Aust. Met. Mag. 46 (1997) 203-210

Monitoring UV-B at the earth's surface

C.R. Roy, H.P. Gies and S. Toomey
Australian Radiation Laboratory, Yallambie, Victoria, Australia

(Manuscript received December 1996; revised June 1997)

High skin cancer rates, stratospheric ozone depletion and increased public interest and concern have resulted in a strong demand for solar ultraviolet radiation measurements and information. The Australian Radiation Laboratory (ARL) has been involved since the mid-1980s in the measurement of solar ultraviolet radiation (UVR) using spectroradiometers and a network of broadband detectors at 18 sites in Australia and Antarctica. Measurement locations range from tropical (Darwin, 12.4°S) to polar (Mawson, 67.6°S) and as a result there are many difficulties associated with maintenance and calibration of the network detectors and transfer of data to ensure an accurate and reliable data collection. Calibration procedures for the various detectors involve the comparison with simultaneous spectral measurements using a portable spectroradiometer incorporating a double monochromator, calibrated against traceable standard lamps. Some laboratory measurements of cosine response and responsivity are also made. Detector-datalogger systems are intercompared at the Yallambie site for a number of months before installation at another location. As an additional check on the calibrations, computer models of solar UVR at the earth's surface for days with clear sky and known ozone are compared with the UV radiometer measurements.

Introduction

Evidence of stratospheric ozone depletion has stimulated new research programs within a variety of disciplines. The demand for data on solar UVR has increased markedly and this has led many researchers to establish their own UVR measurement systems. There are often considerable difficulties and errors in using detectors on the basis of the provided characterisation data.

Australia has one of the highest incidence rates for both non-melanoma skin cancer and cutaneous malignant melanoma in the world. This, together with the publicity given to the annual large-scale ozone depletion in Antarctica has made the Australian population increasingly concerned about exposure to solar UVR.

Accurate data on the UVR levels to which the population is exposed have not been readily available and to this end the ARL solar UVR monitoring network was set up in the mid 1980s. Human exposure to solar UVR depends on factors including the ambient UVR levels, outdoor behaviour and the anatomical distribution of individual exposure for different activities (Herlihy et al. 1994; Gies et al. 1995). Data on solar UVR are required for population studies and in public educational campaigns including the daily reporting of the Global Solar UV Index (ICNIRP 1995) during summer months.

The extraterrestrial solar spectrum contains UV-C (100-280 nm), UV-B (280-315 nm) and UV-A (315-400 nm) radiation, however, due to absorption by oxygen and ozone in the upper atmosphere, no UV-C and only a small fraction of the UV-B (approximately 10 per cent) reaches the earth's surface (Fig. 1). With all other environmental factors being equal a reduction in ozone will

---

Corresponding author address: Dr C.R. Roy, Australian Radiation Laboratory, Lower Plenty Road, Yallambie, Vic. 3085, Australia.

Fig. 1 Spectral irradiance at the earth's surface for clear skies, a SZA of 5° and for three different ozone columns (270, 300 and 330 DU (Dobson Units)). The extraterrestrial spectral irradiance is also shown.

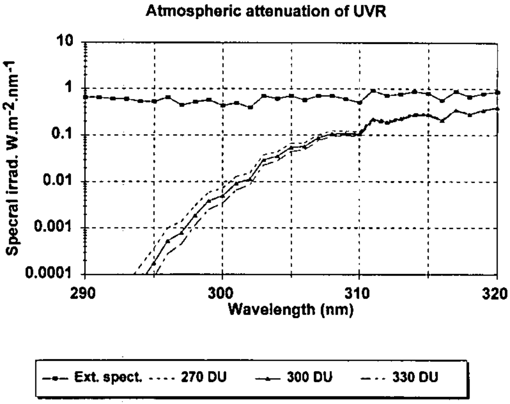


Fig. 2 Schematic of the ARL solar UVR datalogger network, showing the location of permanent measurement sites. Spectroradiometers are at Melbourne and Davis in Antarctica.

lead to an increase in solar UV-B at the earth's surface. An increase in UV-B will affect not only man but will also impact on other animal, plant and marine ecosystems. ARL is a radiation protection laboratory and it is primarily concerned with human health effects. Hence much of the data reported are related to erythemally effective radiation. A program to measure radiation of more relevance to ocular exposure is being planned.

