G. Schauburger and M. Blumthaler (2019) The Austrian UVA-Network. *Photochem. Photobiol* **95**, 1258-1266.
33. du Preez, D. J., J. V. Ajtić, H. Bencherif, N. Bègue, J. M. Cadet and C. Y. Wright (2019) Spring and summer time ozone and solar ultraviolet radiation variations over Cape Point, South Africa. *Ann. Geophys.* **37**, 129-141.
34. Antón, M., D. Loyola, M. López, J. M. Vilaplana, M. Bañón, W. Zimmer and A. Serrano (2009) Comparison of GOME-2/MetOp total ozone data with Brewer spectroradiometer data over the Iberian Peninsula. *Ann. Geophys.* **27**, 1377-1386.
35. Kalakoski, N. (2009) O3M SAF OUV Validation.
36. Singh, S., N. K. Lodhi, A. K. Mishra, S. Jose, S. N. Kumar and R. K. Kotnala (2018) Assessment of satellite-retrieved surface UVA and UVB radiation by comparison with ground-measurements and trends over Mega-city Delhi. *Atmos. Environ.* **188**, 60-70.

37. McKenzie, R. L., P. V. Johnston, D. Smale, B. A. Bodhaine and S. Madronich (2001)
Altitude effects on UV spectral irradiance deduced from measurements at Lauder, New
Zealand, and at Mauna Loa Observatory, Hawaii. *J. Geophys. Res. Atmos.* **106**, 22845-22860.