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Horizontal and sun-normal spectral biologically effective ultraviolet irradiances

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Abstract

The dependence of the spectral biologically effective solar UV irradiance on the orientation of the receiver with respect to the sun has been determined for relatively cloud-free days at a sub-tropical Southern Hemisphere latitude for the solar zenith angle range 35–64°. For the UV and biologically effective irradiances, the sun-normal to horizontal ratio for the total UV ranges from 1.18 ± 0.05 to 1.27 ± 0.06. The sun-normal to horizontal ratio for biologically effective irradiance is dependent on the relative effectiveness of the relevant action spectrum in the UV-A waveband. In contrast to the total UV, the diffuse UV and diffuse biologically effective irradiances are reduced in a sun-normal compared with a horizontal orientation by a factor ranging from 0.70 ± 0.05 to 0.76 ± 0.03.

Keywords: UV; Solar UV; Sun-normal radiation; Diffuse

1. Introduction

Measurements of the terrestrial solar ultraviolet (UV) environment are required in order to increase the understanding of solar UV radiation and its effects on the biosphere, so that appropriate strategies may be developed to minimize UV exposure and any detrimental effects it may have. Spectroradiometers, broad-band meters and passive dosimeters may be employed for measurements of solar UV [1]. The advantage of spectroradiometers compared with broad-band instruments is that they can be more accurately calibrated to a standard lamp having its calibration traceable to the UV standard at a National Measurements Laboratory [2]. Spectroradiometers provide information about the UV spectrum in increments of the order of 1 nm compared with a broad-band UV meter, which provides information over a broad waveband. Another advantage of spectral irradiance measurements compared with broad-band data is that they can be accurately weighted with the biological action spectrum for any biological process.

Spectral UV measurements have been undertaken in the tropics [2,3], at sub-tropical latitudes [1] and at higher latitudes [4–6]. The effect of different altitudes on spectral UV data has been measured [7], along with the influence of geographical location [8]. The spectral surface albedo over different surfaces has also been measured [9,10]. This previous research employed the input aperture of the spectroradiometer on a horizontal plane, measuring either the upwelling or downwelling spectral irradiances. The receiving surfaces for humans and plants may at times be orientated normal to the sun and the irradiances may be higher at these orientations.

McKenzie et al. [11], have compared the erythemal UV irradiances measured with broad-band meters on horizontal surfaces and on surfaces perpendicular to the sun (sun-normal). Other research has measured the erythemal UV irradiance with polysulfone dosimeters on inclined surfaces and on the human face [12,13]. Schauberger [14] has modelled the biologically effective UV irradiance on inclined surfaces. However, none of this previous research measured the UV spectrum with a spectroradiometer on sun-normal and horizontal surfaces to provide information on the comparison of the UV spectrum and biologically effective UV dose for the two orientations. This current research compares the UV spectrum on a sun-normal surface with that on a horizontal surface and investigates the effect on the biologically effective irradiance for humans and plants. This is undertaken both for total and diffuse UV light.

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2. Materials and methods

2.1. Spectroradiometer

A spectroradiometer fitted with a 15 cm diameter integrating sphere (model OL IS-640, Optronics Laboratories, Orlando, FL, USA) that can be manually orientated was employed. The integrating sphere can be orientated to any angle between the vertical and the horizontal and the spectroradiometer is based on a double holographic grating (1200 lines mm^{-1}) monochromator (model DH10, Jobin–Yvon, France) connected to a R212 photomultiplier tube (Hamamatsu, Japan) temperature stabilized to 15 ± 0.5°C. Prior to each series of scans, the dark signal was measured, the spectroradiometer was wavelength calibrated against mercury spectral lines and the absolute irradiance calibrated against a quartz tungsten halogen lamp (250 W) operated at 9.500 ± 0.005 A d.c. with a calibration traceable to the Australian UV standard housed at Lindfield, CSIRO. The variations in the spectral irradiance recorded by the spectroradiometer are of the order of 5% [1].