Experimental details

The ARL solar UVR monitoring network

Detector locations include most of the capital cities, and some other major population centres (Fig. 2), and would thus cover 80 to 90 per cent of the Australian population, although differences of up to 50 per cent in daily total irradiance can occur between the inner city and outer regions because of local cloud differences (Nunez et al. 1994). Other detector sites were chosen because of current collaborative epidemiological studies or other factors such as unique climatic conditions. On-site cooperation is provided by a number of different organisations, who send data cartridges back to ARL and look after the equipment including optics cleaning and troubleshooting any minor problems. About half of the measurement units are directly linked to ARL by modem.

ARL detector systems incorporate up to four detectors from the following:

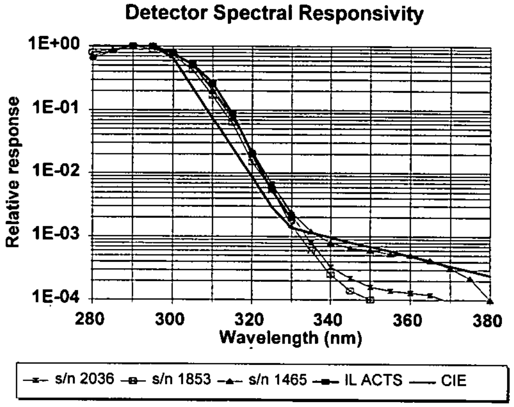
- Eppley PSP total solar radiation radiometer;
- Eppley TUV total UVR detector (290 to 400 nm);
- International Light (IL) UV-B detector (NS297~290 to 310 nm);
- International Light (IL) actinic detector (ACTS270); and
- Solar Light UV UVBiometer (model 501B).

Potentially the most accurate and precise form of UVR measurement involves spectroradiometric measurement. Spectroradiometers generally incorporate double monochromators in order to provide the necessary stray light rejection in the UV-B region. To fulfil the potential of the equipment complete characterisation and regular calibration with traceable sources is required. However, the manpower and cost of such equipment becomes prohibitive for a large network as is required in Australia. Radiometric detectors, while having limitations, such as drift and stability, departures from ideal cosine response and temperature effects, can fulfil a useful role in gathering data, especially if these limitations are carefully addressed.

Spectral responses of UVR detectors

Solar UVR contains contributions from both UV-A (>97%) and UV-B (<3%) radiation. Figure 3 shows the responses of the various UV-B detectors used in the monitoring network. The CIE erythemal effectiveness

Fig. 3 **The spectral response of the various detectors used in the ARL measurement network. The spectral effectiveness of UVR as a function of wavelength as defined in CIE (1987) is also shown.**



function (CIE 1987) is also shown. This function indicates that wavelengths in the UV-B are about 1000 times more effective at producing an erythema than wavelengths in the UV-A. In measurements of ambient solar UVR, a number of quantities are of interest, since the different wavelengths of UVR produce different effects and responses. From a human health aspect the detectors which mimic the erythemal function are the most important.

Both the IL actinic detectors and the Solar Light Model 501 UVBiometers have spectral responses similar to that of the erythemal effectiveness shown in Fig. 3, in that the detectors respond mainly to UV-B radiation but also have a lesser response to UV-A radiation. Although the spectral responsivities are similar, when convoluted with a measured spectral power distribution there can be up to a factor of two between the detector weightings and the CIE weighting. This is accounted for in the detector electronics and finally in the calibration procedure. The UV-B component of sunlight is very important, although in any spectral weighting of solar UVR with either of these effectiveness functions, UV-A still contributes approximately 20 to 30 per cent to the total summation.

