A Comparison of Solar Ultraviolet Radiation Exposure in Urban Canyons in Venice, Italy and Johannesburg, South Africa

Caradee Y. Wright[1,2]*, David Jean du Preez[2,3], Bice S. Martincigh[4], Martin W. Allen[5], Danielle A. Millar[1], Bianca Wernecke[6,7] and Suzana Blesic[8,9]

[1]Environment and Health Research Unit,South African Medical Research Council,Pretoria,South Africa
[2]Department of Geography, Geoinformatics and Meteorology,University of Pretoria,Pretoria,South Africa
[3]LACy,Laboratoire de l'Atmosphère et des Cyclones (UMR 8105 CNRS, Université de La Réunion, Météo-France),Saint-Denis de La Réunion,France
[4]School of Chemistry and Physics,University of KwaZulu-Natal,Durban,South Africa
[5]MacDiarmid Institute for Advanced Materials and Nanotechnology,University of Canterbury,Christchurch,New Zealand
[6]Environment and Health Research Unit,South African Medical Research Council,Johannesburg,South Africa
[7]Department of Environmental Health,Faculty of Health Sciences,University of Johannesburg,Johannesburg,South Africa
[8]Institute for Medical Research,University of Belgrade,Belgrade,Serbia
[9]Center for Participatory Science,Belgrade,Serbia

ABSTRACT

Urban environments can have high-risk spaces that can provide excess personal sun exposure, such as urban or street canyons, and the spaces between buildings, among others. In these urban spaces, sun exposure can be high or low depending on several factors. Polysulphone film (PSF) was used to assess possible daily solar ultraviolet radiation (UVR) exposure in urban canyons in Venice, Italy and, for the first time in Africa, in Johannesburg, South Africa. The photodegradation of PSF upon solar exposure was monitored at a wavelength of 330 nm by ultraviolet-visible spectrophotometry, and the resultant change was converted to standard erythemal dose (SED) units (1 SED = 100 J m^{-2}). Mean daily ambient solar UVR exposure measured for Venice and Johannesburg ranged between 20–28 SED and 33–43 SED, respectively. Canyon-located PSF exposures were lower in Venice (1–9 SED) than those in Johannesburg (9–39 SED), depending mainly on the sky view factor and orientation to the sun. There was large variation in solar UVR exposure levels in different urban canyons. These preliminary results should be bolstered with additional studies for a better understanding of excess personal exposure risk in urban areas, especially in Africa.

INTRODUCTION

Excess exposure to solar ultraviolet radiation (UVR) is associated with skin cancer, some forms of cataract and immune suppression (1-6). Personal solar UVR exposure can be high depending on duration and timing of time spent outdoors, sun protection applied, and clothing worn, and nature of activity undertaken while outdoors (1,3,6). On the contrary, low solar UVR exposure has been linked to insufficient vitamin D production and other diseases (3,7,8). There are several factors that influence solar UVR levels at ground-level including latitude, altitude, stratospheric ozone levels, aerosols, cloud cover and albedo (9,10). The nature of the environment also plays a part in potential levels of personal exposure, for example, sitting on the beach next to the ocean can result in high solar UVR levels due to reflection from the water and sand (10,11).

As urbanization increases globally (12), urban environments, consisting of buildings of varying heights, different building materials and structures, as well as roads, alley ways and street canyons, are growing (13,14). Urban or street canyons are places on a street where the street is flanked by buildings on both sides creating a canyon-like environment. Depending on width, depth, and the orientation of the urban canyon in relation to the passage of the sun through the sky, solar UVR levels can either be low or high at ground-level within the canyon. A study in Lodz (altitude 278 m), Poland, found that "sunlit" versus "shadowed" sites received between 70–88% and 13–28% of ambient levels, respectively (15). Patterns of solar UVR between high-rise buildings are influenced by solar zenith angle, seasonal variations of aerosol loadings and cloud effects (16).

