Real-time measurement of outdoor worker's exposure to solar ultraviolet radiation in Pretoria, South Africa

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The city of Pretoria in South Africa receives considerable solar ultraviolet radiation (UVR) because of its low latitude (22–35°S) and relatively clear skies. Certain meteorological factors affect the amount of solar UVR that reaches the ground; the most dominant factors being stratospheric ozone, cloud cover and solar zenith angle. It is known that overexposure to solar UVR may lead to the development of adverse health conditions, the most significant being skin cancer. Outdoor workers spend a significant amount of time outside and are thus susceptible to this risk. In this case study, we estimated, for the first time, the real-time solar UVR exposure of an outdoor worker in Pretoria. Measurements were made on 27 and 28 May 2013 using a handheld ultraviolet index (UVI) meter calibrated against a science-grade biometer at the South African Weather Service in Pretoria. Personal exposure estimation was used to discern the pattern in diurnal and annual sunburn risk for the outdoor worker. Ambient UVR levels ranged from 0 UVI to 4.66 UVI and the outdoor worker's potential exposure estimates regularly exceeded 80% of these levels depending on the time of day. The risk of sunburn was evident; however, actual incidents would depend on individual skin photosensitivity and melanin content, as well as sun protection used. Further research is needed to determine the personal exposure estimations of outdoor workers in other provinces in which solar UVR levels may be equally high, or higher than those in Pretoria.

Introduction

People living in South Africa can potentially experience intense personal exposure to solar ultraviolet radiation (UVR). This potential is because of the country's low latitude (22–35°S), high altitude in the interior, annual average daytime temperature of 22 °C (thereby encouraging time spent outdoors) and high ultraviolet index (UVI) occurrences almost year-round.[1,2] The global UVI is a measure of solar UVR intended to inform the general public about UVR intensity; the index ranges from 0, which is considered low, to 11 or higher, which is considered extreme.[3,4]

Exposure to UVR is known to have both beneficial and harmful photobiological effects on humans. The most significant benefit is the endogenous production of vitamin D.[5] Vitamin D is essential for, among other processes, bone metabolism in the human body.[6] Harmful effects of UVR occur as a result of either underexposure or overexposure to UVR. Underexposure is harmful as it may result in a deficiency in vitamin D in the body.[5] Some of the main harmful effects of overexposure are damage to the skin (in the form of sunburn) and to DNA. Excess solar UVR exposure is known to be a carcinogen.

UVR is subdivided into three bands: UVA (400–315 nm), UVB (315–280 nm) and UVC (280–100 nm). UVR at wavelengths shorter than 320 nm is more photobiologically active than UVR at longer wavelengths.[7] However, radiation from 250 nm is sufficiently biologically active to cause erythema in the skin. Therefore, although UVA penetrates the human skin more deeply than UVB, because of its shorter wavelength, UVB poses a greater risk for initiation of the carcinogenic process in skin.[5]

Several factors influence the amount of solar UVR that reaches the ground. These factors include stratospheric ozone, cloud cover, sun position (determined by time of day, season, geographic latitude and solar zenith angle), altitude, surface reflection and air pollution.[3] A previous study has shown that total ozone, solar zenith angle (SZA) and cloud cover are among the dominant meteorological factors that influence the amount of UVB that reaches the ground.[8,9] It is important to determine the relationship that exists between each of these factors and solar UVR.

The main absorber in the atmosphere that determines the amount of UVR that reaches the ground is stratospheric ozone. Ozone production and destruction require solar radiation with wavelengths shorter than 240 nm (which is mainly UVC radiation).[10] Total column ozone is measured in Dobson units (DU) where 1 DU = $2.69\text{x}10^{16}$ mol O^3/cm^2.[11] Total column ozone is usually measured with a satellite-based instrument. A typical DU value for ozone in the mid-latitudes is found in the region of 300 DU.[12] A distinct seasonal cycle is observed at middle and high latitudes with the highest values typically occurring in spring in the southern hemisphere.[13,14] In the absence of all other factors, less ozone in the atmosphere allows for more solar UVR to reach the ground, and vice versa.[10]

Cloud cover has been found to be the second most effective shield (after stratospheric ozone) to limit the amount of solar UVR that reaches the earth's surface.[15] Cloud cover can either attenuate or enhance the amount of solar UVR reaching the ground.[10] Whether attenuation or enhancement occurs is determined by factors such as cloud location (which refers to cloud height and whether or not the cloud is covering the solar disc), percentage cover, optical thickness and liquid water content.[16] A reduction in solar UVR of 50% has been found over the USA and 70% over Sweden during overcast conditions.[17]

The intensity of the sun rays, and therefore of solar UVR, as they reach the ground is strongly dependent on SZA.[7] SZA is the angle that is formed between directly overhead and the centre of the disc of the sun (using a horizontal coordinate system). A zenith angle of 0° means that the sun is directly overhead; this angle occurs at solar noon. When the sun is directly overhead (i.e. the SZA is smaller), all of the emitted rays are focused on a relatively small, solid area on the earth's surface. However, once the SZA starts to increase, the sun's rays are distributed over a larger area of the earth's surface, thereby decreasing the intensity of solar UVR. SZA is smaller in the summer months when the sun is higher in the sky and larger in the winter months when the sun falls lower in the sky. Therefore solar UVR is more intense during summer and less intense in winter.[7]

South Africa has a high occurrence of skin cancer, accounting for about 30% of all histologically diagnosed cancers. An important risk factor for skin cancer is skin phototype (including skin colour). Six skin phototypes have been defined according to the skin's response to solar UVR exposure. People with darker skin types have more melanin in their skin and therefore a higher degree of protection against solar UVR. People with fairer skin types have less melanin and therefore a lower degree of natural protection.[18] The Fitzpatrick classification can be used as a guide to prevent overexposure. Table 1 shows the different skin phototypes and their respective minimum standard erythemal dose values needed to elicit sunburn according to Fitzpatrick.

