Measurement variation and the factors influencing the UV index

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ABSTRACT

The article presents a technique to measure the ultraviolet index using a personal hand held ultraviolet meter to illustrate concepts of physics. Measurements of the erythemally effective (sun-burning) direct solar beam, diffuse skylight, and total global ultraviolet irradiance are converted to daily ultraviolet index measurements. Daily ultraviolet index measurements are then compared to the daily forecast ultraviolet index. The influence of the local environment on the measured and forecast ultraviolet index is further examined with respect to surface reflection, shade structures, trees and buildings placed within the local environment, which each play a significant role in influencing the ultraviolet index at any one location. The measurement techniques presented in the article are provided to suit primary and secondary school aged children.

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INTRODUCTION

School playgrounds in Australia experience significant levels of ultraviolet (UV) radiation. The risk of the development of solar UV induced diseases, particularly skin cancer, is increased in a school population due to periods of peak UV radiation occurring between 9:00 am and 3:00 pm, high solar elevations due to Australia's relatively low latitude, lower ozone concentrations with respect to the northern hemisphere, a high number of sunshine days, and a predominately fair skin type among the school aged population. For children under 16 years of age, exposure to solar UV incurred while at school or any other environment has the potential to cause most harm, particularly in regards to the development of melanoma skin cancers occurring later in life (Armstrong 1988; Weinstock et al. 1989; Longstreth et al. 1998). Campaigning by state cancer councils has increased awareness among the Australian population to the danger of excessive exposure to solar UV (Gies et al. 1998) and the implementation of 'SunSmart' programs by schools in Australia has contributed significantly to reducing the risks of over exposure to UV radiation in school populations. It has been observed however, that sun protective behaviours decrease with age, particularly in high school populations (Dixon et al. 1999; Balanda et al. 1999; Lowe et al. 2000). The article presented here aims to increase awareness of the local UV environment experienced in schools through the active measurement of UV radiation by students under various conditions and situations experienced while at school. A convenient unit of measurement is the Ultraviolet Index.

The Ultraviolet Index (UVI), recently revised (WHO 2002) and adopted by the World Meteorological Organization (WMO 1994) as the international standard for reporting variations in the daily ultraviolet climate to the public is regularly reported in Australia. It is represented by a linear scale, divided into five ranges that report various levels of risk associated with outdoor ultraviolet exposure. The UVI scale is open ended and daily maximums are typically reported as ‘low’ (UVI - 0 to 2); ‘moderate’ (UVI - 3 to 5); ‘high’ (UVI - 6 to 7); ‘very high’ (UVI - 8 to 10) or extreme (UVI $\geq$ 11). This scale was originally determined by dividing a ‘typical’ clear sky solar noon erythemally effective (sun-burning) ultraviolet irradiance of 250 mW/m^2 by 25, giving an approximate maximum of 10. This original definition introduced in Canada in 1992 (McElroy et al. 1997) and subsequently adopted by other countries is still relevant today in terms of the standardised international UVI, however values exceeding 10 are common especially in the southern hemisphere due to lower ozone concentrations (McKenzie 1991). At lower latitudes such as those observed in the tropics, the Sun’s path moves closer to the zenith than is observed over higher latitudes. This further increases the UVI in tropical locations, particularly during the summer months as the absorption of UV radiation by stratospheric ozone is reduced by the smaller direct path of the UV through the atmosphere.

The erythemally effective, or sunburn weighted response of human skin to ultraviolet radiation determined by McKinlay and Diffey (1987) is higher in the ozone moderated UVB waveband (280 nm to 320 nm) than the more terrestrially abundant UVA (320 nm to 400 nm). Sunburn, although dependent on skin pigmentation, is common wherever the UVB waveband is present and the UVI is therefore a good indicator of the likely human sunburn response. Additionally, there are other biological responses including melanoma, or other UV induced human disorders including skin photoageing and immunosuppression that may respond to other wavelengths of the UV spectrum (Young 1998; Kim et al. 1990). Furthermore, the UVI varies depending on the surrounding environment, the level of protection offered (both personal and environmental), and the atmospheric conditions at the time. A detailed understanding of the UVI and its variation due to these conditions is of significant benefit to school aged children undertaking studies of the Sun, atmosphere, the environment and their immediate effects on humans living in those environments.