Urban canyon geometry can be described by the sky view factor (SVF) which is the ratio of sky visible from a point on the ground (17). In urban canyons, the sky is obstructed by buildings, trees and other structures which decrease the amount of UVR reaching the surface (16). The glass facades of buildings that reflect incoming solar UVR can potentially increase UVR at street level. Trees, grass lawns and awnings help to attenuate the reflected UVR (18). Few studies have measured solar UVR exposure in pedestrian areas and seating areas of restaurants in urban canyons (18-21); and no such studies have been carried out in Africa. We measured the solar UVR exposure in urban canyons in Venice, Italy and Johannesburg, South Africa to determine and compare the effect of urban canyon types on resultant solar UVR exposures.

*Corresponding author email: cwright@mrc.ac.za (Caradee Wright)

MATERIALS AND METHODS

Study locations. The study locations were selected to represent pedestrian urban canyons in different hemispheres. The two study sites were Venice (45.44° N, 12.32° E; 1 m asl—meters above sea level), Italy and Johannesburg (26.14° S, 28.05° E, 1 753 m asl) South Africa. Venice is an older city with architecture characterized by dense urban surroundings (22). It is a historical town of about a hundred small islands with buildings that are close to each other and are separated by rather narrow streets; its islands are connected by equally narrow canals and bridges (23). This contrasts with Melrose Arch in Johannesburg, a relatively new precinct in the City of Johannesburg was selected as the study location instead of the central business district of the City of Johannesburg to ensure safe fieldwork conditions for the research team. Both Venice and Melrose Arch (hereafter called Johannesburg have residences and hotels and are frequented by tourists. Figure 1 illustrates the typical summertime UVI (24) in (a) Italy and (b) South Africa. The seasonal average was calculated from the daily solar noon UVI value (2005–2018) obtained from the Ozone Monitoring Instrument (OMI) (25).

Polysulfone film measurements. PSF was first identified as an inexpensive and reliable means of measuring cumulative solar UVR exposure in the 1970s (26). PSF is a polymer that is photo-sensitive, so it degrades when irradiated by solar UVR. By measuring the change in absorbance at a wavelength of 330 nm (ΔA_{330nm}) pre and postexposure, the degree of degradation may be quantified in terms of standard erythemal dose (SED, 1 SED = 100 J m^{-2}) (27). Square pieces of PSF were secured in cardboard mounts that left the PSF exposed from top and bottom. Each PSF badge was labelled with a unique identifying number. PSF badges were always kept in a dark envelope, except when exposed to solar UVR for the experiment days, to avoid unintended degradation.

Pre and postexposure absorbance values for each PSF badge were obtained with a Biochrom Libra S12 UV-visible spectrophotometer. PSF badge ΔA_{330nm} measurements were converted to SED by making use of a previously determined calibration equation (28).

A total of 24 PSF badges were deployed in the study on four days in Venice and two days in Johannesburg. As a control, one PSF badge was used daily to measure unshaded, ambient solar UVR exposure on a horizontal surface. The remaining PSF badges were attached to flat surfaces in the street canyons to measure a variety of urban spaces in which people move through, stand or sit in during the day. As many north–south and east–west orientations as well as trees/ no trees/ awnings/ no shade sites were selected in each study location according to the number of PSF badges available for deployment in the study which was limited by budget.

For Johannesburg, the PSF badges were placed at their sites from 8h00 until 16h00 and replaced every 2 h to avoid badge saturation due to the relatively high solar UVR levels. The daily cumulative exposure for a site was determined from the sum of the exposures of the individual badges at the site. In Venice, the badges were placed at different starting times since there was only one researcher coordinating the set-up and a single badge was used to determine the daily exposure at each site.

Fieldwork took place on 10–15 June (early summer) and 9–10 March (early autumn) in Venice and Johannesburg, respectively, when UVR levels are relatively high compared to winter. There was some delay between the conclusion of the field campaign and the measurement of the postexposure absorbance values of the PSF badges so tests for the dark reaction (29) were conducted. PSF exhibits a dark reaction that refers to the continuation of the depolymerization process initiated by ultraviolet radiation once the ultraviolet radiation exposure period has ceased (30). Results showed an ~12% increase in ΔA_{330nm} was likely, like the finding of 11.6% found for a one-week postexposure (30), and this correction was therefore made to all the ΔA_{330nm} values used in this study (the inclusion of this correction on average lowered the total daily exposure by 1.8 and 2.8 SED at Venice and Johannesburg, respectively). The PSF ΔA_{330nm} data were used to determine solar UVR levels by study day at both cities' urban canyon sites. Urban canyon PSF data were compared to ambient PSF data to determine the percentage of the ambient solar UVR levels received in street canyons.