Calibration

The quality of solar UVR measurements is critically dependent on the system calibration. Most UVR detectors commercially available come with a calibration or are meant to be direct reading. Often the calibration is dependent on the source being measured and it is important that all calibrations be checked.

Spectral measurements

Solar UVR spectral measurements are made using installed spectroradiometers (SRM) at Yallambie (37.8°S) and Davis (69.0°S) in Antarctica and at other locations (Australia and overseas) using a portable SRM. The PC-controlled SRM incorporates a Spex 1680B double grating monochromator. The monochromator has two 50 x 50 mm (1200 grooves mm^{-1}) gratings blazed at 250 nm, resulting in a dispersion of 1.8 nm mm^{-1} and a limiting resolution of 0.2 nm. The detector is an EMI 9653QA end-on photomultiplier tube cooled to -10°C. The current is measured with a Keithley 616 digital electrometer.

The typical dark current is 50 picoamps which results in a noise equivalent spectral irradiance of approximately 1 W m^{-2} nm^{-1} at 300 nm. Input optics consist of a 100 mm integrating sphere coupled to the DM entrance slit by a 1 m liquid light guide. The cosine response has been characterised in two planes and the error is <±10% for all solar zenith angles (SZA) up to 70°. Normal measurements are of global radiation falling on a horizontal plane. The diffuse component, when required, is determined by blocking the direct component with an occulting band. Scans are made at 1 nm intervals over the range 280-400 nm with a bandwidth of approximately 1 nm. The usual scan rate is 1 nm per six seconds and twelve data points are collected, averaged and stored before moving to the next wavelength. The slit function of the monochromator has been determined by scanning the 254 nm line from a low-pressure mercury lamp. Wavelength calibrations are made using the mercury emission lines from a low-pressure mercury lamp. The maximum error across the 280-400 nm range is ±0.1 nm. Radiation calibrations are achieved in the field using a calibrated 100 W quartz halogen lamp which is traceable via the ARL 1000 W quartz halogen standard lamps to the Australian standard held by the National Measurement Laboratory. The overall calibration accuracy is approximately ±10% which includes all systematic and statistical uncertainties associated with the irradiance calibration.

Results

Broadband detectors

To calibrate the broadband monitors the spectral measurements of incident solar UVR for clear, cloudless days are weighted with appropriate factors and compared with the simultaneous radiometric detector readings. Figure 4 shows the calibration of a UVBiometer before installation in the network. There is a strong linear correlation between the effective irradiance from the spectroradiometer and the biometer output.

Fig. 4 Calibration of a Solar Light UVBiometer against simultaneous spectral measurements, showing the relation between detector calibration and incident effective radiation (UVR_{eff}) in W m^{-2}.

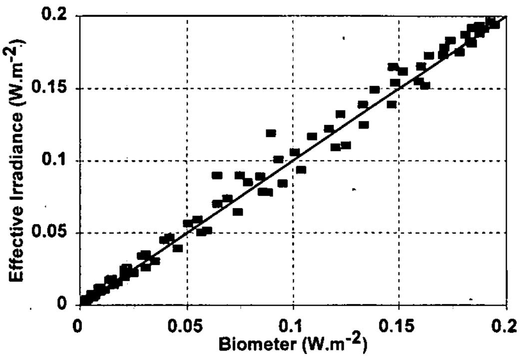


Fig. 5 Measured cosine response of three Solar Light UVBiometers and one IL UV-B detector. Data are plotted as the ratio of measured response to ideal cosine response.