METHOD AND IMPLEMENTATION

This paper will present two methods for investigating the UVI. These include:

1. Measurement and comparison of the daily UVI with the expected forecast; and
2. Measurement of the UVI in local environments

Comparing measurements of the daily UVI with expected forecasts

UVI forecasts

Many countries provide forecasts of the daily UVI. Some of these can be found readily online (EPA 2007, Met Office 2007, BOM 2007, HSC 2006) and most report variation with time of day and different levels of cloud cover. Below is a figure of two forecast images available from the Australian Bureau of Meteorology website showing the daily national UV index chart and local UVI variation (BOM 2007). Both of these UVI predictions were provided for clear sky conditions on 9 November 2007.

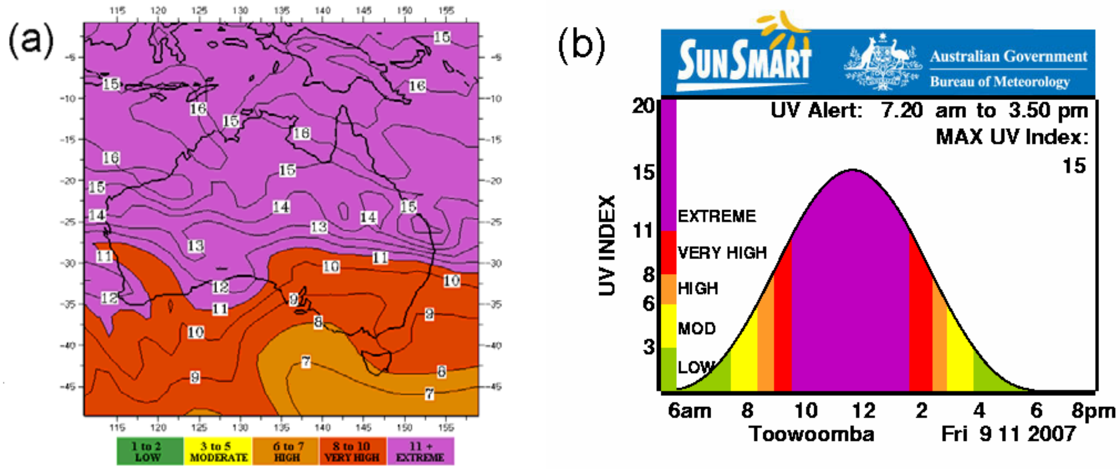

Figure 1. (a) Australian national noon UVI forecast chart. (b) Local UVI forecast for Toowoomba (28° S, 152°E) (BOM 2007).

In addition to the UVI, the Australian Bureau of Meteorology site lists the UV Alert time. This time is taken as the time when the UVI exceeds 3 and represents times when forms of sun protection including hat, sunglasses and sunscreen use, shade provision, and exposure avoidance are most appropriate. Similar UV alerts are provided in the United States (EPA 2007), though the requirements for issuing alerts differ from those required in Australia. It follows however, that students performing outdoor measurements for the activity presented here should follow precautions that minimise exposure to solar ultraviolet.

Monitoring the daily UVI

A personal UV meter (Edison, UV checker (pocket UV meter)) available at Jaycar Electronics (2008) at a cost of approximately 25 Australian dollars, was used to measure the daily erythemally effective UV irradiance (measured in mW/m^2) in 1 hour intervals from 9:00 am to 3:00 pm. Measurements of the direct solar beam, global (total) and diffuse (skylight) ultraviolet were taken at each hourly interval (Figure 2). In these cases, the direct solar beam is sunlight that creates a shadow, diffuse ultraviolet is ultraviolet scattered by the atmosphere and global ultraviolet is the sum of vertically incident direct UV and the total diffuse UV coming from the sky (The total UV irradiance that can be measured and is incident to a horizontal surface).

