DIFFUSE SOLAR ULTRAVIOLET RADIATION AND IMPLICATIONS FOR PREVENTING HUMAN EYE DAMAGE

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Parisi, Alfio and Green, A. and Kimlin, M.G. (2001) *Diffuse solar ultraviolet radiation and implications for preventing human eye damage.* Photochemistry and Photobiology, 73 (2). pp. 135-139.
Accessed from USQ ePrints http://eprints.usq.edu.au

Running Title: Diffuse Solar UV and Eye Damage

Keywords: UV; eye; diffuse; sun protection; prevention; solar

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†*Abbreviations*: EST, Australian Eastern Standard Time; UVA, 320-400 nm; UVB 280-320 nm.

Abstract

Ocular UV exposure is a function of both the direct and diffuse components of solar radiation. Broadband global and diffuse UV measurements were made in the morning, noon and afternoon. Thirty sets of measurements were made in summer and fifty in each of the other seasons at each of the periods in full sun. Corresponding sets were made in the shade of Australian evergreen trees: 42 trees in summer and 50 in each of the other seasons. The percentage diffuse UV was higher for the shorter UVB than for UVA. The percentage diffuse UVB ranged from 23% to 59%, whereas the percentage diffuse UVA ranged from 17% to 31%. The percentage diffuse UV was lower at noon than in the morning and afternoon with the difference more pronounced for the UVB. The average percentage diffuse UVB over all the measurements in the tree shade for the morning, noon and afternoon was 62%, 58% and 71% respectively and the average percentage diffuse UVA was 52%, 51% and 59% respectively.

INTRODUCTION

A range of eye disorders including, cataracts, age-related macular degeneration, pterygium and photokeratitis have previously been shown to be sun-related (for example, 1-3). Cataracts are a major public health problem, being the primary cause of loss of vision in humans (4). Even low UV irradiances have been reported to increase the risk of human cataracts (5,6). Both physiological and environmental factors influence UV exposure of the eyes (2). Solar UV irradiances are one of the most important environmental determinants and ocular UV exposures have been evaluated by direct measurements with polysulphone dosimeters (7), polysulphone contact lenses (8,9), measurements to an eyeglasses frame (10) and by the development of models (11,12).

Minimisation of ocular exposure to UV radiation is essential to prevent these eye disorders, and for this to occur, greater understanding of the solar UV environment is necessary. The ocular UV environment is a function of both the direct and diffuse components of the solar radiation. The diffuse component, the topic of this paper, has an effect on the eye because it is incident from all directions and because the diffuse UV spectrum is altered from the spectrum for global (direct plus diffuse) UV radiation (13). Specifically, there is an increased proportion of the shorter damaging UVB[†] (280 - 320 nm) wavelengths. One of the reasons for this is the greater scattering by molecules and particles at the shorter wavelengths resulting in five- to ten-fold more UVB being scattered compared to visible radiation (14).

The aim of this paper is to provide quantitative data on the percentage diffuse component of solar UV radiation for each season of the year in both full sun and in the shade of Australian trees.

MATERIALS AND METHODS

Action Spectrum

Each of the target tissues in the eye has a different action spectrum for UV-induced biological damage. However, each of the known action spectra for biological damage, for example keratitis, conjunctivitis, cataract and DNA damage has a higher relative effectiveness at the shorter UVB wavelengths of the solar UV waveband (15). The actinic action spectrum has been provided by the International Radiation Protection Association (16) for the calculation of exposure limits for both public and occupational UV exposures to the skin or eye. One of the features of this action spectrum is the higher effectiveness at the shorter UVB solar wavelengths, in a same manner to the action spectra for keratitis, conjunctivitis, cataract and DNA damage.