2.2. Spectral UV irradiances

The solar UV spectrum was recorded with the spectroradiometer on mostly cloud-free days in an open unshaded field in late winter and early spring on 10 August and 3 September, 1998, in Toowoomba (27.5°S), Australia. The spectrum was scanned from 280 to 400 nm in 1 nm increments, with each scan taking approximately 45 s to complete. Over the period of a scan the solar zenith angle did not change significantly. The spectroradiometer was levelled to ensure the input aperture of the integrating sphere was on a horizontal plane. For the sun-normal measurements, the base board holding the integrating sphere, monochromator, photomultiplier tube and stepper motor control was orientated to the correct solar azimuth angle and the integrating sphere rotated to provide the plane of the input aperture approximately normal to the sun direction. The final sun-normal alignment was by using a hollow tube, approximately 10 cm long and 1 cm diameter, placed normal to the input aperture; the spectroradiometer position was adjusted in azimuth angle, and the input aperture adjusted in elevation angle until the tube cast a shadow of zero length.

In this manner, a series of horizontal-plane and sun-normal total UV spectra were recorded. For each series, the diffuse UV spectra were recorded for both the horizontal-plane and sun-normal orientations by placing an occluding disc of 10 cm diameter approximately 20 cm between the aperture of the integrating sphere and the sun direction. The occluding disc was moved to stay in position between the input aperture and the sun as the input aperture was rotated. The time taken for each series of measurements was on average 10 min and the effect of changing solar zenith angle on the solar spectral irradiances over this period was minimal. On 10 August, five series of measurements were undertaken, starting at 08:45 Australian Eastern Standard Time (EST) and stopping at 10:58 EST, for solar zenith angles from 64 to 46°. Similarly, on 3 September, seven series were recorded, starting at 08:49 EST and stopping at 11:52 EST, for solar zenith angles from 57 to 35°. The sky was predominantly cloud free during the measurement period for both days.

2.3. Biologically effective UV

For a particular biological process with an action spectrum, $A(\lambda)$, the biologically effective UV irradiance, UVBE, was calculated employing:

$$\mathrm{UVBE} = \int_{\mathrm{uv}} S(\lambda) A(\lambda)\, \mathrm{d}\lambda \qquad (1)$$

where $S(\lambda)$ is the measured spectral irradiance. In this research, the erythema [15], actinic [16] and DNA [17] action spectra along with the action spectra for photoconjunctivitis [18] and photokeratitis [19] of the eye have been employed for humans. For plants the action spectra employed are for generalized plant damage [20], i.e., the average of eight different action spectra, and for plant damage [21], i.e., the action spectrum for a combination of results for a variety of photoresponses in intact cucumbers. For erythema, DNA and generalized plant damage, the parameterization of the action spectra available in the literature has been employed. For the other action spectra, linear interpolation between the data points of the respective action spectrum has been employed to provide values in 1 nm increments and the integral in Eq. (1) replaced by a summation in 1 nm steps. The error in employing a linear interpolation for the action spectra and the summation in Eq. (1) is estimated to be of the order of 2%.

3. Results

3.1. Spectral UV irradiances

Eight typical UV spectra for the cloud-free day 3 September are presented in Fig. 1 for early morning at a solar zenith angle of 57° and near noon at a solar zenith angle of 38°. The fluctuations of the spectra are due to the solar Fraunhofer absorption lines and occur at reproducible wavelengths in each of the spectra. For the UV spectrum, the spectral irradiance for the sun-normal orientation is higher than for the horizontal one. In comparison, for the diffuse UV, the spectral irradiances for the sun-normal are lower than for the horizontal. This may be due to the higher proportion of the diffuse component compared with the total UV for an orientation away from the sun compared with a sun-normal direction. At the higher solar zenith angle of 57° in the early morning, the diffuse UV spectral irradiances comprise approximately one third to a half of the total UV spectral irradiances. Near noon for a solar zenith angle of 38°, the diffuse component com-