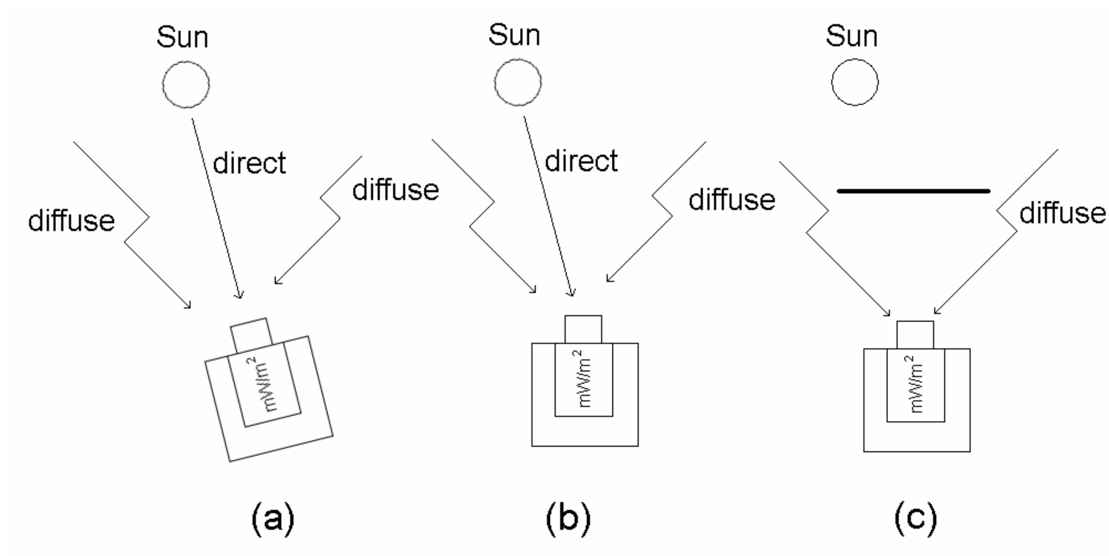

Figure 2. The components of solar ultraviolet radiation reaching the Earth's Surface as measured by a hand held UV sensor. (a) direct solar beam; (b) global; (c) diffuse.

Direct solar beam measurements required the meter to be pointed directly at the Sun. Diffuse measurements were taken with the meter held such that the sensor pointed vertically toward the zenith while at arms length and covered by a shadow cast using a ruler held approximately 30 cm above the sensor. Global ultraviolet measurements were taken with the meter held as for the diffuse measurement but without a casting shadow. The dimensionless UVI was calculated by dividing each recorded UV irradiance measured in mW/m^2 by 25. Figure 3 below illustrates the technique used in monitoring the diffuse UVI on 9 November 2007 at Highfields State Primary School (Toowoomba). The results are listed in Table 1 and plotted in comparison to the daily UVI forecast in Figure 4. It should be noted however, in keeping with the correct scientific definition, the UVI is the global or total UV incident to a horizontal plane. The terms diffuse UVI, and direct sun UVI, including UVI measurements that are taken orientated away from the horizontal plane as referred to in the table and subsequently throughout this article, are measurements of the UV irradiance that have been converted into an equivalent UVI value by dividing the measured UV irradiance in mW/m^2 by 25 and are included here for ease of comparison with the true global UVI as provided in forecasts and other forms of measurement. The terms that do not strictly relate to the global UVI have therefore been presented in italics in the sections that follow to clarify this difference. Students performing the activities presented in this paper using measurements expressed in *UVI* terms get an understanding of how the true global UVI varies depending on where the solar disk is located in the sky and the amount of diffuse skylight that is available at the measurement location.

(a)

(b)

Figure 3. (a) Year 6 students Emily Youngberry and Emma Thornton (Highfields State Primary School) download the daily UVI forecast for Toowoomba and (b) demonstrate the technique used to measure the diffuse *UVI*. The meter shown in (b) is held at arms length to increase the sky view that may be blocked if held too close to the body.