Instrumentation

Measurements of the shorter UVB wavelengths where the action spectra for keratitis, conjunctivitis, cataract and DNA damage have the higher relative effectiveness were undertaken with a meter (model 3D, V2.0, Solar Light Co., Philadelphia, USA) with an erythemal UV detector. The action spectrum for erythema (17) and the actinic action spectrum approximately overlap (see Figure 1) for the solar UV waveband (18). For the meter the response at the UVB wavelengths is higher by a factor of more than 1000 compared to the UVA wavelengths. Hereafter, the waveband measured by this detector is termed UVB.

The meter was also fitted with a UVA (320 - 400 nm) detector. The response of the UVA detector is not weighted with any action spectrum. Measurements of UVB and UVA wavebands were undertaken in the grounds of the campus of the University of Southern Queensland, Toowoomba (27.5 °S), Australia. The two detectors were calibrated against a calibrated UV spectroradiometer (19) based on a dual holographic grating monochromator and a temperature stabilised photomultiplier tube detector, with calibration of the system traceable to the Australian UV standard lamp at the National Measurement Laboratory, Lindfield, Australia. The calibrations were undertaken for each detector between 9.00 Australian Eastern Standard Time (EST) and noon and repeated in each season in order to take into account the influence of the variation in the solar spectrum with the change in solar elevation angle. Although, the UVB waveband is more biologically damaging for eyes than the UVA, the diffuse UVA was also measured as it may contribute to human lens damage (6,20) and eyewear generally transmits more UVA than UVB.

Diffuse UV Measurements

The global UV spectra were measured on a relatively cloud free day with the input optics of the spectroradiometer on a horizontal plane or pointing directly upwards for solar elevation angles of 33^o and 52^o. Directly after each global UV spectrum scan, a shadow band (approximately 3 cm wide) was placed approximately 20 cm above the input optics and between the input optics and the sun direction and the diffuse UV spectrum measured. Additionally, diffuse broadband UVB and UVA measurements were taken with the Solar Light detector in each season between December, 1998 and November, 1999 inclusive. The broadband UVB and UVA irradiances were measured at ground level on a horizontal plane for the global UV and directly afterwards for the diffuse UV by holding a shadow band above and shading the respective detector. The error in the calculated percentage diffuse UVA and UVB is of the order of 10% due to factors such as measurement errors, levelling of the meter and the height of the shadow band.

Each pair of broadband global and diffuse UV measurements were made in the morning, noon and afternoon between 8.30 and 9.30 EST, 11.30 and 12.30 EST and 14.30 and 15.30 EST respectively, hereafter referred to as 9.00 EST, noon and 15.00 EST. All the measurements were over areas with short mown grass. Thirty sets of measurements were made in summer (November to February) and fifty in each of the other seasons (autumn - March to May; winter - June to August; spring - September to November) at the three study times. Corresponding sets of global and diffuse UV measurements were made in the shade of a range of mainly Australian gum trees (Eucalyptus sp.): 42 trees in summer and 50 in each of the other seasons. Canopies did not join or overlap and tree canopy widths ranged from 2.2 to 13 m; tree heights from 6.4 to 25 m; and the height above the ground to the first branches from 0.4 to 10 m. All measurements were made in the approximate centre of the visible shade for each tree (no measurements were made if there was cloud blocking the sun and eight-eighths of the sky dome was cloud covered). The effect of sunflecks in the shadow of each tree canopy was estimated by measuring the reduction by the tree shade of the irradiances in the visible waveband at approximately ground level on a horizontal plane with a LUX meter (model EMTEK LX-102, supplier, Walsh’s Co., Brisbane, Australia) as compared to that in full sun. These were measured within approximately 10 minutes of the respective UVB and UVA measurements.

The atmospheric conditions including clouds, total atmospheric ozone and aerosols were highly variable, for example, season-specific cloud cover could vary between zero and seven-eighths of the sky dome covered as evaluated by an observer. Up to 50 sets of measurements in each season at each of the three times of the day were undertaken in order to provide an average of the range of conditions that may be encountered.