Outdoor workers are susceptible to overexposure to solar UVR as they spend the majority of their day outside.[23] Many previous studies (particularly in Europe, Australia and New Zealand) have measured the solar UVR exposures of outdoor workers. Larko and Diffey[24] found that outdoor workers received between 10% and 70% of ambient UVR depending on the amount of work time spent outdoors. Reducing sun exposure is not a feasible option for outdoor workers.[25] Studies among New Zealand and Australian outdoor workers found that sun protection is not seen as a priority. Poor and inconsistent sun protection measures are employed and many outdoor workers find certain measures (such as wearing hats and clothing that covers exposed areas) inconvenient to use while working. Many of the workers are not required to wear hats or use sunscreen, despite working in areas that receive high amounts of solar UVR.[26,27] It has been shown that employer-led interventions may lead to an increase in the use of sun-protective measures by outdoor workers.[28]

Potential sunburn risk among outdoor workers in South Africa based on ambient solar UVR readings has been estimated in a study.[1] The study concluded that, for almost all seasons, locations considered and six skin types, there was at least one day (but usually many more days) when outdoor workers were at risk of sunburn; however, it also was concluded that real-time measurements of outdoor workers' exposure were needed to validate these findings.

Our primary aim in this study was to measure the personal exposure to solar UVR of an outdoor worker in Pretoria. We conducted a case study in which levels of solar UVR were measured at a site where an outdoor worker was working. The results were used to determine the worker's time-stamped and average daily exposure to solar UVR. Our secondary aim was to investigate the relationship between solar UVR and the three above-mentioned meteorological factors – cloud cover, total column ozone and SZA – that influenced the amount of solar UVR that reached the ground in Pretoria in 2012 for the whole year and for each season. This investigation was done in order to understand both the static risk and the dynamic risk of overexposure to solar UVR. In this study, the static risk is the basic risk one would be exposed to on any given day. This risk is represented by the estimated exposure determined by the primary aim. The dynamic risk is the actual amount of solar UVR one is at risk of being exposed to. This risk changes according to the amount of solar UVR that reaches the ground. It is therefore influenced by the meteorological factors considered in this study. This study is the first in South Africa in which the exposure of an outdoor worker is determined using actual measurements of solar UVR. Ultimately, the results of this study will be used to develop a full-scale study to then produce recommendations for sun protective measures for outdoor workers in South Africa.

Data

Case study

The solar UVR measurements for the case study were collected using two handheld UVI meters. These instruments are available commercially and were made by the same company (name withheld). Two instruments were used just in case one of the instruments failed. The readings (in UVI) were manually captured in a logbook. Wright and Albers[29] detail the accuracy of the instruments. The recorded values were later corrected using calibration equations obtained by calibrating the UVI meters against the UVB biometer at the South African Weather Service (SAWS) in Pretoria.[29] Ambient solar UVR data for Pretoria were measured by the SAWS' UVB biometer.

Meteorological factors

Five data sets were used for the purpose of analysing the relationships between solar UVR and the three meteorological factors: cloud cover, total column ozone and SZA. These data sets were cloud cover data, sun elevation data, total column ozone data, ground-based solar UVR measurements and satellite solar UVR data. The ground-based solar UVR data and the cloud cover data were obtained from the SAWS in

Table 1: The Fitzpatrick skin phototype classification[19-22]

Skin type	Unexposed skin colour	Constitutive characteristics	History of sunburn	Ultraviolet radiation sensitivity	Continuous ultraviolet radiation exposure needed for sunburn (SED)
I	White	Fair skin, blue or light eyes and freckles	Always burns on minimal sun exposure	Extremely sensitive	2–3
II	White	Red or blonde hair, blue, hazel or brown eyes and freckles	Burns very readily	Very sensitive	2.5–3
III	White/light brown	Brown hair and blue, hazel or brown eyes	May burn on regular sun exposure with no protection	Moderately sensitive	3–5
IV	Light brown	Brown hair and dark eyes	Burns rarely	Relatively tolerant	4.5–6
V	Brown	Brown eyes and dark brown or black hair	Despite pigmentation, may burn surprisingly easily on sun exposure	Very variable	6–20
VI	Black	Brown eyes and dark brown or black hair	Rarely burns, although sunburn is difficult to detect on very pigmented skin	Relatively insensitive	6–20

SED, standard erythemal dose

Pretoria. The sun position data were obtained from the National Oceanic and Atmospheric Administration. The satellite solar UVR data and the total column ozone data were obtained from GIOVANNI, a web-based portal site that allows access to data collected by various satellites. The measurements were local noon readings taken by the OMI/Aura satellite instrument (measured in UVI and DU, respectively). All of the data covered the area in which the SAWS UVB biometer is located in Pretoria. All of the data were for 1 January 2012 to 31 December 2012. The ground-based solar UVR data set had missing values for 10 days between 3 September and 12 September. The satellite solar UVR data set had a period of 53 days between 9 September and 1 November in which no data were recorded. All the days of missing data were omitted from the respective calculations.