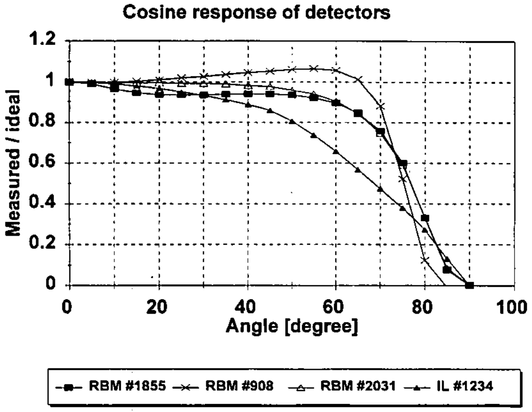
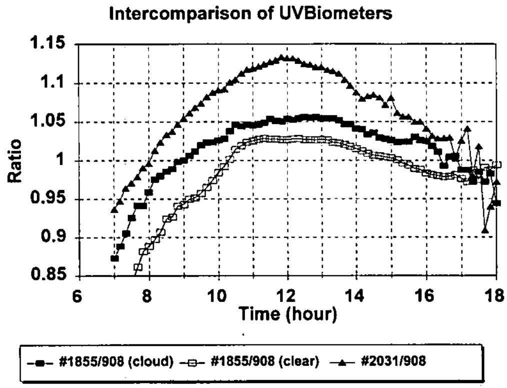


Fig. 6 Intercomparison of three UVBiometers under clear and cloudy skies.



Most detectors only approximate an ideal cosine response, and all show some departures from the ideal for small solar elevations (large SZA). Figure 5 shows the measured response for a number of detectors. The Solar Light UVBiometer clearly has a cosine response closer to the ideal than the International Light detector. As with earlier models of the UVBiometer there is a departure from both the ideal response and the manufacturer's claims. Algorithms to correct for the departure from a true cosine response are available (Seckmeyer and Bernhard 1993).

Detectors are intercompared at Yallambie before placement in the field. Figure 6 shows the intercomparison of three UVBiometers. The problems at large SZAs are quite evident in the intercomparisons. Small differences are also apparent when the diffuse/direct ratio changes in cloudy conditions. In addition, field trips to the different sites with a portable SRM system provide checks on the performance of the various detectors. Rotation of the detector-datalogger units after about three years also allows refurbishment and recalibration at ARL. The earlier version of the UVBiometer, the Robertson-Berger meter has been extensively investigated and much of that assessment is valid for the current model (DeLuisi et al. 1992; Frederick and Weatherhead 1992; Kennedy and Sharp 1992).

Spectroradiometer performance

The SRM has been intercompared in campaigns in New Zealand in 1993 (McKenzie et al. 1993) and Germany in 1994 (Seckmeyer et al. 1995). In Germany, instruments used in significant monitoring programs in Australia, New Zealand, United States of America, Antarctica and Germany were intercompared and a typical result is shown in Fig. 7. Scans from all instruments were synchronised so comparisons could be made under all weather conditions. Spectral irradiances were measured under solar zenith angles ranging from 30° to 80°. At wavelengths longer than 310 nm the spectra agreed to within ±5%. At shorter wavelengths differences were larger especially at large SZAs. Improvements in SRM performance in the 295-305 nm region is vital if data are to be used to investigate trends in UV-B resulting from changes in stratospheric ozone.

Dosimetry

Solar UVR is strongly dependent on the elevation of the sun as can be seen in Fig. 8 where the SZA varies from 53.4° to 15.1°. At a SZA of 30.1° the UV-B has dropped to 79 per cent of its value at 15.1°. At 53.4° the corresponding value has dropped to 28 per cent. Solar UVR, however, is much less dependent and the corresponding values are 86 per cent (30.1°) and 47 per cent (53.4°).

