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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 are 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 underestimations found at the three sites. These results indicate that satellite estimates of surface UVA over South Africa do not exhibit the same behavior as other stations around the world and therefore require further validation.

INTRODUCTION

The risks and benefits of exposure to solar ultrhaviolet 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 photobiologically 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) program 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 esitmates 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) reflectance. 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 toward 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), modeling to predict UVR exposure (22), and for public

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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 and 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 spectroradiometer 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 subtropical 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 intercomparisons, 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 subtropical 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-min intervals (25). The AC SAF offline UVA data have a horizontal resolution of 0.5° and spectral range from 315 nm to 400 nm, 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-min 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 in satellite UVA estimates (26). Daily CF data refer 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).

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 modeled UV irradiances. The SAWS and SAURAN provided the 1-min 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., the Netherlands. The radiometer at Stellenbosch was last calibrated in October 2012. To our knowledge, none of the radiometers were taken to intercomparison campaigns but the performance of the radiometers is consistent with other intercomparisons (31). Previous intercomparisons 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).

Analysis. To compare the satellite and ground-based UVA data, the 1-min 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-min 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 were 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 whether 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.

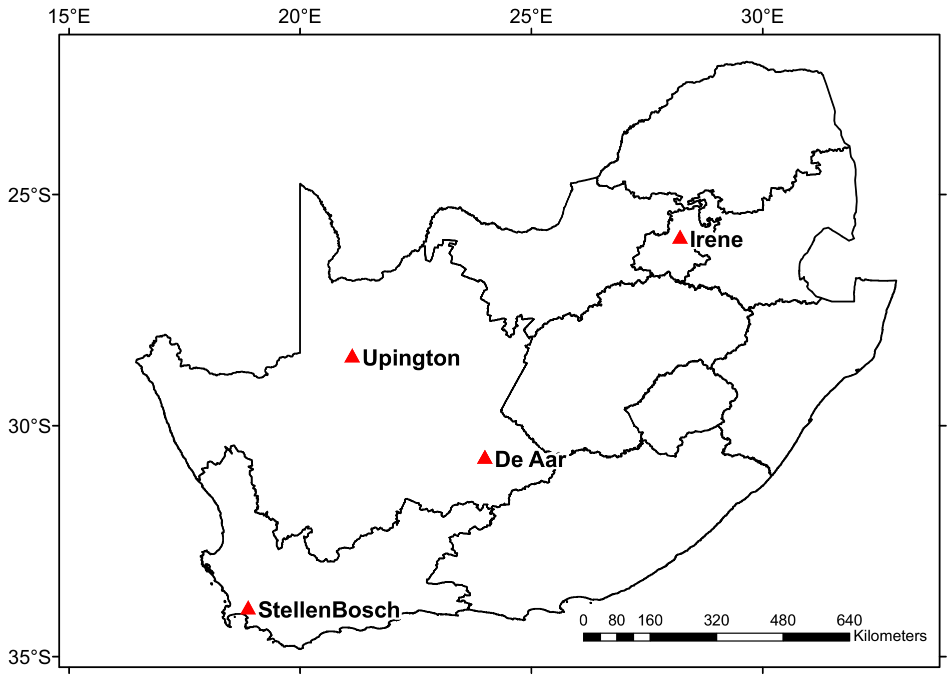

Figure 1. Map of South Africa indicating the location of the four stations used for the comparison of satellite and ground UVA data. [Color figure can be viewed at wileyonlinelibrary.com]

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

	Irene	De Aar	Upington	Stellenbosch
Coordinates	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)	1523	1284	848	119
Site characteristics	Polluted, large city in temperate climate region (28)	Unpolluted, located in a semidesert region away from in large cities (29)	Unpolluted, located in an arid c limate region away from in large cities (28)	Polluted, city in Mediterranean climate region (30)

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 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 1.59×10^5 J m^{-2} and 0.27×10^5 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 show a systematic shift between ground-based and GOME-2 measurements. The underestimations at Irene, De Aar and Upington were visible under both sets of sky conditions. The factors contributing toward these findings are discussed below.

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 in De Aar and Upington with lower amplitudes. At Stellenbosch, the annual cycle differs, maximums occur during winter and minimum in summer.

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 analyzed 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