Methods

Case study

Site and participant selection

Pretoria was chosen as the site for this case study because in a previous study Pretoria was found to have some of the highest solar UVR levels in South Africa.[1] An outdoor worker was selected and agreed to partake in the case study. The participant had skin type VI according to the Fitzpatrick skin phototype classification. The case study was approved by the University of Pretoria Research Ethics Committee (reference EC130610-054). The participant was chosen because he met the following requirements: spends the majority of the work day outdoors, works outdoors for more than 3 days per week, and the work site is in Pretoria. The case study was conducted over 2 days with minimal cloud cover to minimise the solar UVR attenuation effect of clouds.

Instruments

Two handheld UVI meters – UVI meter 1 and UVI meter 2 – were used to measure solar UVR reaching the worker at 30-min intervals for 7 h each day. They were used in a study in which they were compared to the research-grade UVB biometer at the SAWS in Pretoria. One of the monitors, UVI meter 2, was found to be in sufficient agreement with the UVB biometer. The other monitor, UVI meter 1, overestimated the solar UVR by up to 4 UVI units. The instruments were calibrated during a previous study against the UVB biometer to ensure that their readings provided a true measure of solar UVR received.[29]

Data collection

Half-hourly readings were taken from 08:30 (South African Standard Time) when the participant began his working day until 15:30 SAST when he finished his working day. The solar UVR readings were manually recorded by one of the authors. Half-hourly readings were taken at the times corresponding to those made at half-hourly intervals at the South African Weather Service. These readings were manually recorded in a logbook and later entered into a computer database. Before these values were used in the analyses they were corrected using calibration equations. Each UVI meter had its own calibration equation as follows:

$$y=1.7508x \text{ (UVI meter 1)} \qquad \text{Equation 1}$$

$$y=1.0503x \text{ (UVI meter 2)} \qquad \text{Equation 2}$$

where y is the UVI-meter reading and x is the corrected value.[29]

Data analysis

The corrected values of solar UVR from the UVI meters were plotted for each case study day. The ground-based solar UVR measurements from the SAWS UVB biometer for the 2 days were overlaid on the readings of the handheld meters. A calculation was done to work out what percentage of the SAWS-measured ground-based solar UVR the UVI meters measured during the study period. This calculation gives an indication of how much solar UVR reached the site at which the outdoor worker was working, and therefore how much solar UVR the worker was exposed to during the study period. On a different set of axes, the handheld meter solar UVR readings were plotted and overlaid with skin type exposure dose (see Table 1). This comparison was done in order to assess whether the outdoor worker was exposed to a sunburn risk on the case study days. The same procedure was followed with the 2012 SAWS-measured ground-based solar UVR values in order to assess whether sunburn was a possibility for the outdoor worker on any day during 2012.

Meteorological factors

Data processing

The ground-based solar UVR data were processed in several ways. Firstly, the measured values were converted from minimal erythemal dose (MED) to standard erythemal dose (SED) by multiplying the recorded MED values by 2.1 (as 1 MED = 210 J/m^2 and 1 SED = 100 J/m^2).[3] Next, the values were converted into UVI units for easier comparison with both the satellite solar UVR values (which were measured in UVI) and cloud cover values (which are within the range of the ground-based solar UVR measurements as the maximum possible value for cloud cover is 8 octas). The following equation was used for this conversion:

$$\text{UVI}=\frac{(\text{SEDx}100)\text{x}40}{1800} \qquad \text{Equation 3}$$

The 12:00 values were isolated from the data set and plotted on a scatter plot in order to see the annual distribution. These daily values were grouped according to season as follows: summer (December, January, February), autumn (March, April, May), winter (June, July, August) and spring (September, October, November). The daily 12:00 values were then plotted on scatter plots in order to show the seasonal distributions.

The solar elevation angle values were converted into SZA values. This conversion was done by applying the trigonometric rule

$$\varnothing=(90^{\circ}-\Theta) \qquad \text{Equation 4}$$

where $\varnothing$=SZA and Θ=solar elevation angle. The SZA values were then plotted on a scatter plot in order to see the change in SZA over Pretoria for the year 2012. This plot was overlain with the ground-based solar UVR readings in order to see the annual distribution of the two readings. The daily ground-based and satellite solar UVR values for the year 2012 were also plotted on one set of axes in order to assess how closely they relate. The cloud cover data were separated into the four seasons, then within each season they were further separated according to the number of days that had 5 octas or more of cloud cover. This separation was done in order to see the seasonal distribution of cloud cover over Pretoria.

Data analysis

Non-linear regression analyses were performed in order to show the relationship between solar UVR and each of the three meteorological factors. R^2-values were obtained from the non-linear regression analyses; values closer to 1 showing a stronger correlation between solar UVR and the meteorological factor. In order to gauge the difference between the satellite-based and ground-based solar UVR measurements, the root mean square error (RMSE) was found using the following equation:

$$\text{RMSE}=\left[\frac{1}{N}\sum_{i=1}^{N}(S_i-G_i)^2\right]^{\frac{1}{2}}, \qquad \text{Equation 5}$$

where S_i is the satellite-based value and G_i is the ground-based value.