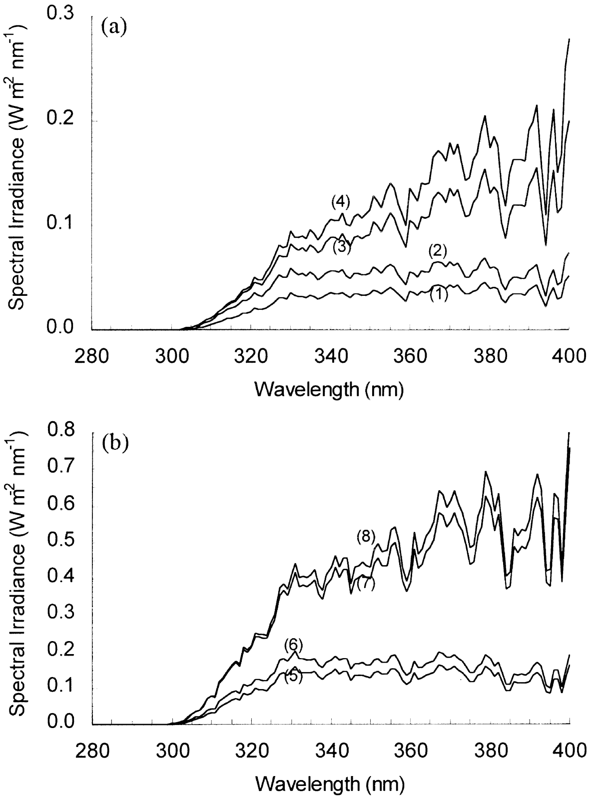

Fig. 1. Eight UV spectra for 3 September for early morning and near noon. The spectra are: (a) (1) sun-normal and diffuse UV at 08:52 EST, (2) horizontal and diffuse UV at 08:57 EST, (3) horizontal and total UV at 08:55 EST, (4) sun-normal and total UV at 08:49 EST; (b) (5) sun-normal and diffuse UV at 10:54 EST, (6) horizontal and diffuse UV at 11:00 EST, (7) horizontal and total UV at 10:57 EST and (8) sun-normal and total UV at 10:50 EST.

prises approximately one third of the total UV spectral irradiances.

3.2. Biologically effective UV

A set of biologically effective spectral irradiances, $S(\lambda)A(\lambda)$, in the early morning of 3 September for the erythemal and actinic action spectra is provided in Fig. 2 and a set for the plant-damage and generalized plant-damage action spectra is provided in Fig. 3. Additionally, the UV and UVBE irradiances for two solar zenith angles on 10 August are provided in Table 1. Each set comprises the sun-normal and diffuse UV, horizontal and diffuse UV, horizontal and total UV and sun-normal and total UV. In Figs. 2 and 3, the differences between the biologically effective spectral irradiances for sun-normal and horizontal directions is greater in the UV-A (320–400 nm) waveband compared with the UV-B (280–320 nm) for action spectra that extend into the UV-A, namely, the erythema, actinic and plant-damage action spectra.

This is further illustrated in Table 2, where the averages of the ratio of the irradiances for the sun-normal and horizontal orientations are presented. The results are the averages of each of the measurement times over both days. The error for

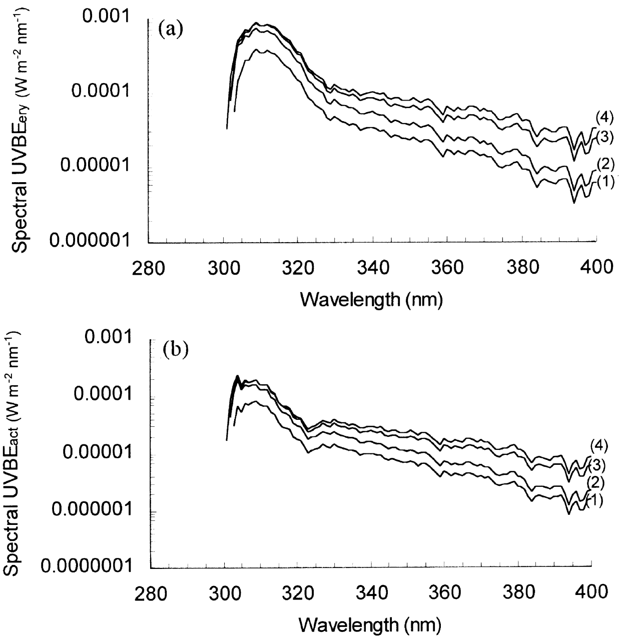

Fig. 2. Set of biologically effective irradiances in the early morning of 3 September for the (a) erythemal and (b) actinic action spectra. Each set comprises (1) sun-normal and diffuse UV, (2) horizontal and diffuse UV, (3) horizontal and total UV and (4) sun-normal and total UV.