Table 1. Observations and calculations of the *UVI* monitored at Highfields State Primary School on 9 November 2007.

Time	Direct Sun UV (mW/m^2)	Direct Sun *UVI*	Diffuse UV (mW/m^2)	Diffuse *UVI*	Global UV (mW/m^2)	Global UVI	observations
9:00am	192	8	40	2	164	7	Clear
10:00am	206	8	46	2	204	8	Mostly clear, some cloud
11:00am	228	9	48	2	231	9	Mostly clear, some cloud
12:00pm	238	10	69	3	235	9	Patchy cumulus
1:00pm	214	9	50	3	197	8	Patchy cumulus
2:00pm	173	7	51	2	150	6	Patchy cumulus
3:00pm	52	2	19	1	50	2	Heavy cloud cover

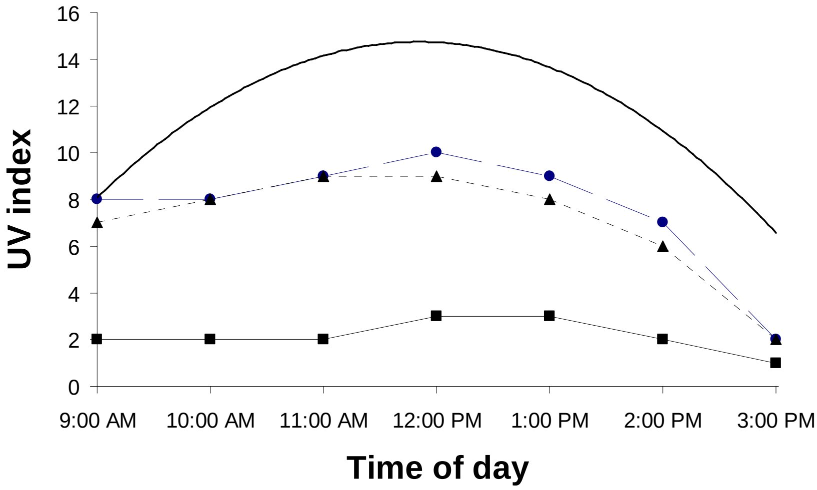

Figure 4. The measured direct solar beam (dashed circles), global (dashed triangles) and diffuse (solid squares) *UVI* plotted with respect to the daily clear sky UVI forecast (solid line) provided for Toowoomba, 9 November 2007. The Australian Bureau of Meteorology forecast for the daily maximum UVI on this day was: (clear sky 15), (patchy cloud 10), (overcast 7).

In Figure 4, the direct solar beam, diffuse skylight and global total UV components are plotted. Figure 2 is a simple diagrammatic representation of each of these UV components as measured by students on 9 November 2007. Note from Figure 2, direct solar beam measurements are the greatest as these include the solar beam and diffuse skylight UV measurements. Global UV measurements are the next most significant including diffuse UV and a considerable component of the direct solar beam but are taken with the meter orientated toward the zenith rather than toward the Sun. Shaded diffuse skylight measurements are smaller but can account for more than 50 percent of the total UV irradiance affecting sunburn exposures.

It is important to note that the ultraviolet received at the Earth's surface includes not only the direct solar beam ultraviolet but also diffuse skylight scattered in the atmosphere. Therefore measurements of the direct solar beam and global horizontal plane ultraviolet include as part of their measurements, a diffuse skylight component. Students may like to experiment with ways of eliminating this component before measurement. One simple way of shielding the meter sensor from diffuse skylight UV may involve the use of a toilet roll placed over the sensor. This was trialled using the personal UV meter with some success when measuring the direct solar beam. Shielded direct beam (toilet roll) and shaded (ruler shadow) diffuse skylight measurements add to give the global ultraviolet irradiance when the meter is pointed toward the zenith. A shielded beam and shaded diffuse measurement can be used to verify this. At low latitudes in the southern hemisphere, the Sun moves to within a few degrees of the zenith during summer months. These times provide the best opportunity to measure the direct and diffuse UV components for comparison with the global UV using a toilet roll and ruler shadow as explained above as shielded direct measurements covered by a toilet roll may not register on the meter when the Sun is lower in the sky and the meter orientated toward the zenith (Figure 5).