Satellite-derived solar UVR exposures. The daily erythemal doses were obtained for Venice and Johannesburg from the EUMETSAT Satellite Application Facility on Atmospheric Composition Monitoring (31). A radiative transfer model and observations of ozone and clouds from Metop satellites are used to estimate surface UVR. The data has a resolution of 0.5° × 0.5°. The daily erythemal dose is given kJ m^{-2} m^{-2} and this was converted to SED.

Sky view factor. The SVF can be determined from many methods such as digital image analysis (18,32) or with the use of GIS software (17). For simplicity, we chose to use Eq. (1) to evaluate SVF for our measuring sites, as it remains a logical method to use based on the available data of each site that evaluates the effect of trees and awnings on solar UVR exposure at street level. The SVF was calculated as (19):

$$\text{SVF}=\cos\left(a\tan\left(\frac{2H}{W}\right)\right) \tag{1}$$

where H is the building height of the canyon and W the width of the canyon. The SVF factor takes values from 0 to 1; a large SVF number would indicate that a large percentage of the sky is visible (21) and 1 is therefore a completely visible sky.

Personal UVR dosimetry. In Venice, in addition to the canyon PSF measurements, a separate study measuring personal exposure to solar UVR (pUVR) was conducted by making use of personal UVR dosimeters (not PSF) (33) (Human Research Ethics clearance from the CSIR 64/2013). Dosimeters were attached as wrist watches to ten individuals that visited the city during summer of 2017 (34). Dosimeters used a sampling rate of 60 s and are designed to measure erythemal exposure in the wavelength range of 290–400 nm to capture both UVA and UVB radiation. A solid-state detector with a linear response to UVR was used to measure erythemal UVR. The angular response of the

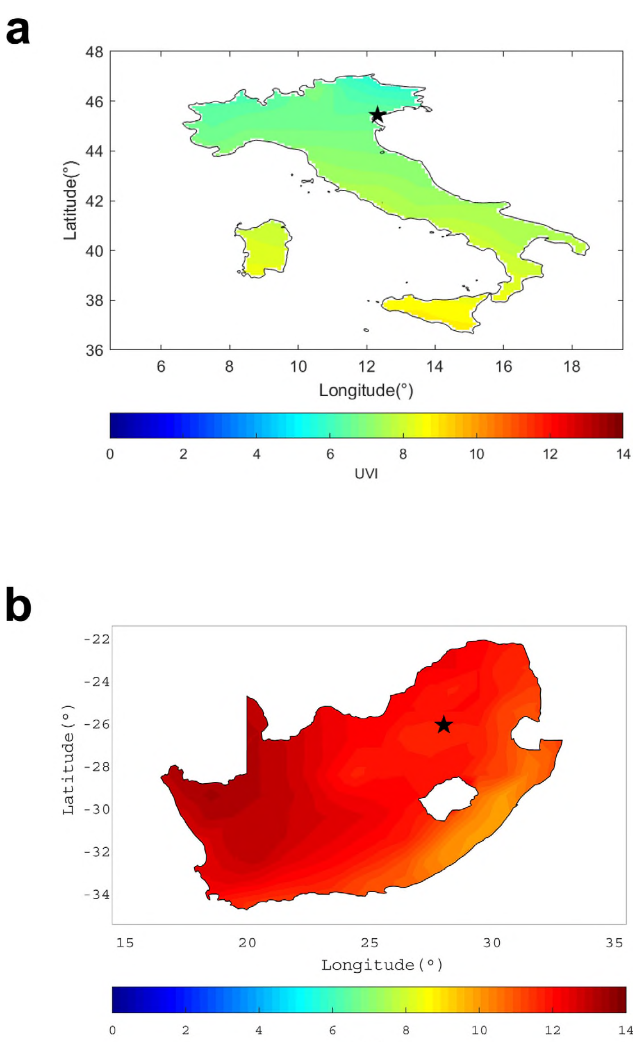

Figure 1. Maps showing the summer UVI for (a) Italy (star illustrates location of Venice) and (b) South Africa (star illustrates location of Johannesburg).

instrument is close to that of the cosine response of human skin due to the weatherproof case over the detector. More details on the specifications and functioning of the dosimeter badges are provided elsewhere (35). All the dosimeters gave records in dimensionless counts that were converted to Ultraviolet Index (UVI) units after calibration against a meteorological-grade instrument that measures UVR. The UVI data points were integrated over the time period and converted to SED units to determine the total personal solar UVR received during that period of time (35).