RESULTS AND DISCUSSION

Diffuse UV Spectrum

Solar UV spectra measured in Toowoomba under predominantly cloud-free skies for solar elevation angles of 33^o and 52^o on a horizontal plane for global UV and diffuse UV are shown in Figure 2. Averaged over the UVB wavelengths the diffuse UVB spectral irradiances were 0.56 of the global UVB spectral irradiances for the higher solar elevation angle, but were 0.81 for the lower elevation angle. The differences between the global UV and diffuse UV spectra were larger in the UVA wavelengths than in the UVB wavelengths. This higher diffuse proportion of the global UV for the UVB waveband coincides with the higher relative effectiveness for biological damage of the actinic action spectrum (16). The higher relative proportion of diffuse UV at the lower elevation angle is due to the longer atmospheric pathlength contributing to a higher relative proportion of scattering. Additionally, the higher proportion of the diffuse UV in the UVB waveband is due to the larger degree of Rayleigh scattering at the shorter wavelengths.

Broadband Diffuse UV in the Sun

The diffuse UV as a percentage of the global UV averaged over the measurements for each of the four seasons for the UVB and the UVA waveband is shown in Figure 3. The error bars are one standard deviation. The diffuse UV component will be higher over high UV albedo surfaces, for example, water and snow. However, these have not been considered in this research. The diurnal variation between 9.00 EST, noon and 15.00 EST is also shown. The percentage diffuse UV was higher for UVB than for UVA. The percentage diffuse UVB ranged from 23% at noon in spring to 59% at 15.00 EST in winter, whereas the percentage diffuse UVA ranged from 17% at noon in spring to 31% at 15.00 EST in winter. Averaged over each of the seasons for each of the three times of the day, the cloud cover in eighths of the sky dome covered at 9.00 EST, noon and 15.00 EST respectively was: 3.2, 3.8 and 3.7 in summer; 1.3, 3.9, 2.6 in autumn; 0.7, 1.4, 2.3 in winter and 3.5, 2.2 and 4.0 in spring. The cloud cover seasonal average is higher in the afternoon than in the morning for each season. This explains the higher percentage of afternoon diffuse UVB and UVA in Figure 3. Atmospheric aerosols and ozone may change throughout the day, however, the scattering effects of cloud are expected to be higher than those of aerosols. The influence of ozone is absorption rather than scattering and the influence on the percentage of diffuse UVA and UVB is not significant compared to cloud.

Although the percentage diffuse UVA was lower than the percentage UVB, it is notable that in absolute terms, the UVA irradiances were higher (Figure 2). The percentage diffuse UV was lower at noon than at 9.00 and 15.00 EST with the difference more pronounced for the shorter waveband UV. Previous research (21) has found that for cloudless skies the percentage of the diffuse UV radiation increases with decreasing solar elevation angle, with the solar elevation angle depending on the time of day, season and latitude. This is verified in Figure 4, showing the variation of the percentage diffuse UVB and UVA in the sunlight with solar zenith angle. The diffuse UV is averaged over each season at the times of 9.00 EST, noon and 15.00 EST and the solar zenith angle is the average for the season at the respective time.

Broadband Diffuse UV in Tree Shade

Table 1 shows diffuse UVB and UVA measurements in tree shade as a percentage of the respective global irradiances in the shade. For each season, the percentages were higher in the tree shade than in the full sun. Previous research has found this for the summer (22), but these results show that this is also the case for the other seasons. The average percentage diffuse UVB over all the measurements in the tree shade for 9.00 EST, noon and 15.00 EST was 62%, 58% and 71% for each period respectively and the average percentage diffuse UVA was 52%, 51% and 59% respectively. The influence of sunflecks was evaluated by plotting the percentage diffuse UVB in the tree shade averaged over each season at the times of 9.00 EST, noon and 15.00 EST and the corresponding percentage of visible radiation in tree shade to that in sunlight in Figure 5. The percentage of the visible radiation ranged from 19% to 33%.