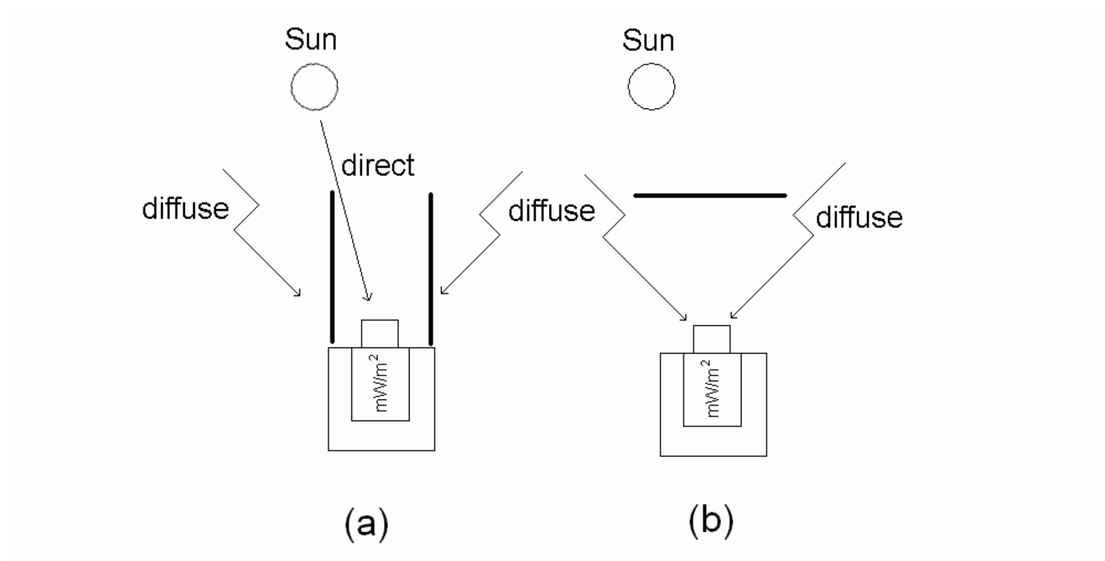

Figure 5. (a) Measurement of the direct solar ultraviolet radiation shielded by a toilet roll and (b) measurement of diffuse ultraviolet radiation. The total of (a) and (b) should be the same as a global ultraviolet measurement provided the Sun is at a sufficiently high position in the sky.

Experimental outcomes of monitoring the daily UVI

UVI forecasts monitored by students and compared to daily measurements of the *UVI* using the same process as demonstrated here provide a reference for class discussion. Students should consider the reasons why measurements of the daily *UVI* do not match the forecast, and consider why the direct solar beam, diffuse and global measurements are different from each other. They may also find that measurements of the local UVI show consistent trends not reported in the UVI forecast if monitored throughout periods of the year. This may be due to variation in local altitude, atmospheric conditions including cloud and local pollutants or the surrounding environment depending on chosen measurement sites. Students performing the activity may find that stray UV reflections and absorption from nearby buildings and surface structures influence their readings causing significant variation from the daily forecast UVI. Students wishing to study this effect may find it useful to complete the second part of the activity detailed below and completed for presentation here by students from Murgon State High School (26°S, 152°E).

Variation of the UV irradiance in local environments

Although the global UVI is easily measured by positioning the sensor in a horizontal plane relative to the ground, contributions due to surface reflection and partial absorption in the UV waveband occur due to the local surroundings. A more complete understanding of the *UVI* in a real environment can be achieved by taking measurements in all directions surrounding the measurement location. Such measurements can be used to make realistic estimates of the actual *UVI* at a given location. This is particularly important due to UV contributions made by surfaces in the local environment as such contributions are not directly measured when taking upward facing global, direct and diffuse *UVI* measurements.