Australian UVR environment

The biologically effective UVR, denoted UVR_{eff} is obtained by weighting the UVR spectral power distribution with the CIE (1987) erythemal response function and summing over the wavelength range 280-400 nm. Assuming the minimal erythemal dose (MED) required to induce a barely perceptible erythema in people with Skin Type I (Diffey 1992) is 200 J m^{-2} of biologically effective UVR then it can be shown that under clear-sky conditions around solar noon in summer in Australia there would be approximately 5 MEDs per hour and a daily total of more than 30 MEDs. This is supported by measurements, the average daily number of MEDs for each month of 1991 is shown in Fig. 9 for five Australian cities (Gies et al. 1994).

Differences between the daily totals for each of the sites are due mainly to cloud cover and ozone, with aerosols, water vapour and particulates having some effect on measured UVR levels. The sites reported here can have very different climatic conditions. Cities south of the Tropic of Capricorn have a temperate climate, with clearer skies and warmer weather in summer. The closer the location to the equator, the more tropical the weather pattern, and the greater the influence of the summer wet season on the ambient solar UVR. While there are a number of detector sites inside the Tropic of Capricorn, only Darwin is reported here, although Brisbane's climate, with cloudy skies in summer and clear skies in winter, is more tropical than temperate. Alice Springs, in the centre of Australia, has clear skies for most of the year. Perth has long periods of cloud-free conditions in summer and as a result has higher UVR_{eff} than Brisbane which is closer to the equator. Brisbane has higher UVR_{eff} in winter, when cloud cover is less than Perth. Importantly, in all the cities shown, the amount of ambient UVR available daily in summer is well in excess of that required to induce sunburn. In Australia, for skin type I, there are ~20-30 MEDs per day in summer, in agreement with the computer model predictions.

Comparisons of the measured daily totals for Darwin (12.5°S) and Hobart (42.8°S), the two most widely separated cities, provides an interesting contrast (Fig. 10). In summer (December to February) the daily total MEDs for both cities are not too dissimilar. Hobart, in winter, has low total daily MEDs because of low solar elevation and cloud. Darwin, since it is much closer to the equator, has its wet season during summer and this can significantly affect solar UVR levels. Also, since it is inside the Tropic of Capricorn, the sun is directly overhead twice a year, once in February and once in October, and this is evident in the measurements. Figure 10 shows considerable scatter in the day-to-day solar UVR totals, reflecting the effects of varying cloud cover and, to a lesser extent, ozone.

Fig. 7 **Intercomparison of five spectroradiometers at Garmisch-Partenkirchen in southern Germany (47.48° N, 11.07° E) during August 1994. Each plot represents the ratio of a particular unit against the mean of all units.**

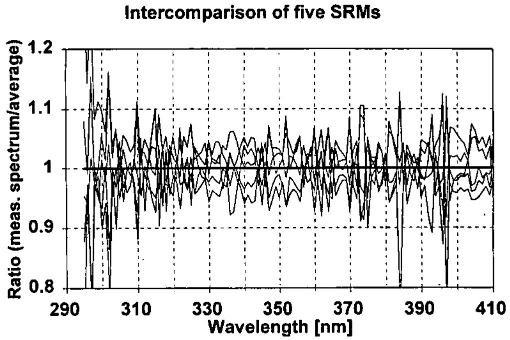


Fig. 8 **Measured solar UVR spectral power distribution (SPD) as a function of the SZA. Measurements made at Melbourne (37.8°S), Australia, during summer 1996 for SZAs of 15.1°, 30.1°, 41.6° and 53.4°.**

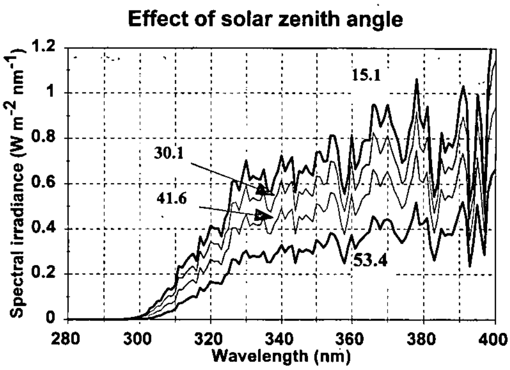


Fig. 9 **The average daily Minimal Erythemal Doses (MEDs) for each month for 1991 for Darwin (12.4°S), Alice Springs (23.7°S), Brisbane (27.5°S), Perth (32.0°S) and Melbourne (37.8°S).**