Results and discussion

Case study results

Results of the case study are summarised in Tables 2 and 3 and Figures 1 and 2. The UVI-meter-measured solar UVR values are averages of the values measured by the two instruments used. Three categories were used to describe where the outdoor worker was in relation to direct sunlight: sun, which describes the outdoor worker being in direct sunlight (therefore higher exposure to solar UVR); shade, which describes the outdoor worker being under partial or total shade (therefore exposed to less solar UVR); and inside, which describes the outdoor worker being indoors (therefore exposed to the least possible amount of solar UVR). It can be seen that measurements taken when the outdoor worker was either in shade or inside were lower than when he was in direct sunlight. It can also be seen in Figure 1 and Figure 2 that the UVI-meter-measured values are higher than the SAWS-measured values in the earlier hours of the day and later in the afternoon when the sun was at lower angles relative to the horizon. In the middle of the day, when the sun was further away from the horizon, the SAWS-measured values tend to be higher than or in agreement with the UVI-meter-measured values. This tendency could be an overestimation error within the UVI meters or a result of the albedo effects of the surface at the fieldwork site (dry yellowing grass) compared to the surface of the roof of the SAWS (grey concrete) where the UVB biometer is situated. The maximum solar UVR value on Day 1 exceeded 5 UVI, whereas the maximum value on Day 2 did not. There are two possible reasons for this difference. Firstly, the study period was at a time of the year when the SZA is still increasing. An increase in SZA is associated with a decrease in solar UVR. Secondly, there was more cloud cover on Day 2 than on Day 1; high-level cloud moved in at intervals throughout the day. This cloud cover could also have had an attenuating effect on the amount of solar UVR that reached the ground on Day 2.

Table 2: Ultraviolet radiation values and position of outdoor worker on Day 1 of fieldwork

Time	Handheld-meter-measured ultraviolet radiation (UVI)	Calibrated ultraviolet radiation (UVI)	Biometer-measured ultraviolet radiation† (UVI)	Position
08:30	0.5	0.29	0.61	shade
09:00	3.5	2.57	1.15	sun
09:30	4.5	3.14	1.81	sun
10:00	4.5	3.14	2.69	sun
10:30	1.5	1.05	3.56	shade
11:00	6	4.38	4.23	sun
11:30	2	1.33	4.77	shade
12:00	6	4.38	5.19	sun
12:30	6.5	4.66	5.22	sun
13:00	0.5	0.29	4.87	inside
13:30	1	0.76	4.31	inside
14:00	4	2.86	3.62	sun
14:30	4	2.86	2.80	sun
15:00	4	2.86	2.00	sun
15:30	3	2.09	1.20	sun

UVI, ultraviolet index
†Measured at the South African Weather Service in Pretoria

Table 3: Ultraviolet radiation values and position of outdoor worker on Day 2 of fieldwork

Time	Handheld-meter-measured ultraviolet radiation (UVI)	Calibrated ultraviolet radiation (UVI)	Biometer-measured ultraviolet radiation† (UVI)	Position
08:30	3	2.09	0.60	sun
09:00	4	2.86	1.14	sun
09:30	5	3.43	1.90	sun
10:00	5.5	3.90	2.75	sun
10:30	0.5	0.29	3.52	sun
11:00	6	4.19	3.96	inside
11:30	6.5	4.66	4.55	sun
12:00	6.5	4.66	4.83	sun
12:30	6.5	4.66	4.73	sun
13:00	0.5	0.26	4.59	inside
13:30	0	0	3.84	inside
14:00	5	3.62	3.67	sun
14:30	4	2.86	2.83	sun
15:00	4	2.86	2.00	sun
15:30	3	2.09	1.26	sun

UVI, ultraviolet index
†Measured at the South African Weather Service in Pretoria

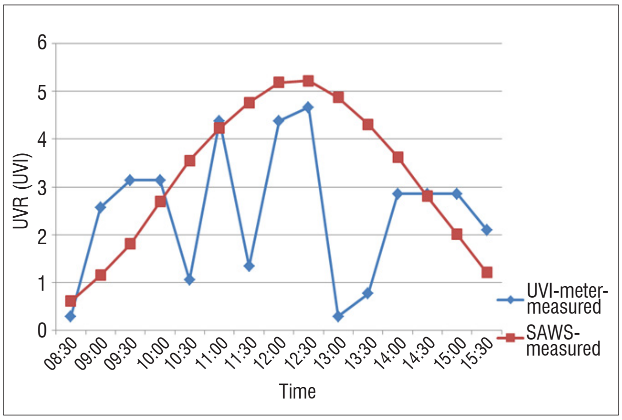

Figure 1: Solar ultraviolet radiation (UVR) on Day 1 measured as an ultraviolet index (UVI) by a handheld device on site and a biometer at the South African Weather Service (SAWS).

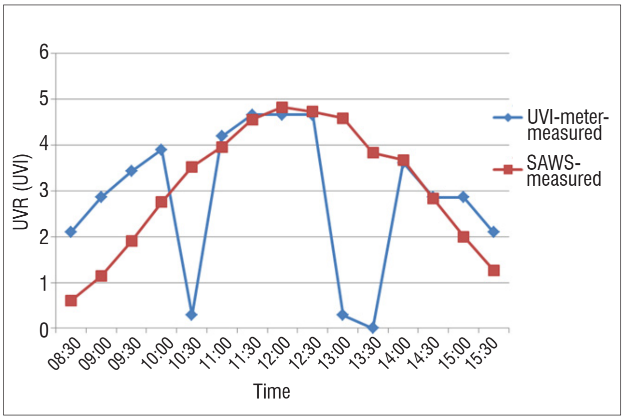

Figure 2: Solar ultraviolet radiation (UVR) on Day 2 measured as an ultraviolet index (UVI) by a handheld device on site and a biometer at the South African Weather Service (SAWS).