RESULTS AND DISCUSSION

Solar UVR exposures at ambient and urban canyon sites

PSF readings were obtained for seven and nine urban canyon sites (excluding ambient sites) in each of the study locations, Venice and Johannesburg, respectively. The solar UVR exposures (SED units) for Venice and Johannesburg are given in Tables 1 and 2, respectively. Ambient PSF badge readings on exposed sites and readings for all urban canyon sites varied greatly between city sites. Mean daily ambient PSF UVR exposures for Venice and Johannesburg ranged between 21–28 SED and 29–38 SED, respectively. While the magnitude and range variations were likely due to the latitude and altitude effects of the different cities, these measured total daily ambient ranges are high and could pose health risks to individuals spending all day in a horizontal, exposed site (which most people do not do as they go about daily activities).

Urban canyon-located PSF exposures were generally lower in Venice (ranging from 0.8–23 SED) than those in Johannesburg (8–35 SED). Several reasons may have contributed toward these

Table 1. Description of PSF badge locations and solar UVR exposure in Venice.

Date	Location description	Sky view factor	Start and end time	Total daily SED value	Satellite total daily SED	Canyon PSF badge as % of PSF ambient	Canyon PSF badge as % of satellite ambient
10 June 2019	*Ambient (S. Elena)*	*1*	*9h37-18h00*	*21*	*31*	–	*68*
10 June 2019	*Ambient (S. Elena)*	*1*	*10h09-18h00*	*20*	*31*	–	*65*
10 June 2019	Canyon east–west on pavement beside building	0.15	10h39-18h15	9	31	40	28
10 June 2019	Canyon north–south on step beside building	0.16	10h42-18h30	9	31	42	29
10 June 2019	Canyon east–west on pavement beside building	0.08	11h08-19h00	5	31	23	15
13 June 2019	*Ambient (S. Elena)*	*1*	*8h37-17h30*	*28*	*47*	-	*60*
13 June 2019	Canyon northeast–southwest on windowsill beside street	0.08	11h00-18h30	3	47	10	6
14 June 2019	*Ambient (S. Elena)*	*1*	*9h24-17h30*	*26*	*49*	–	*53*
14 June 2019	Canyon north–south on windowsill beside street	0.08	10h17-18h00	3	49	13	6
14 June 2019	Canyon north–south on windowsill beside walkway	0.05	10h35-18h15	0.8	49	3	1
15 June 2019	*Ambient (S. Elena)*	*1*	*8h41-17h30*	*26*	*47*	–	*55*
15 June 2019	Canyon northwest–southeast	0.32	9h39-18h30	23	20	87	17

Ambient solar UVR exposures are provided in italics.

Table 2. Description of PSF badge locations and solar UVR exposure in Johannesburg.