Although, the percentage diffuse UV at each time varied with season, the results have been averaged over the year for each respective time period of the day to allow comparison of the diffuse UV in tree shade to that in full sun. In full sun, the UVB averages were 39%, 29% and 49% for the morning, noon and afternoon periods respectively and 26%, 19% and 30% for UVA.

Implications for Human Eye Damage

The risks of ocular disorders such as cataracts, age-related macular degeneration and pterygium are related to UV exposures to the eye (1). Additionally, photokeratitis is related to acute exposure to UV radiation, such as over snow-covered ground. Other reports have provided the ratio of the ocular to the ambient horizontal plane exposure as: 4±1% and 20±0.4% for clear and overcast sky conditions respectively (9); 28±9% for clear sky conditions (8); and 19.5% (7). Sliney (2) has reported the field of view angles of the eye for a subject in an upright position as being in the range of 50^o above the horizon to 70 to 80^o below the horizon. This fact and the natural aversion of the eyes from the sun means that the major proportion of the UV exposure to the eyes and the consequent human eye damage are as a result of the diffuse UV component. Combining this with the percentages of the ocular to ambient UV ratios from other research and the percentages of diffuse radiation reported in this paper suggests that approximately one sixth to one half of the ambient diffuse UV radiation is entering the eye.

The ocular damaging effect of UV radiation is related to the energy, and consequently the wavelength of the incoming photons. A UV photon from the diffuse component is just as biologically damaging as a photon from the direct component. The UV irradiances to the eye are reduced by squinting and it may be expected that the amount of eyelid opening is influenced by the irradiances in the visible waveband. For diffuse UV radiation, this natural protection strategy would not be as prevalent (except over high albedo ground surfaces). Consequently, other UV minimisation strategies must be employed for the eyes.

We have shown that there is a higher percentage of the diffuse component at the shorter UV wavelengths in the winter and also in the morning and afternoon. Consequently, the amount of visible radiation is not an indication of the ocular damaging UV radiation. Additionally, as the diffuse UV is incident from all directions, hats and shade (14) are not as effective at reducing all of the diffuse UV (although they remain important in a UV minimisation strategy).

Sunglasses are promoted as a means for reducing ocular UV exposure. Specifically, the argument that there is a greater influx of UV radiation to the eye due to greater pupil dilation when sunglasses are worn is not valid (23). In Australia, a standard for sunglasses has been implemented (24), and for UV wavelengths less than 325 nm, the maximum possible mean transmittance allowed by the Standard is 1%. However, in determining compliance with the Standard, no information is provided about the diffuse UV radiation that may be entering the eye around the frame of the glasses since the transmittance of sunglasses is measured through the lens in a calibrated spectrophotometer.

CONCLUSION

Serious errors result if there is an attempt to estimate the diffuse UV from the irradiances in the visible waveband. This is also the case in tree shade where in, general, the percentages of diffuse UV in the tree shade are of the order of 20% to 30% higher than in full sun. Given the high relative percentages of diffuse UV radiation measured in this study, wearing sunglasses with small lenses results in a higher amount of ocular UV than wearing wrap-around sunglasses or sunglasses with lateral shields. Consequently, it is important to promote the wearing of sunglasses which have lateral protection, among children and teenagers at schools in tropical and sub-tropical latitudes.

Acknowledgments: Technical staff in Physics at the University of Southern Queensland and Dr Joe Wong, David Turnbull, Rick Lester and Meegan Wilson. Partial funding was provided by the Queensland Department of Health.

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Table 1 – The ranges of the tree shade diffuse UV as a percentage of the global UV in tree shade for the UVB and UVA wavebands.

	Percentage Diffuse UV	
	UVB	UVA
Summer	59 – 61	54 – 59
Autumn	65 – 79	53 – 61
Winter	67 – 85	53 – 64
Spring	41 – 60	36 – 55

FIGURE CAPTIONS

Figure 1 - The (1) human erythema (17) and (2) actinic (16) action spectra. The feature of these action spectra is the higher effectiveness at the shorter UVB solar wavelengths, in a same manner to the action spectra for keratitis, conjunctivitis, cataract and DNA damage.