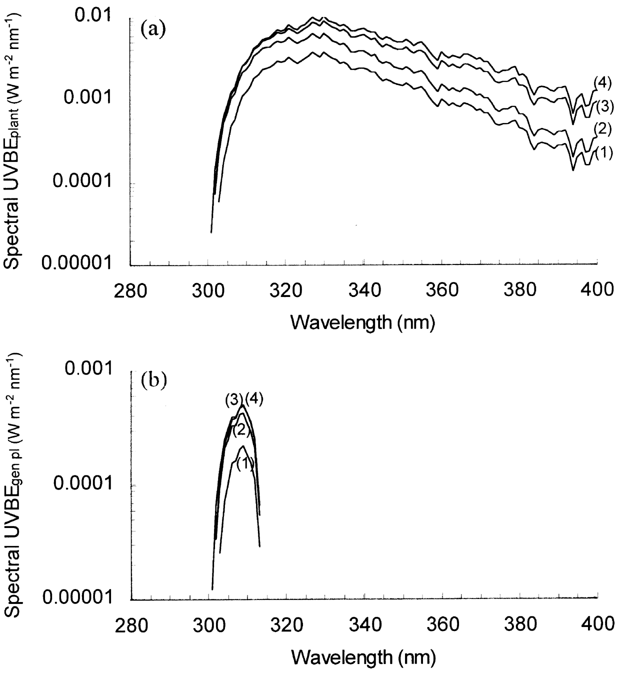

Fig. 3. Set of biologically effective irradiances in the early morning of 3 September for the (a) plant-damage and (b) generalized plant-damage action spectra. Each set comprises (1) sun-normal and diffuse UV, (2) horizontal and diffuse UV, (3) horizontal and total UV and (4) sun-normal and total UV.

each value is represented as one standard error in the mean. The sun-normal to horizontal ratio for the UV-A waveband is 1.33 ± 0.06 compared with 1.20 ± 0.05 for the UV-B waveband. This may be due to the higher proportion of the diffuse component in the UV-B waveband. Consequently, an orien-

Table 1
The UV and UVBE irradiances for horizontal and normal total and diffuse radiation at two solar zenith angles (SZA) on 10 August

SZA (°)	Type	UV irradiances ($W m^{-2}$) UV-B	UV-A	Erythemal	Actinic	DNA	UVBE irradiances ($W m^{-2}$) Photoconjunctivitis	Photokeratitis	Genalized plant damage	Plant damage
49	Horizontal total	0.88	19.3	0.051	0.013	0.023	0.00015	0.029	0.013	0.89
	Normal total	1.03	25.1	0.061	0.015	0.028	0.00019	0.034	0.015	1.10
	Horizontal diffuse	0.57	8.2	0.032	0.008	0.016	0.00011	0.019	0.009	0.48
	Normal diffuse	0.40	6.1	0.023	0.006	0.012	0.00009	0.014	0.006	0.35
45	Horizontal total	1.5	30.5	0.085	0.021	0.039	0.00027	0.049	0.022	1.45
	Normal total	1.7	39.0	0.101	0.025	0.046	0.00031	0.058	0.026	1.77
	Horizontal diffuse	0.83	11.6	0.046	0.011	0.022	0.00015	0.028	0.013	0.69
	Normal diffuse	0.60	8.8	0.034	0.008	0.017	0.00011	0.020	0.009	0.51

Table 2
The averages of the sun-normal to horizontal ratio for the total and diffuse irradiances for UV in the first two rows and UVBE for the remainder. The error is represented as one standard error in the mean

UV Component	Average sun-normal/horizontal ratio: Total	Diffuse
UV-B	1.20 ± 0.05	0.71 ± 0.03
UV-A	1.33 ± 0.06	0.76 ± 0.03
Erythemal	1.21 ± 0.05	0.72 ± 0.03
Actinic	1.21 ± 0.05	0.71 ± 0.04
DNA	1.19 ± 0.05	0.71 ± 0.04
Photoconjunctivitis	1.18 ± 0.05	0.70 ± 0.05
Photokeratitis	1.18 ± 0.05	0.71 ± 0.04
Generalized plant damage	1.18 ± 0.05	0.70 ± 0.04
Plant damage	1.27 ± 0.06	0.74 ± 0.03

tation normal to the sun will produce an enhanced UV exposure, with the enhancement effect being marginally greater in the UV-A waveband. Student's *t*-test for the statistical difference between the ratios for the UV-A and UV-B wavebands provided $p = 0.05$. For the biologically effective irradiances, the sun-normal to horizontal ratios for the total UV are 1.18 ± 0.05 to 1.21 ± 0.05 for the erythema, actinic, DNA, photoconjunctivitis, photokeratitis and generalized plant-damage action spectra, with a ratio of 1.27 ± 0.06 for the plant-damage action spectrum. This higher ratio is due to the higher effectiveness of this action spectrum in the UV-A waveband.