Date	Site characteristics	Sky view factor	Total daily SED value	Satellite total daily SED	Canyon PSF badge as % of PSF ambient	Canyon PSF badge as % of satellite ambient
9 March 2019	*Ambient (roof top, open space)*	*1*	*30*	*58*	–	*52*
9 March 2019	Canyon northeast–southwest, trees	0.70	19	58	60	34
9 March 2019	Canyon northeast–southwest, no trees or awnings	0.63	23	58	78	45
9 March 2019	Canyon north–south, trees	0.42	14	58	45	26
9 March 2019	Canyon north–south, trees and awnings	0.43	8	58	28	16
9 March 2019	Canyon north–south, trees	0.21	10	58	33	19
9 March 2019	Canyon east–west, trees	0.39	22	58	74	42
9 March 2019	Canyon east–west, awning	0.51	20	58	67	39
9 March 2019	Open space, north-facing	0.71	30	58	100	57
9 March 2019	Canyon east–west	0.34	23	58	78	45
10 March 2019	*Ambient (roof top, open space)*	*1*	38	*56*	-	*68*
10 March 2019	Canyon northeast–southwest, trees	0.70	24	56	63	49
10 March 2019	Canyon northeast–southwest, no trees or awnings	0.63	31	56	80	62
10 March 2019	Canyon north–south, trees	0.42	16	56	40	31
10 March 2019	Canyon north–south, trees and awnings	0.43	9	56	23	18
10 March 2019	Canyon north–south, trees	0.21	8	56	21	16
10 March 2019	Canyon east–west, trees	0.39	17	56	44	33
10 March 2019	Canyon east–west, awning	0.51	25	56	65	50
10 March 2019	Open space, north-facing	0.71	35	56	90	69
10 March 2019	Canyon east–west	0.34	22	56	59	45

Ambient solar UVR exposures are provided in italics.