On both days the outdoor worker was dressed in long, royal-blue overall trousers. On both days, for the first half of the morning, i.e. from 08:30 to 10:30, the outdoor worker dressed in a royal-blue, long-sleeved overall jacket. From 10:30 until the end of his working day at 15:30, he wore a short-sleeved, navy-blue T-shirt. It is unknown whether the change from a long-sleeved to a short-sleeved shirt was his personal preference or employer-led. For the entire duration of his working day he wore a peak cap. He did not wear sunglasses at any stage. The outdoor worker's arms were therefore protected in the early hours of his working day, but were exposed for 4 h during the late morning and afternoon (except during the 1-h lunch break between 12:30 and 13:30, which he spent inside). The peak cap provided protection for his face and eyes throughout the working day, but did not shield his neck and ears.

The activities that the outdoor worker undertook on Day 1 included sweeping and tending to bushes and shrubs. These activities led to his face being bent downwards, and less exposed, for the majority of the time; however, when these activities took place in the sun, his neck and ears were more exposed. A large amount of cumulative time was also spent walking from one area to the next (as he works within a very large area). On Day 2, he spent almost his entire working day in the middle of a field (away from possible shade), thus causing his arms, neck and ears to be exposed to direct solar UVR.

There are limitations to studies involving outdoor workers. Study observation of this nature is labour intensive and difficult when numerous participants are to be observed. Self-report diaries may be used by workers to provide these data, but researchers must still verify these reports.

There are restrictions to measures for the amelioration of excess sun exposure among outdoor workers, for example, required use of specific personal protective equipment such as goggles that may or may not have UV-protective tinting. Workers may also be forced to work in full-sun conditions because of the nature of the work, thereby making practical suggestions for sun protection constrained by the workplace and nature of activities. Many of these factors may be overcome when a consultative process for addressing the problem includes the employer, employee and the Safety, Health and Environmental Quality officer, and practical, acceptable solutions are sought. Mechanisms for sun protection among outdoor workers include sunscreen; long-sleeve, cool shirts (of appropriate fabric); wide-brimmed hats or construction hard hats with a flap; and sunglasses.

A calculation was done to determine the percentage of the measured ground-based solar UVR that the UVI meters measured during the study period. It was found that 76.29% and 91.92% of the SAWS-measured solar UVR was measured by the UVI meters on Day 1 and Day 2, respectively. A higher percentage was recorded for Day 2 because, as previously mentioned, the outdoor worker spent more time in the sun on Day 2 than on Day 1. The average of these two percentages is 84.11% and can be considered the static risk of overexposure for an outdoor worker. This value was then applied to the SAWS-measured solar UVR measurements for the year 2012. There is, however, a possibility that this value is overestimated because of the possible overestimation of UVI measurements by the UVI meter. Figure 3 shows the amount of solar UVR that an outdoor worker would be exposed to in 2012 based on the static risk that was calculated above.

Figure 3 also shows the difference in the risk of sunburn for outdoor workers with different skin types in 2012. It can be seen that outdoor workers, regardless of skin type, would have been at risk of sunburn on several days in 2012. This result of 84.11% is much higher than the proposed 20% that was applied in the study by Wright et al.[1] There have been several studies in which the personal exposure risk of outdoor workers was investigated. Larko and Diffey[24] found that an outdoor worker was at risk of being exposed to between 10% and 70% of the ambient solar UVR depending on the amount of time spent outside. Another study conducted by Holman et al.[30] found that some outdoor workers were exposed to 44.85% of ambient solar UVR and also that different parts of the outdoor worker's body were exposed to different levels of solar UVR.[25,30,31] These results are within the range of our findings in the current study.

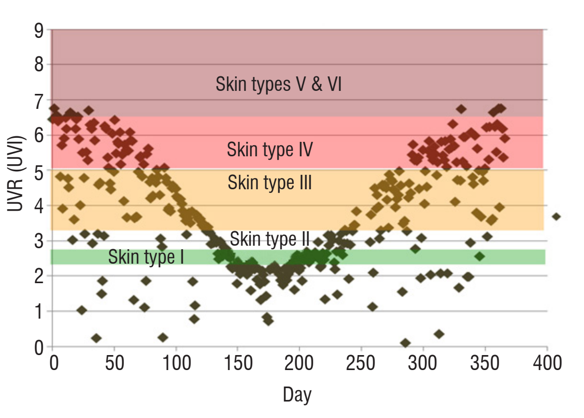

Figure 3: Sunburn thresholds over Pretoria in 2012 for various skin types using 84.11% of the solar ultraviolet radiation (UVR) measured as an ultraviolet index (UVI).

Meteorological factors

The results of the non-linear regression analysis are summarised in Table 4. All of the R^2-values are low, indicating weak correlations, which could be attributed to the fact that many meteorological factors, other than those considered in the current study, play a part in attenuating solar UVR. For all seasons, excluding summer, SZA was found to have the strongest relationship with solar UVR reaching the ground. This finding was also true for the entire year in general, which means that, of all the factors considered, sun position had the greatest effect on the amount of solar UVR that reached the ground in Pretoria in 2012. In agreement with our findings, in a study conducted in Norway, it was found that, between 1995 and 2007, the greatest seasonal UVR-controlling factor was sun position.[32] In summer, the strongest relationship with solar UVR reaching the ground was found with cloud cover. The number of days on which Pretoria had 5 or more octas of cloud cover were examined for each season. Of all the seasons in 2012, Pretoria experienced the most days with 5 or more octas of cloud cover in summer, also suggesting that cloud cover could be a major influencer in summer. This result is supported by the climatology. Typically, in summer over the northeastern interior of South Africa, synoptic conditions are favourable for cloud formation and rainfall, whereas, in winter, the presence of a strong continental anticyclone causes cloud-supressing subsidence. Therefore, there is more cloud cover during summer than during winter in Pretoria.[33]

