DIFFUSE SOLAR

ULTRAVIOLET RADIATION

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The solar UV exposure to the eyes of humans is due to the direct and diffuse components of solar radiation. The direct ocular UV exposures to the eyes are reduced due to the natural aversion of the majority of people from looking directly at the sun. The diffuse UV is incident from all directions and as a result, it is more difficult to minimise the ocular exposure to this component of the solar UV. As a result, a greater proportion of the ocular UV exposure is due to the diffuse UV radiation then due to the direct component.

Atmosphere

The short wavelength cut-off of the solar UV wavelengths incident on the surface of the earth is generally between 290 and 295 nm. The wavelengths below the cut-off are absorbed by atmospheric diatomic oxygen (O_2), ozone (O_3) and other atmospheric trace constituents. The solar UV that reaches the surface of the earth is the UVA (320 - 400 nm) and part of the UVB (280 - 320 nm) wavebands. The short wavelength cut-off is dependent on the solar zenith angle and the concentration of atmospheric ozone. For larger solar zenith angles, the cut-off wavelength shifts to longer wavelengths, along with an associated decrease in the irradiance. For higher levels of atmospheric ozone, the cut-off wavelength also shifts to longer wavelengths. The ozone absorption of UV is highest at the shorter wavelengths with a sharp decrease for increasing wavelengths to approximately 340 nm[1] with negligible ozone absorption for longer wavelengths. Consequently, there is no solar UVC (100 - 280 nm) incident on the earth's surface.

The global solar UV radiation is comprised of the diffuse and direct UV. A component of the diffuse UV is due to that scattered and reflected by the atmosphere, specifically molecules and aerosols in the atmosphere and clouds. The scattering that occurs due to atmospheric gas molecules, for example oxygen and nitrogen, when the scattering particle is small compared to the wavelength of the radiation is called Rayleigh scattering. This scattering of UV radiation occurs even for a cloud free sky and the amount of Rayleigh scattering is inversely proportional to the fourth power of the wavelength of the radiation. This leads to a higher relative proportion of scattered UVB compared to the longer wavelengths of the UVA and the visible wavebands. The difference between the relative proportions of diffuse UVB and UVA is shown by research where the percentage diffuse UVB ranged from 23% at noon to 59% at 3 pm and the percentage diffuse UVA ranged from 17% to 31% for the same times.[2] These values are averaged over each season, with the maximum value of the percentage of diffuse UV reaching 100%. Similarly, on clear days, the diffuse UVB has been measured to range from 48% to 70% for solar zenith angles of 15^o and range to 100% for solar zenith angles of 75^o.[3]

As an example, the global and diffuse erythemal UV for a typical summer's day at a sub-tropical Southern Hemisphere site are provided in Figure 1. The exposures are in units of MED/5min where an MED is defined as the minimum erythemal dose. The data was collected with Solar Light meters (model 501, Solar Light Co., Philadelphia, PA. USA) and the calibration provided a conversion of 277 J m^{-2} for an MED.

The other form of atmospheric scattering of UV radiation is Mie scattering that occurs when the radiation wavelength is comparable to the particle size. This scattering occurs for particles such as water vapour and aerosols. Aerosols are small solid or liquid particles suspended in the air, for example soot and dust. The amount of Mie scattering is inversely proportional to wavelength. As a result of the wavelength dependence of the Rayleigh and Mie scattering, the amount of scattering in the UVB waveband is five to ten fold more compared to the visible waveband.[4] Consequently, the amount and distribution of visible radiation is a very poor indicator of the UV exposures.

The diffuse UV incident on a horizontal plane has been compared to that incident on a plane normal to the sun's direction for a predominantly cloud free day.[5] At a sub-tropical site, for solar zenith angles of 35^{o} to 64^{o}, the ratio of the diffuse UV irradiances on a sun-normal plane to those on a horizontal plane were 0.71±0.03 and 0.76±0.03 for the UVB and UVA wavebands respectively. In comparison, the same ratios were 1.20 and 1.33 for the total UV. This difference is expected to be as a result of the higher proportion of diffuse UV on a plane with a larger amount of sky view compared to a plane with a lower amount of sky view. The higher ratio for the UVA is due to the lower proportion of diffuse radiation at the shorter wavelengths.