Figure 2 – Solar UV spectra on a horizontal plane for solar elevation angles of 33^o for (1) diffuse UV and (2) global UV and 52^o for (3) diffuse UV and (4) global UV.

Figure 3 - The diffuse UV as a percent of the global UV for each of the four seasons at 9.00 EST, noon and 15.00 EST for the (a) UVB and the (b) UVA wavebands. The error bars are one standard deviation.

Figure 4 - The percentage diffuse UVB and UVA in the sunlight averaged over each season at the times of 9.00 EST, noon and 15.00 EST and the solar zenith angle. The solar zenith angle is the average for the season at the respective time.

Figure 5 – The percentage diffuse UVB in the tree shade averaged over each season at the times of 9.00 EST, noon and 15.00 EST and the corresponding percentage of visible radiation in tree shade to that in sunlight.

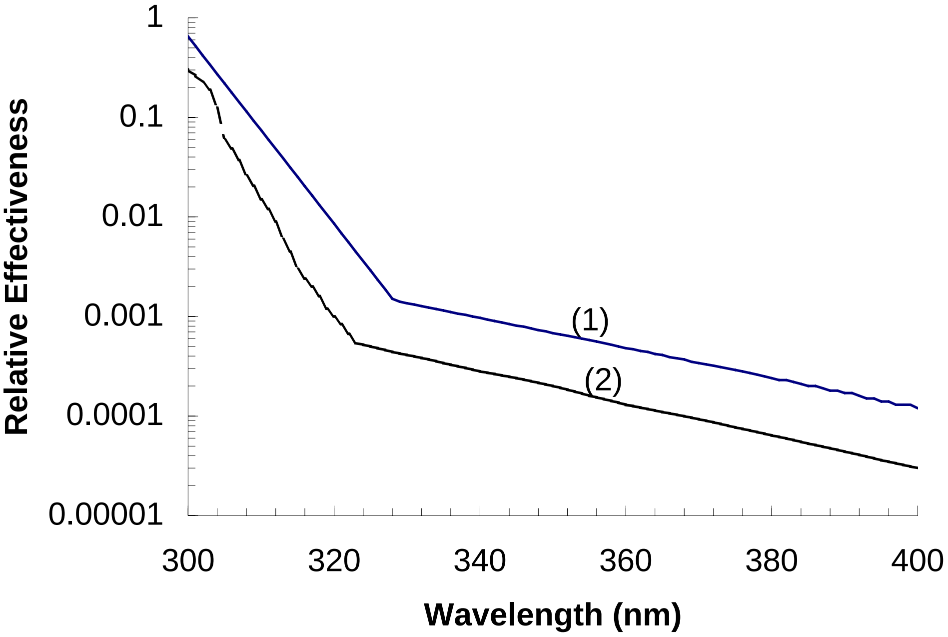
Relative Effectiveness
1
0.1
0.01
0.001
0.0001
0.00001
300
320
340
360
380
400
Wavelength (nm)
(1)
(2)