Table 4: R^2-values for the relationships between solar ultraviolet radiation and cloud cover, total column ozone and solar zenith angle for each season of 2012 and for the entire year

2012	Cloud cover	Ozone	Solar zenith angle
All year	0.2581	0.0517	0.567
Autumn (March, April, May)	0.3294	0.0864	0.6347
Winter (June, July, August)	0.436	0.1257	0.6458
Spring (September, October, November)	0.2871	0.2502	0.4587
Summer (December, January, February)	0.3439	0.121	0.1028

It is shown in Figure 4 that solar UVR is distributed in an envelope shape, in which higher values were recorded in the summer months (December, January and February) and lower values were recorded in the winter months (June, July and August). The SZA measurements have a bell-shaped distribution in which the lowest angles occurred in the summer months and the highest angles occurred in the winter months. These findings correspond to literature reports about the annual distribution of SZA measurements.[7] Figure 4 therefore shows that, overall, an increase in SZA is associated with a decrease in solar UVR and a decrease in SZA is associated with an increase in solar UVR at the ground. In terms of this study, lower SZA values are likely to lead to a higher dynamic risk of overexposure to solar UVR as more solar UVR reaches the ground. Therefore, of cloud cover, total column ozone and SZA, SZA is the meteorological factor that is likely to increase the dynamic risk of overexposure in all seasons except summer. Figure 4 also shows that solar UVR is strongly bounded in the upper limits, similarly to the distribution of SZA measurements.

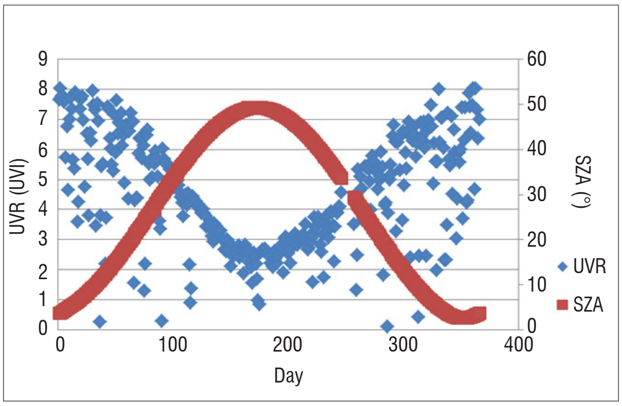

Figure 4: Distribution of solar ultraviolet radiation (UVR) and solar zenith angle (SZA) over Pretoria for the year 2012.

Figure 5 shows that ozone does not vary significantly during the year. This is also reflected in the results of the regression analysis. Research has shown that sites at lower latitudes have a small annual variation in total column ozone, while sites at high latitudes have a large annual variation in total column ozone.[32] In Oslo, Norway, which is at latitude 59° 57'N, ranges of over 250 DU between the highest and the lowest measured ozone values have been measured.[32] In the year 2012, the range between the highest and the lowest measured total column ozone values over Pretoria (which is at latitude 25° 45'S) was 75.832 DU, thus showing relatively small annual variation. That being said, the relationship between solar UVR and total column ozone for spring was the strongest of all the seasons; this finding is to be expected as relatively higher values of ozone over South Africa are expected to occur during spring.

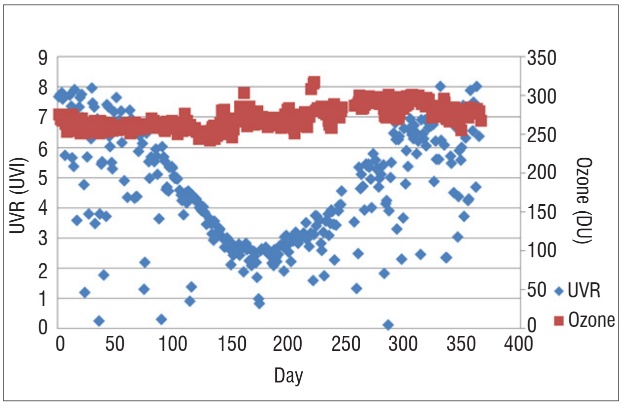

Figure 5: Distribution of solar ultraviolet radiation (UVR) and ozone over Pretoria for the year 2012.

From Figure 6 it can be seen that the shape of the distributions for the satellite-measured solar UVR and the ground-based solar UVR are very similar; on both occasions, higher values are generally observed in the summer months and lower values are seen in the winter months. However, the satellite-based values are larger than the ground-based measurements. A RMSE of 5.287 UVI was found over the whole year for the 12:00 values, which means that on average there was a difference of 5.287 UVI between the satellite-based and ground-based measurements. This large difference between the two measurements could be an indication of the strength of attenuation by the various meteorological factors. However, because change in cloud cover is not taken into account in the algorithm of the satellite values, the attenuating meteorological factor is most likely to be cloud cover. Validations between satellite-based and reference ground-based measurements done in various studies have found that, on average, the satellite overestimates the UVR by 0–30%.[34] It can also be seen in Figure 6 that there seems to be a larger difference between ground-based and satellite-based solar UVR in the summer portion rather than the winter portion of the year. Because cloud cover was found to have the strongest relationship with solar UVR in summer, this observation further substantiates the likelihood that cloud cover was the attenuating factor.