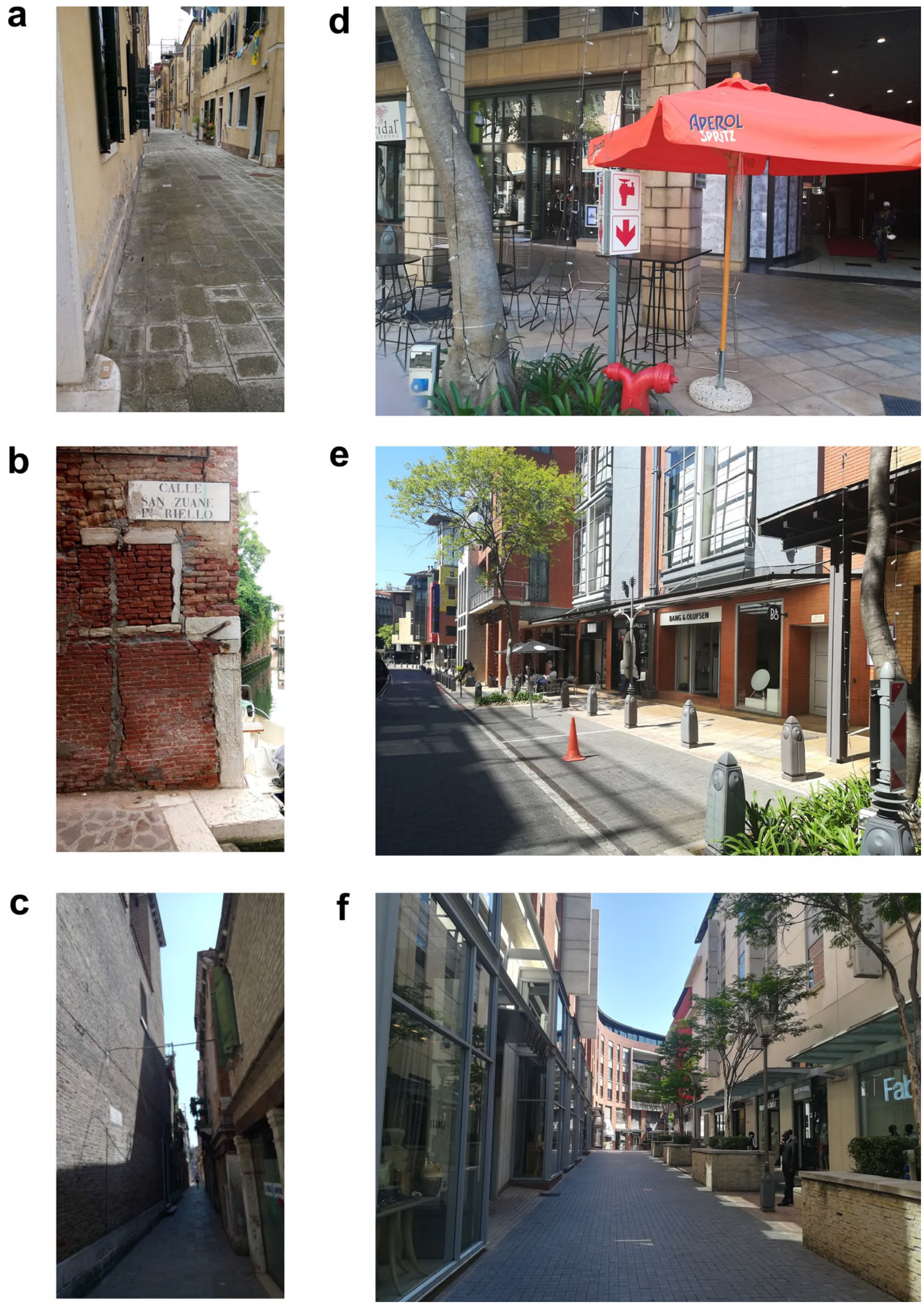

Figure 2. Examples of PSF badge sites in Venice at (a) a sidewalk; (b) a walkway on the canal; and (c) an alley; and in Johannesburg, at (d) a restaurant; (e) a pedestrian area and (f) an avenue of shops.

differences in general terms, or for urban environments in modern terms. Location of the PSF badge on the street, the number of trees and amount of tree foliage or anthropogenic shade such as awnings and open shutters in relation to the building, etc., would influence the SVF and amount of solar UVR reaching the urban canyon PSF site. In our study, the density of the urban environments has contributed to these differences. SVF values given in Tables 1 and 2 show the average of the estimated SVF value of Johannesburg streets is 3.7 times higher than the average estivated SVF for Venice streets. The SVF values contributed to solar UVR that reached the street sites, in comparison to the total daily ambient solar UVR, particularly, or almost exclusively for Venice urban canyons.

At Johannesburg, there was a moderately strong correlation (0.45–0.70) between the SVF and total daily SED. This correlation was strongest on 10 March 2019 and may be due to the clear-sky morning compared to the partly cloudy conditions on 9 March 2019. In Venice, there was a strong correlation between the SVF and total daily SED, but the sites are fewer and further apart than the study sites in Johannesburg. The orientation of the urban canyon in relation to the sun would also likely affect solar UVR exposure; however, our results showed few instances