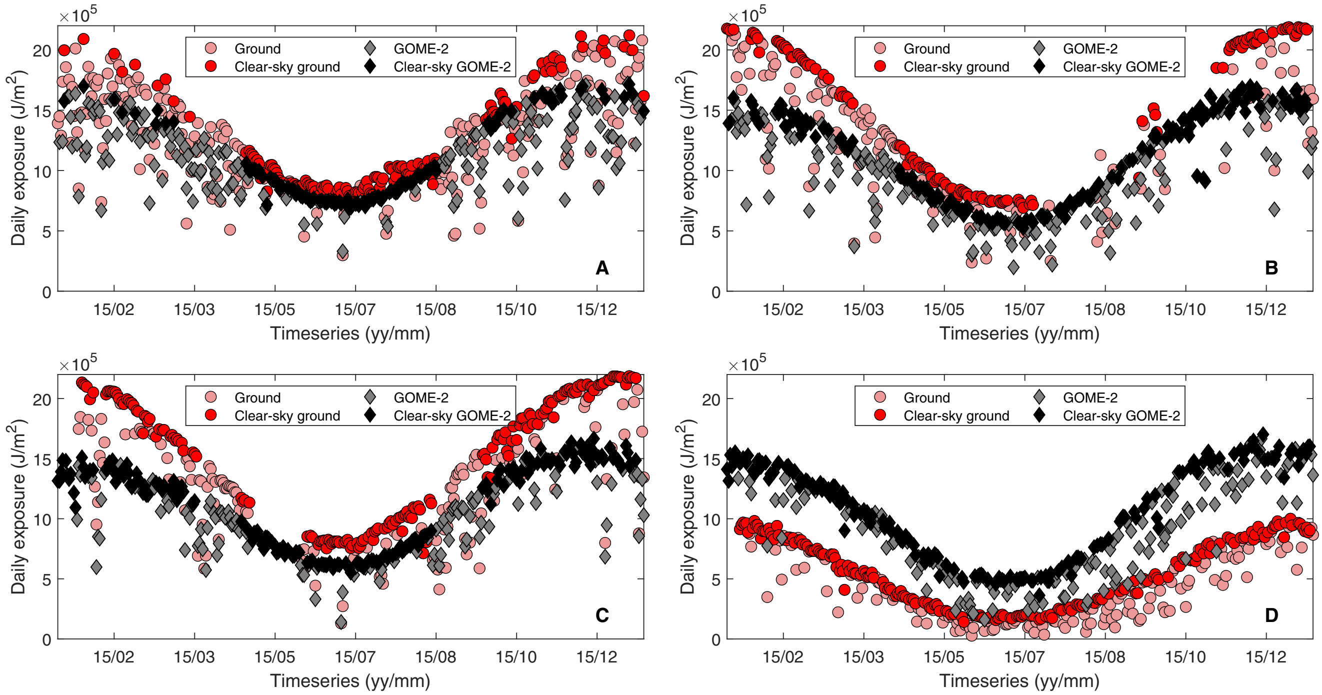

Figure 2. Time-series daily exposure at (A) Irene, (B) De Aar, (C) Upington and (D) Stellenbosch for 2015.

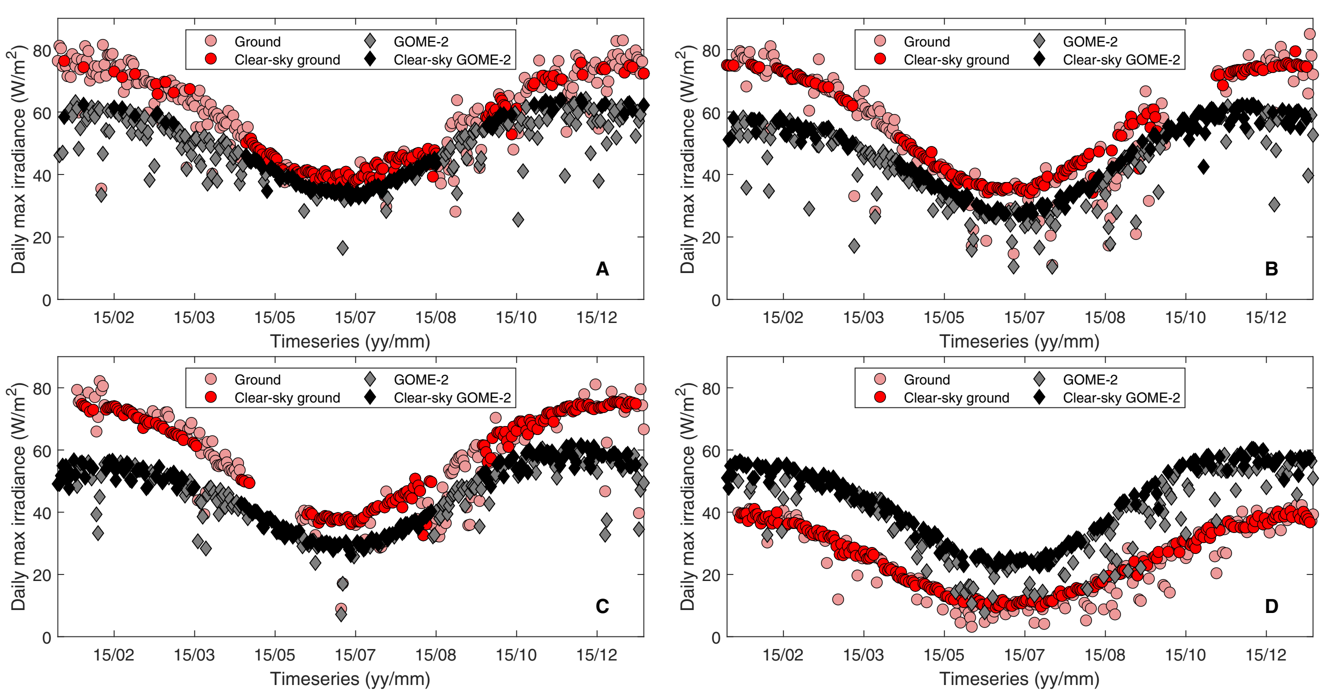

Figure 3. Time-series daily maximum irradiance at (A) Irene, (B) De Aar, (C) Upington and (D) Stellenbosch for 2015.