The influence of the local environment on daily *UVI* was examined at three locations on 10 December 2007 within the grounds of Murgon State High School. The locations included an open environment, a tree shaded area and a large shade structure (Figure 6). At these locations, ground surfaces included, grass, bitumen, and pavers. Measurements of the reflected surface UV were taken at approximately 20 cm from the surface with the meter orientated along the surface normal. Under cloudy conditions, measurements of surface reflected *UVI* were difficult to make due to the low sensitivity of the meter, therefore each of the measurements listed in Table 2 below was the maximum recorded reflected UV found at each of the three sites.

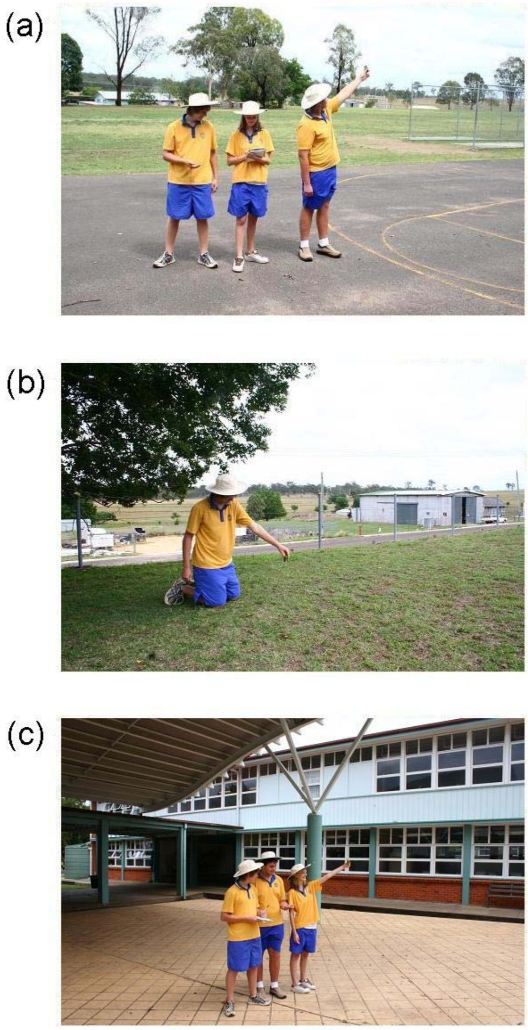

Figure 6. Year 9 Students from Murgon State High School take measurements of the environmental *UVI* at three sites in the school playground. (a) Jordan Sippel measures the *UVI* at 60^{o} elevation while facing North in an open environment. (b) Peter Laughton measures the surface reflection at a tree shaded site. (c) Fiona Schultz measures the global *UVI* under a shade structure.

Table 2. Measurements of surface reflection at three sites located within the Murgon State High School playground.

Site	Surface	UV (mW/m^2)	*UVI*
Site 1 – Tree shade	Grass	12	0
Site 2 – Open environment	Bitumen	17	1
Site 3 – Shade structure	Pavers	21	1

Variation in UV surface reflections

The surface reflection contribution to the *UVI* at each of the selected playground sites varied from between 0 and 21 mW/m^2 of erythemally effective UV. This type of measurement is known as the surface albedo and corresponds to an approximate increase in the *UVI* of between 0 and 1 at each of the tested locations. Surface contributions such as those measured here varied depending on the position of the meter sensor relative to the surface and therefore the height at which measurements of the reflected surface *UVI* are taken will have a significant impact on the recorded surface albedo. Measurements taken close to a reflecting surface will be greater than measurements taken further away. This is due both to the nature of the reflecting surface and the diffuse and direct components of terrestrial UV. For all but the smoothest surfaces, reflected direct solar UV radiation will scatter after interacting with a relatively rough surface. Furthermore, due to the scattering of short wavelength UV in air, the intensity of reflected UV will be reduced with increasing distance from the reflecting surface. Students will therefore need to consider a reasonable distance from which to take measurements of surfaces in the surrounding environment. It was found that no contribution could be measured on the day of the activity accurately beyond 20 cm from the surface. It follows that the effects of UV on humans and measuring the *UVI* will change dramatically depending on measurement position relative to the surface within a local environment however such contributions will still affect the total *UVI* at any particular site. Students may like to add the measured surface albedo to measurements of the direct solar beam, diffuse, and global *UVI* to get a better picture of the total UV that causes sunburn.