Figure 1

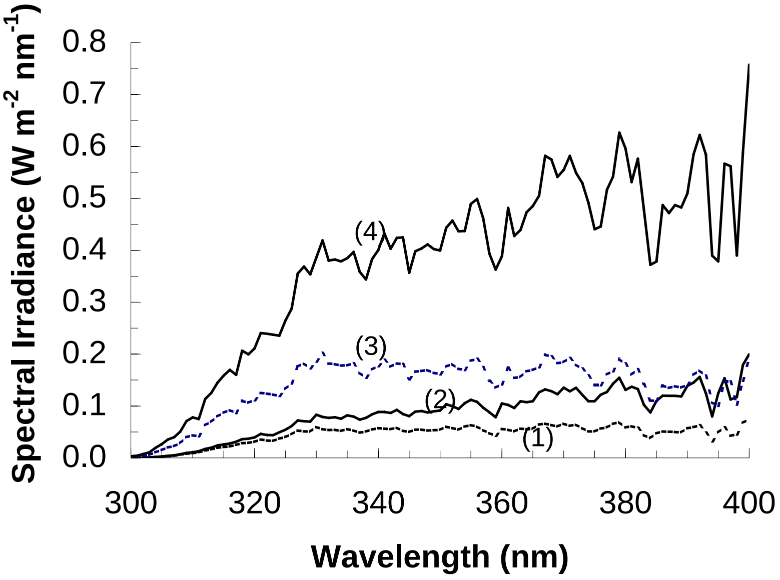
Spectral Irradiance (W m^{-2} nm^{-1})
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
300
320
340
360
380
400
Wavelength (nm)
(4)
(3)
(2)
(1)

Figure 2

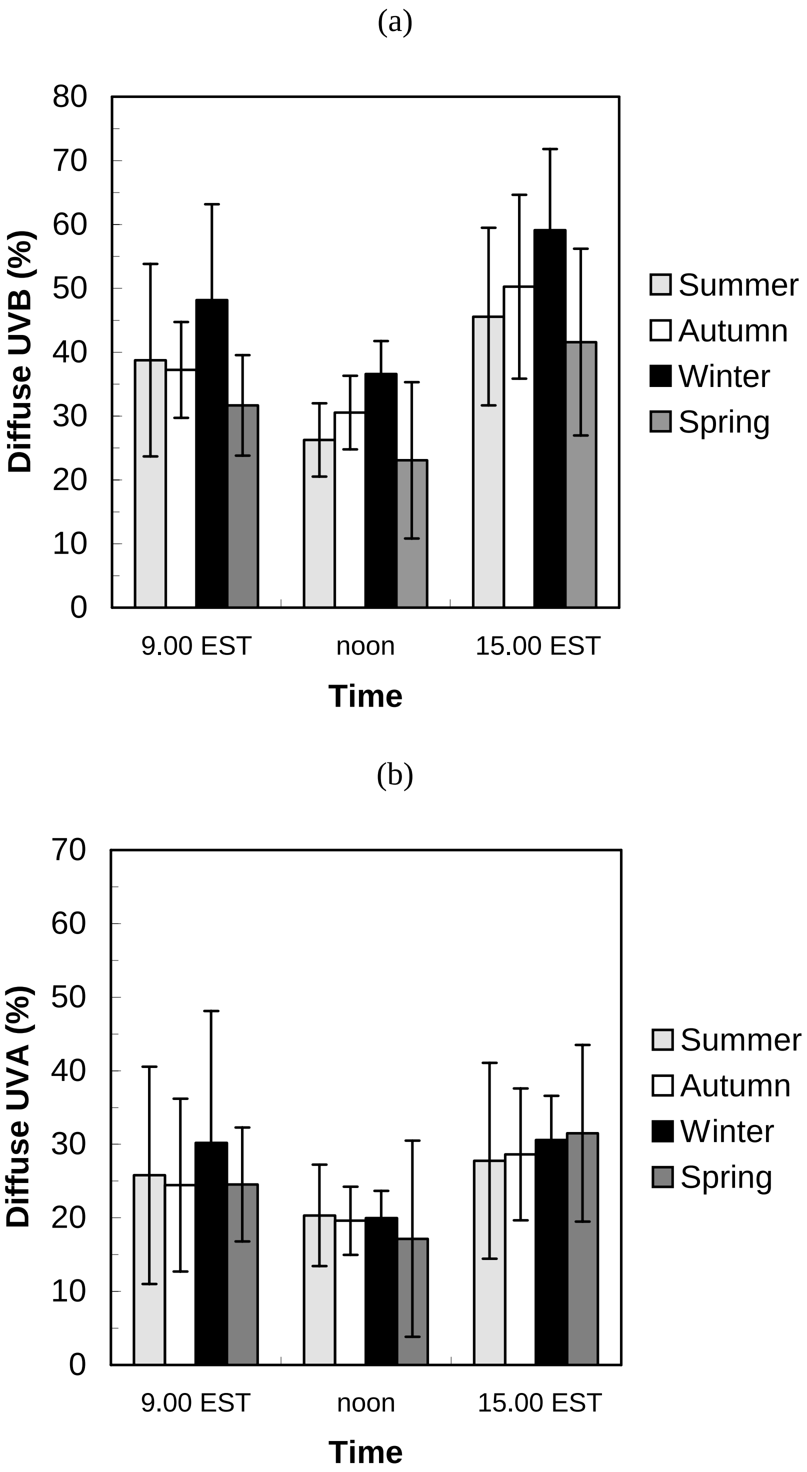
(a)
Diffuse UVB (%)
0
10
20
30
40
50
60
70
80
9.00 EST
noon
15.00 EST
Time
Summer
Autumn
Winter
Spring
(b)
Diffuse UVA (%)
0
10
20
30
40
50
60
70
9.00 EST
noon
15.00 EST
Time
Summer
Autumn
Winter
Spring