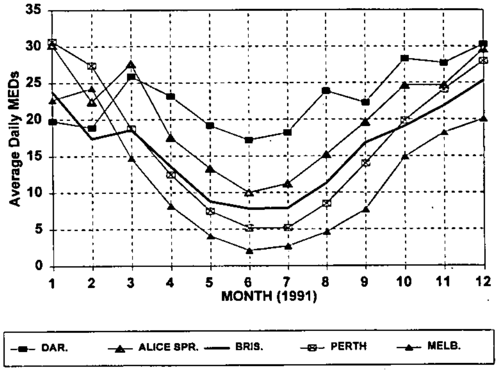
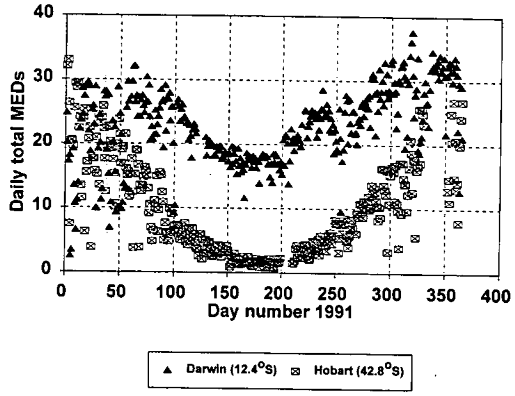


Fig. 10 Daily total MEDs for Darwin (12.4°S) and Hobart (42.8°S) for 1991.



Cloud cover

Cloud cover can have a significant and highly variable effect on ambient solar UVR and this is shown in 1996 Melbourne data in Fig. 11. The period of measurement spans only nine days and the variation of SZA and ozone was not significant. Therefore the large variations in UV-B reflect the variation in cloud cover. February 1 was virtually cloudless and the variation of UV-B throughout the day shows the classic bell-shaped curve, with high levels of UV-B around noon and a daily total of 28 MEDs. February 5 had heavy cloud and the UV-B levels remained extremely low all day and several times approached zero – the daily total was just 5 MEDs. January 27 was largely cloud-free until a front moved through during the early afternoon. UV-B levels then dropped to almost zero at times. On days with scattered cloud the effect on the UV-B levels is of rapid fluctuations from very low to high (virtually identical to the clear sky levels) within a few minutes. Under these conditions clear-sky values can even be exceeded as some radiation can be rescattered from cloud edges and returned to the surface. We have measured increases of up to 15 per cent while it has been reported that cumulus clouds have increased UV-B by more than 25 per cent on occasions (Mims and Frederick 1994).

On average, the Australian cities where measurements are made receive about 75 per cent of the clear-sky irradiance. The ratio $UV_{meas.}/UV_{clear}$ is shown in Fig. 12 for the five cities represented in Fig. 9. Alice Springs, in central Australia, has an annual average of 85-90 per cent while Perth would have that average during summer. It is clear that any long-term change to existing cloud patterns can potentially have a greater impact than stratospheric ozone depletion.

Fig. 11 The variation in measured UV-B (in MEDs) for three days in January/February 1996 in Melbourne. The daily total MEDs is shown in parenthesis in the legend.