Sky Radiance

A more detailed way of examining the influence of the local environment on the *UVI* involves measurements of the *UVI* taken at various positions in altitude and azimuth where altitude is defined here as elevation above the horizon in degrees and azimuth ranges from 0^o to 360^o as specified by compass bearings. The technique that follows was adapted and modified from a more detailed technique presented by Kawanishi (2007) which involved measurements of the total sky radiance to determine the effectiveness of shade structures. Here, at each of the open, tree shade and shade structure sites, students recorded the global UVI and the *UVI* at elevations of approximately 0^o, 30^o, and 60^o facing, North, North-East, East, South-East, South, South-West, West, and North-West. A graph of the *UVI* was then produced on a simple polar plot at each of the three sites. (Figure 7). Each of the plots gives a detailed representation of the *UVI* relative to the above sky view. The effect of tree shade and the covered shade structure in plots (b) and (c) respectively is immediately obvious in the produced plots. The colour levels marked on the polar plots of Figure 6 were colour-coded according to the standardized UVI colour scale. Table 3 provides the results recorded at each of the three playground sites used to produce the plots provided in the Figure. Students were able to produce these plots on paper without difficulty.

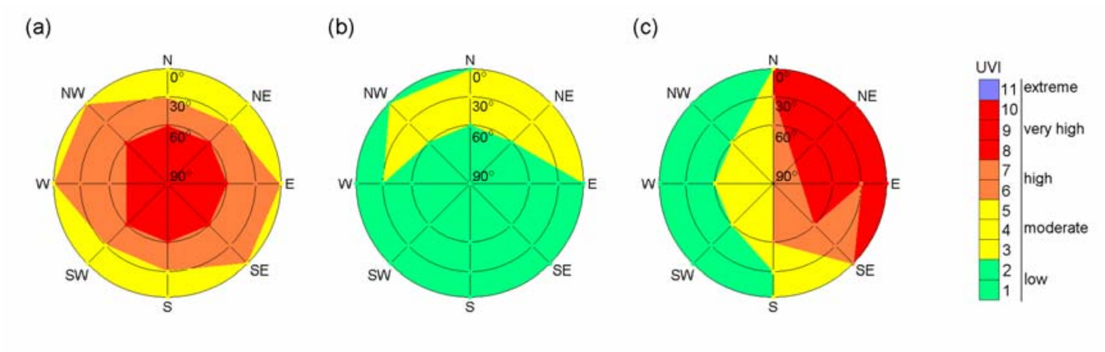

Figure 7. Sky view *UVI* determined from measurements of the *UVI* at various positions in altitude and azimuth. (a) Open Environment; (b) Tree Shade; (c) Shade Structure.

Table 3. Measurements of the *UVI* used to produce the plots above for each of the open, tree shaded and shade structure sites located at Murgon State High School. Units in the table have been converted to the dimensionless *UVI*. Measurements were taken under cloudy conditions between 9:15 am and 9:40 am on 10 December 2007.

Site 1: Open environment

	Orientation in azimuth							
Approximate Elevation	North	North-East	East	South-East	South	South-West	West	North-West
0^o	4	4	4	4	4	4	4	5
30^o	4	5	6	6	4	5	6	6
60^o	8	8	9	9	8	8	7	8
90^o (global)	9							

Site 2: Tree Shade

	Orientation in azimuth							
Approximate Elevation	North	North-East	East	South-East	South	South-West	West	North-West
0^o	2	3	1	1	1	0	2	2
30^o	4	4	2	1	1	0	2	3
60^o	2	2	1	1	1	1	2	2
90^o (global)	1							