Figure 3

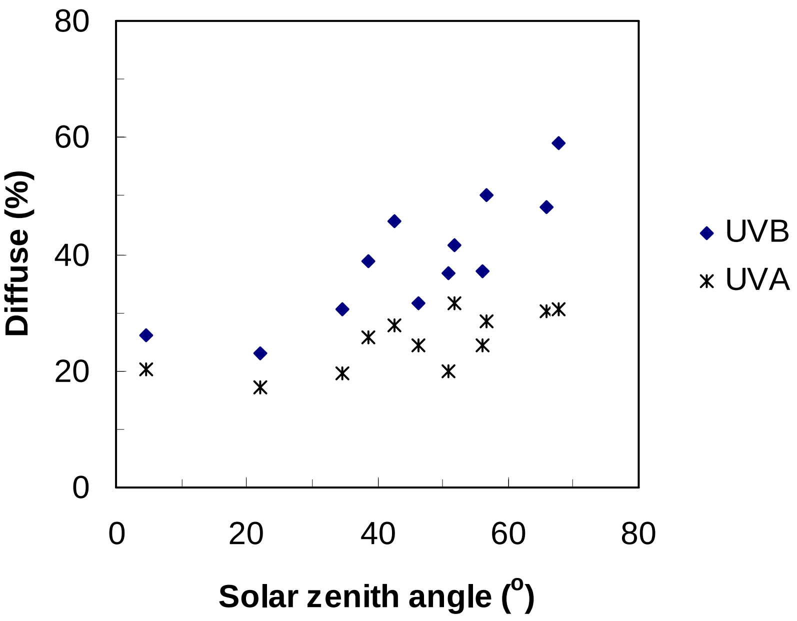

Figure 4

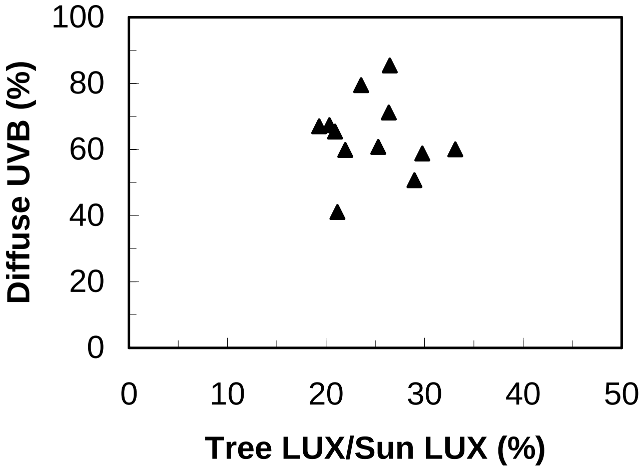

Figure 5