Action Spectra

The biological effectiveness of UV is dependent on the wavelength as the wavelength determines the energy of the UV photons. A UV photon from the diffuse component is just as damaging as a photon of the same wavelength from the direct component. The relative effectiveness of different wavelengths for producing a particular biological response is provided by a function called the action spectrum. This allows the relative weighting of the spectral irradiances in order to take into account the wavelength sensitivity of the biological target. For a particular action spectrum, A(λ), the biologically damaging UV irradiance, UVBE, is calculated by employing the following equation:

$$UVBE = \sum_{UV} S(\lambda)A(\lambda)\Delta\lambda \qquad \mathrm{W\ m^{-2}} \qquad (1)$$

where λ is wavelength, S(λ) is the measured spectral irradiance or the amount of energy from the source in a narrow waveband and Δλ is the wavelength increment of the spectral data.

The action spectra for photoconjunctivitis[6] and photokeratitis[7] of the human eye and cataracts of the porcine lens[8] are provided in Figure 2. Each action spectrum is generally normalised to the response at the wavelength with the highest response. For these action spectra, the UVB wavelengths have a higher relative effectiveness than the UVA wavelengths. Unfortunately, this coincides with the higher relative proportion of scattering and resultant higher relative proportions of diffuse UVB.

A typical solar UV spectrum for a solar zenith angle of 26° on a cloud free day is provided in Figure 3. The spectrum shows the higher irradiances in the UVA waveband and the sharp drop-off in the UVB irradiances. The dips in the spectrum are due to the Fraunhofer absorption lines due to absorption in the sun's atmosphere at these specific wavelengths by elements such as Ca, Fe, Ti, Al and Mg. The corresponding spectral UVBE of this source spectrum for cataracts and photoconjunctivitis are provided in the Figure by multiplying S(λ) by A(λ) at each wavelength.

Clouds

At a given location for a fixed solar zenith angle, clouds provide the major cause of variation of the solar UV.[9] The influence of clouds on the solar UV is less than in the visible wavebands due to the higher relative amount of scattering at the shorter wavelengths. On cloudy days there is the additional contribution of the UV scattered back to the receiver by clouds.

The effect of clouds on the biologically effective UV for cataracts and photokeratitis has been investigated at a sub-tropical site.[10] The ratio of the measured irradiances was compared to those for a cloud free case for the same solar zenith angle. The measured irradiance to the cloud free irradiance was 0.6 or higher for 85% of the cases. A ratio of 0.8 and higher occurred for 76% of the cases.

There are also cases when the UV is increased or enhanced by clouds above that of a cloud free day.[11-14] These cases of enhanced biologically damaging solar UV are due to cases of increased diffuse UV irradiances. Cloud enhanced UV has been reported to occur when the solar disc is obscured, but still visible through cirrus cloud or haze[14] and when the solar disc is cloud free, but there is broken or thin cloud near the sun.[15] The cases of cloud enhanced UV have been investigated over a six month period at a sub-tropical site[12] by concurrently measuring the spectral UV and the amount of cloud cover at five minute intervals. For the cases of cloud enhanced UV, the average ratio of the measured biologically damaging UV to calculated cloud free UV for the photokeratitis and cataracts action spectra was 1.25. On these occasions when cloud has enhanced the solar UV, these UV levels would be above the cloud free irradiances that would be predicted by the UV index and the general public would not be aware of this.

Albedo

The scattering and reflection by the physical environment, for example snow, ground covering and other surfaces also contribute to the diffuse UV component. This is known as the albedo and is dependent on the nature of the surface. The albedo is generally determined as a ratio of the upwelling irradiance, to the downwelling irradiance[16] and is a consequence of the reflection and scattering from the surface of both the direct and diffuse UV. The UV exposures to a receiver contain a component that is reflected or scattered from a surface to the receiving object and a portion that is scattered back by the atmosphere and clouds to a receiver after reflection or scattering from a surface. Alternatively, the upwelling UV may undergo multiple scatterings and reflections between the surface and the atmosphere or clouds before reaching the subject. As a result, any humans over relatively high albedo surfaces will receive higher UV exposures due to the combined result of the downwelling and upwelling UV. For example, McKenzie et al.[17] found over snow covered ground and for clear sky conditions, enhancements in the UVB irradiances to a horizontal plane of approximately 28% above that of snow free ground. The largest enhancements occurred when there was the combined influence of partial cloud cover and snow. For a downward viewing plane, the signal increased to more than 70% of that on an upward viewing plane. This has consequences for ocular UV exposures as the field of view angles for the eyes of an upright human have been reported to range from 50° above the horizon to 70 to 80° below the horizon.[18]

For the UV waveband, the albedo ranges from approximately 0.02 for grass to more than 0.8 for snow covered surfaces.[19,20] For each type of surface, there is a range of albedos due to the nature and condition of the surface, wavelength of the UV and the solar zenith angle. Averaged over the UV waveband, typical albedo values for dry concrete and sand are 0.12

and 0.18 respectively.[20] The UV albedo of metallic roofing material also depends on the surface and the wavelength with a range from 0.04 (coloured metallic surface) to 0.3 (galvanised metallic surface).[21]