Site 3: Shade Structure

	Orientation in azimuth							
Approximate Elevation	North	North-East	East	South-East	South	South-West	West	North-West
0^o	4	8	8	7	4	0	0	0
30^o	6	8	7	7	4	2	0	1
60^o	6	8	8	7	6	4	3	4
90^o (global)	6							

CONCLUSION

This article has provided a simple method that can be used by students to measure the *UVI* in their local environment. Variation in comparisons between the measured *UVI* and the daily UVI forecast are the result of atmospheric variations such as cloud cover and UV interaction within the local surrounding environment. In order to develop a better understanding of UV and its subsequent effects on humans, these considerations need to be taken into account. Students may find that the *UVI* in their local environment exceeds the forecast UVI. Such increases may be due to enhancements caused by cloud or surface object reflections in the UV waveband. Additionally, deficiencies in the measured *UVI* are likely to be the result of cloud and environmental absorptions as would be commonly observed in shady or covered locations. A method for examining variation in the *UVI* due to the surrounding environment under tree shade, and a specifically built shade structure has been presented. Such a technique contributes to student understanding of the UVI forecast as it relates to real environments and improves understanding of the forecast UVI prediction being the likely UV irradiance experienced in an open environment on a horizontal plane. Modifications to the forecast UVI based on analysis of the surrounding environment may prove to be useful in assessing the true UV irradiance and can be used to make better predictions of the UVI forecast as it applies to specific environments measured using the techniques presented here.

The meter used gives students the opportunity to measure the intensity of radiation beyond the visible spectrum and further extension of the activity may include the measurement of the UV irradiance emitted by other non-solar sources. The transmission and subsequent ultraviolet protection factor (UPF) of various materials, including shade cloth, clothing and polycarbonate sheeting could be measured as the ratio of the unprotected to protected UV irradiance. If quartz glass is available, the effectiveness of sunscreens may be determined if applied to adequately thin quartz glass slides. Alternatively the protection offered by glass as an absorber of UV could be investigated, as non-quartz glass is an effective absorber of UVB wavelengths.

Links to the Curriculum

Though the activities presented in this paper were not designed with any particular syllabus in mind, teachers in Queensland may find their application useful in early studies of ‘Science and Society’, and later the ‘Earth and Beyond’ strands of the Queensland core science syllabus. Significantly, no Australian syllabus makes specific mention of studies involving ultraviolet radiation physics, however teachers outside of Queensland should find the presented *UVI* measurement techniques readily applicable to the following strands of the various state science syllabi: ‘Earth and Beyond’ (WA), (ACT) & (NT), ‘Earth and Space’ (SA), ‘Earth and its Surroundings’ (NSW), ‘Physical Phenomena’ (NSW), ‘Level Three Essential Learning Standards’ (VIC), ‘Standard two – Scientific Inquiry’ (TAS), and ‘Standard three – Earth and Space’ (TAS).

In addition to the above mentioned science syllabi, the article described here presents teachers with the opportunity to explore links to scientific literacy, mathematics and information and communication technologies. In particular, the article provides students with the opportunity to develop charts and graphical information from tabulated measurements of the *UVI* collected in open and shaded environments. Students are introduced to the astronomical definitions of altitude (elevation in degrees above the horizon) and azimuth (compass bearings) and use these to construct polar plots. Students could model and make predictions about the expected solar UV irradiance based on the elevation of the Sun and based on a study of previous measurements in given environments. The activity gives students the opportunity to actively engage in the use of information and communication technologies through the use of the internet to find and use the forecast UVI. Through information and communication technologies, students can share measurements of the UVI with other schools in Australia and make further comparisons with the UVI in other parts of the world.

Acknowledgements

The authors would like to acknowledge the contribution of Highfields State School and Murgon State High School for their willingness to be involved in the *UVI* measurement activities presented in this paper. Particular thanks go to school principals Mr Craig Barron (Highfields State School) and Mr Brian King (Murgon State High School) and all of the students involved including Peter Laughton, Fiona Schultz, Jordan Sippel, Emma Thornton, and Emily Youngberry.

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