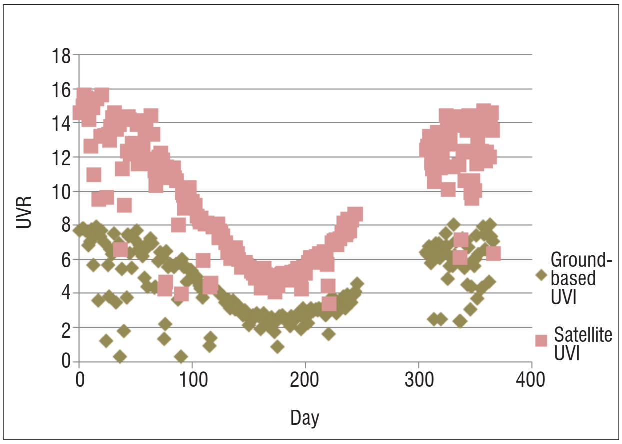

Figure 6: Satellite-based and ground-based measurements of solar ultraviolet radiation (UVR) measured as an ultraviolet index (UVI) over Pretoria for 2012.

Conclusion

In South Africa, outdoor workers may be potentially exposed to up to 84.11% of the total solar UVR that reaches the ground. Based on this figure, and considering ambient solar UVR levels measured during 2012, outdoor workers with any skin type would be at risk of sunburn on many days of the year, including during winter months. Those workers with skin types IV–VI would have greater natural protection compared with workers with skin types I–III; however, ocular exposure and the risk of cataracts and other sun exposure related eye diseases remain a concern if adequate sun protection is not used.

Each of the meteorological factors examined did reduce the amount of solar UVR reaching the ground over Pretoria and certain factors had a stronger influence in different seasons. Sun position was the main meteorological factor of the three factors considered in this study that influenced the amount of solar UVR that reached the ground overall in 2012. Cloud cover was an important meteorological factor in summer. Total column ozone did not show a noteworthy relationship with solar UVR. There was an average difference of 5.287 UVI between satellite-based and ground-based solar UVR measurements in 2012, which is likely a consequence of cloud cover attenuation.

The static risk of exposure showed that it is possible for an outdoor worker to be exposed to over 80% of the ambient solar UVR, and the dynamic risk showed that SZA and cloud cover influence the actual amount of solar UVR an outdoor worker is exposed to. Measuring the amount of solar UVR that outdoor workers may be exposed to may help in the development of sun-protective and skin cancer prevention campaigns for outdoor workers specifically; this awareness is important as outdoor workers have been identified as a susceptible group. Some study limitations do exist when working with outdoor workers, as the nature of their work makes certain sun-protective measures impractical. However, by consulting with the employer, employee and Safety, Health and Environmental Quality officer, practical solutions can be found, which may include the use of sunscreen, long-sleeve cool shirts, wide-brimmed hats or construction hard hats with a flap and sunglasses. The results of this case study suggest that further, more comprehensive research is needed to measure a large sample of outdoor workers in different geographical areas in South Africa to best inform policy development and decision-making for occupational health. Research using electronic solar UVR dosimeters is underway.

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Authors' contributions

M.M. conducted the case study, analysed the data and wrote part of the article. C.Y.W. conceived the core concept of the project, provided the instruments for the case study, acquired the data and wrote part of the article.