Shade

The use of shade in the form of shade structures, trees and other structures forms an essential component of a UV minimisation strategy. Shade reduces the direct component of solar UV; however, a proportion of the diffuse UV is still present. Coupled with this, there is the possibility that some parts of the general population could spend longer outdoors due to the reduced thermal discomfort in the shade. There may be the possible incorrect perception that the shade provides total protection from solar UV radiation. However, the solar UV irradiances are unrelated to temperature as the UV and infrared wavebands are on opposite sides of the visible waveband of the electromagnetic spectrum. The techniques and results for the measurement of diffuse solar UV in different shade environments, for example in tree shade,[22] under public shade settings[23] have been previously reported. A review of research in this field has been provided in Parisi et al.[24]

The UV irradiances in shade are influenced by cloud cover, solar zenith angle and the amount of sky view.[23,25,26] As an example, previous research has measured the ultraviolet protection factor of three typical shade structures provided by a local council to range from 1.5 to 18 for solar zenith angles of 13^{o} to 76^{o}.[23,27] These structures are open on the sides. In this case, the ultraviolet protection factor is calculated as the UV on a horizontal plane in the full sun to the UV in shade on a horizontal plane. As the solar zenith angle increased, the amount of diffuse UV in the shade increased, with a resultant decrease in the ultraviolet protection factor. The cloud increases the relative amount of UV in the shade compared to the UV in full sun.[28] This increase in the diffuse fraction of the solar UV is due to the spectrum of the diffuse UV being altered from that of the global (direct plus diffuse) UV due to an increased relative proportion of the shorter wavelengths. The ratio of the UVA to UVB irradiances for diffuse UV in shade is altered compared to the same ratio in the sun. The ratio is lower in the shade and the consequence is that there is a higher proportion of UVB in the shade compared to the proportion of UVB in the sun.[29] As an example, the ratio of the UVA to UVB irradiances was lower by 26% in tree shade compared to the same ratio in full sun.[29]

Solar Zenith Angle

For a given concentration of atmospheric absorbing and scattering particles and increasing solar zenith angle, the path of the solar UV through the atmosphere is longer. This results in a higher degree of atmospheric scattering and the portion of diffuse UV increases for increasing solar zenith angles. The proportion of diffuse erythemal UV measured in full sun at a sub-tropical site was approximately 26% at noon and 40% in the morning and afternoon.[22] This was averaged for a series of measurements over a season and the maximum proportion of diffuse UV is higher than this.

Measurement of Diffuse UV

UV exposures to the surface of the eye have been directly measured with contact lenses fabricated from polysulphone.[30,31] The ocular UV exposures compared to the horizontal plane UV exposures have been reported to vary from 4% to 23%[31] to 28%.[30] Other research has incorporated personal exposures, behaviour, location, season and job history to estimate cumulative ocular exposures.[32]

Sunglasses

A survey on sunglasses has shown that the sunglasses lenses reduce the UV irradiances to the lens and retina.[33] Standards organisations in Australia and other countries have established minimal standards for sunglasses, for example AS, 1990.[34] These are based on the ocular protection provided by the lens and provide no information of the ocular UV exposure around the lens and frame. Lenses opaque to UV radiation reduce UV exposures through the lenses, however diffuse UV is still possible to reach the eye around the side of the lenses.[35] For sunglasses, side shields and overhead protection or alternatively tightly fitting wrap around sunglasses are essential to reduce the ocular exposures due to the high relative proportions of diffuse UV radiation.[2,35]

Summary

There are a number of influencing factors on the diffuse UV that humans are exposed to on the earth's surface, namely clouds, surface albedo, solar zenith angle, amount of sky view and atmospheric particles and aerosols. The amount of visible radiation is not a good indication of the amount of diffuse UV. A better indicator of the relative proportion of diffuse UV, if the other factors are the same is the amount of sky view available to the receiving object.