In contrast to the total UV, the sun-normal to horizontal ratio for the diffuse UV in Table 2 is less than one, with a range of 0.70 ± 0.05 to 0.76 ± 0.03. This confirms the data in Fig. 1, where the spectral irradiances for the diffuse UV are lower in a sun-normal orientation than in a horizontal orientation. Consequently, the UV exposures due to the diffuse component are reduced in a sun-normal orientation.

The UV-B and UV-A exposures and the biologically effective exposures for each of the action spectra for the horizontal and sun-normal orientations for the 10 August and 3 September are presented in Table 3. The integration periods are 08:45 to 10:47 EST and 08:49 to 11:48 EST for the 10 August and 3 September, respectively. For the UV-B waveband, the sun-normal exposures are 21–24% higher than the horizontal exposures. In comparison, the sun-normal UV-A exposures are 30–39% higher than the horizontal ones. The sun-normal biologically effective exposures are higher by 16–32% than the horizontal exposures. The percentage enhancement is dependent on the action spectrum employed.

Table 3
The broadband and biologically effective exposures between 08:45 to 10:47 EST and 08:49 to 11:48 EST for the 10 August and 3 September, respectively

UV Component	Exposures ($J m^{-2}$) 10 August: Horizontal	Sun-normal	3 September: Horizontal	Sun-normal
UV-B	4.7×10^3	5.8×10^3	14.8×10^3	17.9×10^3
UV-A	106×10^3	148×10^3	288×10^3	375×10^3
Erythema	270	342	878	1065
Actinic	66	84	221	267
DNA	120	151	421	504
Photoconjunctivitis	0.8	1.0	2.9	3.4
Photokeratitis	151	188	517	619
Generalized plant damage	67	83	241	286
Plant damage	4829	6386	13864	17483

4. Discussion

This paper has determined the dependence of the spectral biologically effective solar UV irradiance to humans and plants on the sun-normal and horizontal orientations of the selected site for relatively cloud-free days at a sub-tropical Southern Hemisphere latitude for the solar zenith angle range 35–64°. The research was undertaken in winter and early spring, when the differences between the horizontal and sun-normal UV irradiances may be expected to be larger than in the summer due to the larger solar zenith angles.

Humans or parts of the human body exposed in a sun-normal direction may receive up to 27% higher erythemal UV exposure compared with any measurements or predictions of the UV dose (for example, the UV index) on a horizontal plane. This is also applicable for UV exposure to the eyes when they may be orientated towards the sun, particularly at times of higher solar zenith angle, for example, in the morning and afternoon. Over a period of approximately 3 h before noon on 3 September, the additional erythemal exposure in the sun-normal orientation was 187 J m^{-2} or approximately 0.9 MED, where 1 MED is defined as 20 mJ cm^{-2} [22] and is the amount of biologically effective UV radiation required to produce barely perceptible erythema after an interval of 8–24 h following UV exposure.

The enhancement of the biologically effective UV exposure was also measured for both the plant-damage and generalized plant-damage action spectra. Parts of the plant leaf canopy may be orientated in a sun-normal direction during portions of the day. Additionally, heliotropic plants, for example, sunflowers, orientate the flower in an approximately sun-normal direction. The increased plant biologically effective UV dose in a sun-normal orientation may have a consequence for the effects of increased UV on plants due to stratospheric ozone depletion.

In contrast to the total UV, the diffuse UV is reduced in a sun-normal compared with a horizontal orientation. The consequence of this is that shade structures and trees may be more effective in providing UV protection for sun-normal orientations compared with horizontal orientations. For the total UV, the enhancement of the UV exposure is greater in the UV-A waveband. This is still significant for UV damage, as recent research [23] has found that the UV-A waveband contributes to skin damage. The sun-normal to horizontal ratio is dependent on the relative effectiveness of the relevant action spectrum in the UV-A waveband. This additional UV exposure can accumulate to a significant amount over a period of a year. Epidemiological and laboratory data have shown that the incidence of skin cancer increases in a proportional manner with the UV exposure raised to an exponent, called the biological amplification factor, with values of 1.4 ± 0.4 for basal cell carcinomas and 2.5 ± 0.7 for squamous cell carcinomas [24]. This has important consequences for the total UV exposure of humans and needs to be considered during the development of campaigns to reduce exposure of the population to solar UV radiation.

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