Upington indicated that the GOME-2 data underestimated surface UVA.

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 has 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 and August (JJA) season).

DISCUSSION

During 2015, both the daily exposure and daily maximum irradiance showed a clear annual cycle under both sky conditions.

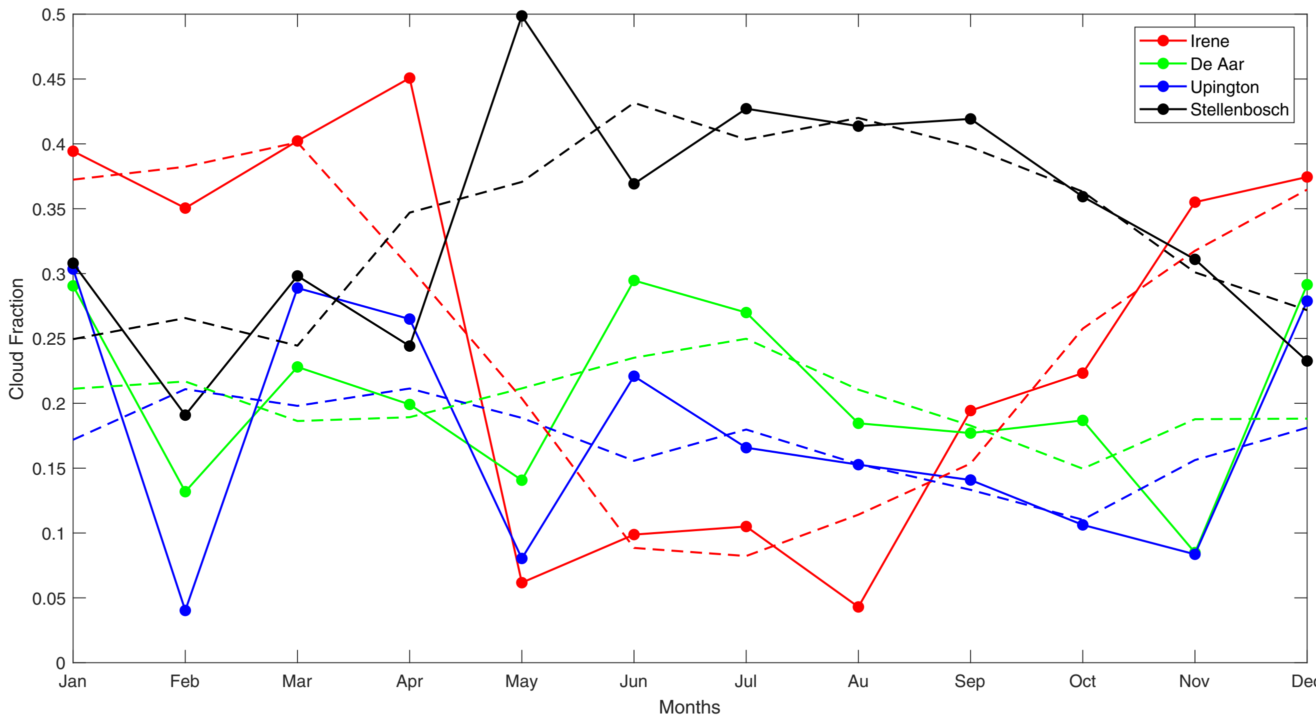

Figure 4. Monthly mean cloud fraction (CF) from AIRS observations for 2015 at Irene (red), De Aar (green), Upington (blue) and Stellenbosch (black). The smoothed seasonal values obtained by using a 3-month running average filter are superimposed for each site with dash lines.

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)
Upington					
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)

DJF = December, January and February; MAM = March, April and May; JJA = June, July and August, SON = September, October and November; *r* = correlation coefficient; MABE = mean absolute bias error; MBE = mean bias error. *Number of observations.

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 overestimate surface UVA. We found that at Irene, De Aar and Upington, the GOME-2 data underestimated surface UVA measurements. The continuous

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)

DJF = December, January and February; MAM = March, April and May; JJA = June, July and August; SON = September, October and November; *r* = correlation coefficient; MABE = mean absolute bias error; MBE = mean bias error. *Number of observations. **Insufficient data.

underestimation occurred throughout the time series for both the daily exposure and daily maximum irradiance. The underestimation of GOME-2 satellite data has 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 underestimations have a seasonal dependence (35).

The statistical results in Tables 2 and 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 underestimation at Irene, De Aar and Upington. The extent of these underestimations at the three stations was approximately the same as the overestimations found at other locations. The overestimation 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 overestimation of daily maximum irradiance was similar to other comparisons (36).

In Figs 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 (Figs 2 and 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 underestimation 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 have 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 was 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 underestimate surface UVA. At Stellenbosch, an overestimation of satellite UVA was found which is consistent with comparisons around the world (23,35). The identified underestimations 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.

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