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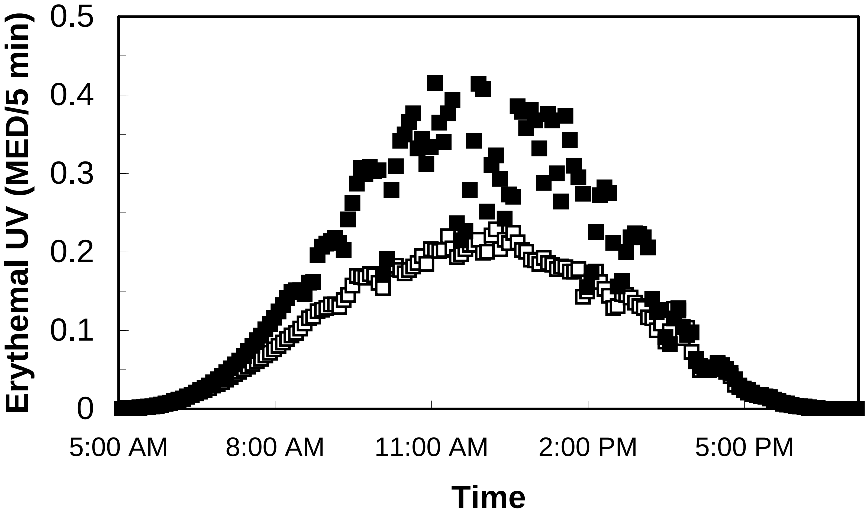
FIGURE CAPTIONS

Figure 1 – The global erythemal UV (■) and the diffuse erythemal UV (□) on a day in summer at a Southern Hemisphere sub-tropical site.

Figure 2 – Action spectra for (a) photoconjunctivitis (CIE, 1986a), (b) photokeratitis of the human eye (CIE, 1986b) and (c) cataracts in the porcine lens (Oriowo et al., 2001).

Figure 3 – (a) The solar UV spectral irradiance for a typical cloud free day at a solar zenith angle of 26o and the corresponding UVBE for (b) cataracts (right axis) and for (c) photoconjunctivitis (right axis).



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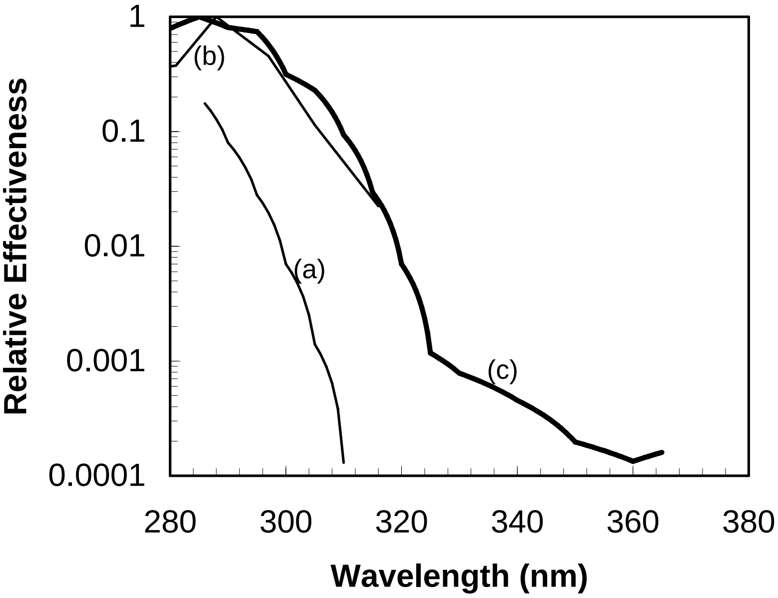

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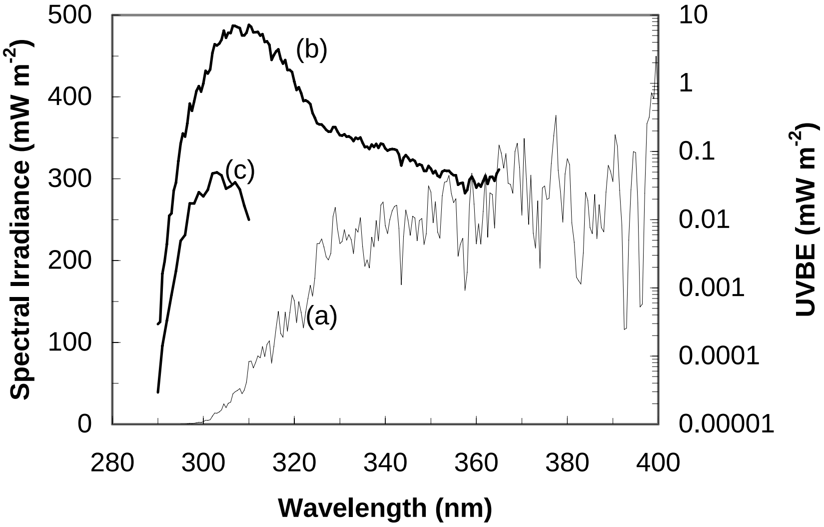

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