References

1. Wright CY, Coetzee G, Ncongwane K. Seasonal trends in potential sunburn risk among outdoor workers in South Africa using monitored ambient solar UV radiation levels. Occ Health Southern Africa. 2011;17(6):22–29.
2. Norval M, Kellet P, Wright CY. The incidence and body site of skin cancers in the population groups of South Africa. Photoderm Photoimmunol Photomed. 2014;30(5):262–265.
3. IARC. Solar and ultraviolet radiation. IARC Monograph Eval Carcinog Risk Chem Hum. 2012;100D:35–102.
4. International Commission on Illumination (CIE). The measurement of absolute luminous intensity distributions. Vienna: CIE; 1987.
5. Lucas R, McMichael T, Smith W, Armstrong B. Solar ultraviolet radiation: Global burden of disease from solar ultraviolet radiation. Environmental Burden of Disease Series No. 13. Geneva: World Health Organization (WHO); 2006.
6. Engelsen O. The relationship between ultraviolet radiation exposure and vitamin D status. Nutrients. 2010;2:482–495. http://dx.doi.org/10.3390/nu2050482
7. Diffey BL. Sources and measurement of ultraviolet radiation. Meth.. 2002;28:4–13. http://dx.doi.org/10.1016/S1046-2023(02)00204-9
8. McKenzie EL, Mattheus WA, Johnson RV. The relationship between erythemal UV and ozone, derived from spectral irradiance measurements. Geophys Res Lett. 1991;18:2269–2272. http://dx.doi.org/10.1029/91GL02786
9. Efstathiou M, Varotsos C, Kondratyev KY. An estimation of the surface solar ultraviolet irradiance during an extreme total ozone minimum. Meteorol Atmos Phys. 1998;68:171–176. http://dx.doi.org/10.1007/BF01030208
10. Hester RE, Harrison RM, Webb AR. Ozone depletion and changes in environmental UV-B radiation. In: Issues in environmental science and technology: Causes and environmental implications of increased UV-B radiation. No. 14. Cambridge: The Royal Society of Chemistry; 2000. p. 17–36.
11. Fishman J, Watson CE, Larsen JC. The distribution of total ozone, stratospheric ozone, and tropospheric ozone at low latitudes deduced from satellite data sets. Presented at: Workshop on Tropospheric Ozone; Quadrennial Ozone Symposium; 1988 Aug 4–13; Göttingen, Germany.
12. Fishman J, Brackett VG, Fakhruzzaman K. Distribution of tropospheric ozone in the tropics from satellite and ozonesonde measurements. J Atmos Terr Phys. 1992;54(5):589–597. http://dx.doi.org/10.1016/0021-9169(92)90099-7
13. Salby ML, Garcia RR. Dynamic perturbations to the ozone layer. Phys Today. 1990;March:38–46. http://dx.doi.org/10.1063/1.881228
14. Diab RD, Barsby J, Bodeker GE, Scourfield M, Salter L. Satellite observations of total ozone above South Africa. S Afr Geog J. 1992;74:13–18. http://dx.doi.org/10.1080/03736245.1992.10586389
15. Fredrick JE, Snell HE. Tropospheric influence on solar UV radiation: The role of clouds. J Climate. 1990;3:373–381. http://dx.doi.org/10.1175/1520-0442(1990)003<0373:TIOSUR>2.0.CO;2
16. Estupi-án JG, Ramen S, Crescenti GH, Streicher JJ, Barnard WF. Effects of cloud and haze on UV-B radiation. J Geophys Res. 1996;101:16807–16816. http://dx.doi.org/10.1029/96JD01170
17. Cutchis P. A formula for comparing annual damaging ultraviolet (DUV) radiation doses at tropical and mid-latitude sites. Federal Aviation Administration Report FAA-EE 80-81. Washington DC: US Department of Transport; 1980.
18. Wright CY. Ultraviolet radiation exposure of NZ schoolchildren [thesis]. Durban: University of KwaZulu-Natal; 2006.
19. Diffey BL. Solar ultraviolet radiation effects on biological systems. Phys Med Biol. 1991;36(3):299–328. http://dx.doi.org/10.1088/0031-9155/36/3/001
20. Fitzpatrick TB. Soleil et peau [Sun and skin]. J Med Esthet. 1975;2:33–34. French.
21. Fitzpatrick TB. Skin phototypes: Evolution and present status. Paper presented at: 29th Annual Meeting of the American Society of Photobiology; 2001 July 7–12; Chicago, USA.
22. National Radiological Protection Board (NRPB). Health effects from ultraviolet radiation. Report of an advisory group on non-ionising radiation. Chilton, UK: NRPB; 2002.
23. Kimlin MG, Tenkate TD. Occupational exposure to ultraviolet radiation: The duality dilemma. Reviews on Environmental Health. 2007;22(1):1–37. http://dx.doi.org/10.1515/REVEH.2007.22.1.1
24. Larko O, Diffey BL. Natural UV-B radiation received by people with outdoor, indoor, and mixed occupations and UV-B treatment of psoriasis. Clin Exp Dermatol. 1983;8:279–285. http://dx.doi.org/10.1111/j.1365-2230.1983.tb01780.x
25. Reeder AI, Gray A, McCool JP. Occupational sun protection: Workplace culture, equipment provision and outdoor workers' characteristics. J Occup Health. 2013;55(2):84–97. http://dx.doi.org/10.1539/joh.12-0182-OA
26. McCool JP, Reeder AI, Robinson EM, Petrie KJ, Gorman DF. Non-melanoma skin cancer: Outdoor workers' perceptions of risk and sun-protection use. Wellington: Cancer Society of New Zealand; 2004.
27. Dobbinson S, Doyle C, Wakefield M. Farmers' and outdoor workers' beliefs about skin cancer and protection from summer sun: A brief report. CBRC Research Paper Series No. 18. Melbourne: Centre for Behavioural Research in Cancer, Cancer Control Research Institute, Cancer Council Victoria; 2005.
28. McCool JP, Reeder AI, Robinson EM, Petrie KJ, Gorman DF. Outdoor workers' perceptions of the risks of excess sun-exposure. J Occup Health. 2009;51:404–411. http://dx.doi.org/10.1539/joh.L9030
29. Wright CY, Albers PN. Comparison of two personal ultraviolet index monitors for sun awareness in South Africa. S Afr J Sci. 2013;109(1/2):88–91. http://dx.doi.org/10.1590/sajs.2013/0014
30. Holman CDJ, Gibson IM, Stephenson M, Armstrong BK. Ultraviolet irradiation of human body sites in relation to occupation and outdoor activity: Field studies using personal UVR dosimeters. Clin Exp Dermatol. 1983;8:269–277. http://dx.doi.org/10.1111/j.1365-2230.1983.tb01779.x
31. Gies P, Wright J. Measured solar ultraviolet radiation exposures of outdoor workers in Queensland in the building and construction industry. J Photochem Photobiol. 2003;78(4):342–348. http://dx.doi.org/10.1562/0031-8655(2003)078<0342:MSUREO>2.0.CO;2
32. Dahlback A, Bjertness E, editors. Global monitoring of atmospheric ozone and solar UV radiation. Solar Radiation and Human Health. Oslo: The Norwegian Academy of Science and Letters; 2008. p. 23–34.
33. Tyson PD, Preston-Whyte RA. The weather and climate of southern Africa. 2nd ed. Cape Town: Oxford University Press; 2000.
34. OMI Team. Ozone monitoring instrument (OMI) data user's guide. Washington DC: NASA; 2012.