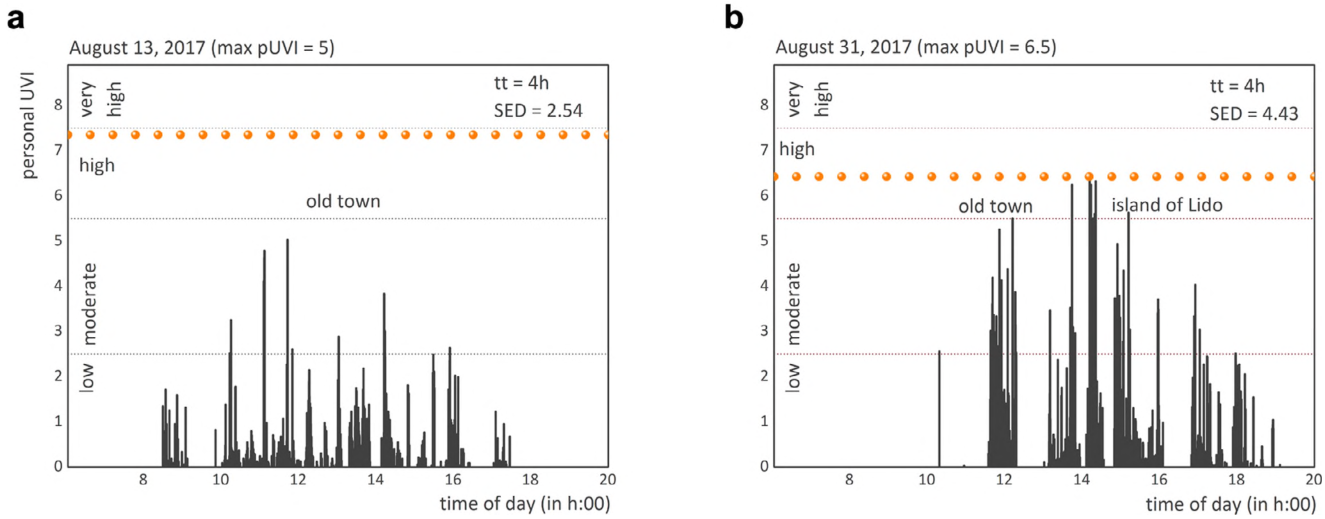

Figure 3. Personal UVI dosimeter measurements during a walking tour in (a) a historic center and (b) historic center and the island of Lido of the city of Venice, Italy. Orange dotted lines represent the maximal UVI for the town for that day. Total time spent exposed to solar UVI is given as tt, while SED gives the entire daily dose of solar UVI a person was exposed to. As in PSF measurements in one of the streets of the city of Venice, SED dose in the old town (a) is below the level of sunburn for all but very sensitive skin types. Measurements given in (a) are typical for pUVR of the historical center from this study.

where this was true. At Johannesburg, canyons with a north-east–southwest orientation and larger SVF had larger total daily exposures than north–south orientated canyons with smaller SVFs.

Figure 2 illustrates the different types of urban canyon sites where the PSF badges were placed in Venice and Johannesburg, respectively. The exposure was highly variable. For example, in Johannesburg, a site with an SVF of 0.43 (about half the sky obscured by trees and awnings) had a PSF reading of 9 SED. A more "open" or exposed site where pedestrians may walk, stop and then cross a road, recorded a total daily cumulative PSF reading equal to 81% of the total daily ambient PSF with an SVF closer to 1. Venice PSF urban canyon findings point to the strong shielding effect that the dense urban structure of the city provides. This is apparent in the case of the narrow north–south canyon PSF site (see 14 June 2017 measurement description in Table 1).

Comparison of PSF measurements to pUVR study

Figure 3a presents a dosimeter UVI count of a person who spent one entire summer day walking around the historic old districts of San Marco, San Polo and Santa Croce of the city of Venice. In Fig. 3b, we provide a comparison of the personal exposure measurements for the old city of Venice and the island of Lido to show how the less dense urban environment of the island of Lido led to higher pUVR exposure, similar to the canyon measurements made in Johannesburg.

Ground-based versus satellite-derived solar UVR exposures

When compared to the satellite-derived SED values for the cities, the measured values at ground-level were between 60% and 80% of the satellite-derived values. The higher levels of surface UVR indicated by the satellite are within the expected range of between 10% and 30%. Factors such as cloud cover, aerosols, surface albedo and changes in terrain height would contribute toward any differences (36).

CONCLUSIONS

Solar UVR exposure can be highly variable in urban canyons and the SVF, trees and awnings had a large impact on UVR exposures. These results though preliminary are important for the design of African cities where the rate of urban development is high. The study, while being a first for Africa, has some limitations because of a limited budget, and human capacity availability. Future studies should monitor more days or more months to include seasonal variability. The start and end times, making of monitoring on each day should be aligned to allow comparison between sites. Future studies should assess a larger sample size to further investigate whether, and how, SVF may be an important factor that influences solar UVR exposure in urban environments.

Acknowledgements—We acknowledge the approval from the Melrose Arch Precinct Management for us to work in the urban environment and have access to rooftops for ambient measurements. Collection of Venice data was fully a citizen science effort. We thank Sonja Krstic and Lazar Nikolic for collecting and organizing crowdsourcing of Venice pUVR data and Visnja and Sasa Lazic for undertaking Venice PSF measurements. We thank the AC SAF project of the EUMETSAT for providing data and/or products used in this paper.

FUNDING

This research was funded by the National Research Foundation, grant number 17/2/4. The APC was funded by the South African Medical Research Council. C.Y.W. receives research funding from the South African Medical Research Council and the National Research Foundation (South Africa). S.B. was funded by the Ca'Foscari University "Marie Curie+1" grant. B.S.M. is funded by the National Research Foundation (South Africa) and the Council for Scientific and Industrial Research National Laser Centre.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization, C.Y.W, D.J.dP, S.B.; methodology, C.Y.W, D.J.dP, S.B., B.S.M.; formal analysis, C.Y.W, D.J.dP, S.B.; investigation, C.Y.W, D.J.dP, S.B.; B.W., M.A., B.S.M.; writing—original draft preparation, C.Y.W.; writing—review and editing, All Authors.

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