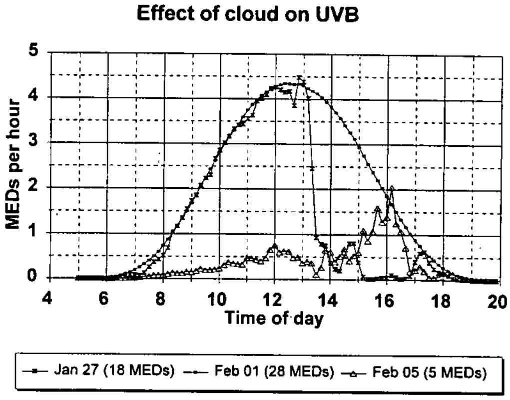
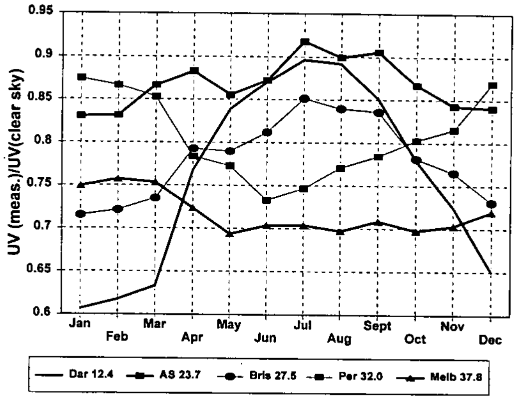


Fig. 12 The ratio UV(meas.)/UV(clear) for 1991 for the five cities represented in Fig. 9.



Ozone – UV-B relationship

The effect of ozone on UV-B can be seen by plotting the ratios UV-B(meas.)/UV-B(mean) and O_3(meas.) /O_3(mean) against time of year. The ratio removes the solar zenith angle effect and minimises the effect of cloud. The expected anticorrelation can be seen clearly in Fig. 13. Using only cloud-free days would illustrate the relationship more clearly and would enable a quantification of the relationship between UV-B and O_3.

The effect of small changes in the total ozone column on the UVR at the earth's surface can be seen in Fig. 1. The spectral irradiance was calculated for different total

Fig. 13 Relationship between solar UV-B and ozone over a period of 30 months from early 1989 to late 1991. Ratio refers to the measured value over the long-term average value.

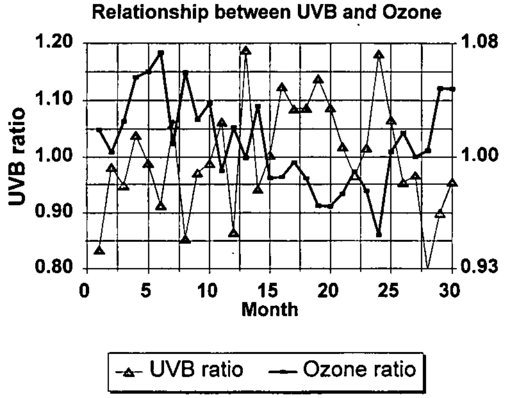
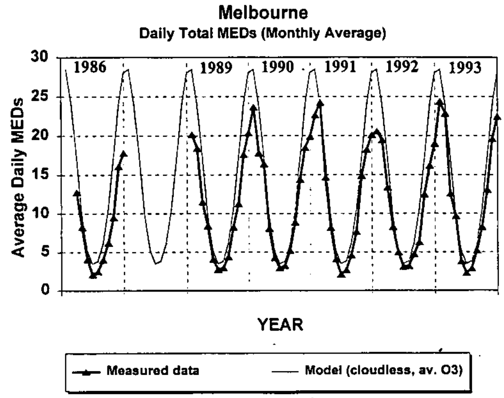


Fig. 14 The average daily total MEDs (as a monthly average) measured in Melbourne over the period 1986 to the end of 1993. The computed clear sky data based on average ozone is also presented.



ozone using an ARL-modified version of the Björn (1989) model. The decrease in the ozone column from 300 to 270 Dobson Units (DU) resulted in UV-B increasing by 95%, 20% and <5% for the wavelengths of 295, 305 and 315 nm, respectively. Overall the 10% decrease in ozone results in about a 10% increase in total UV-B (280-315 nm).

Long-term Melbourne data

Figure 14 shows the monthly average daily total MEDs for Melbourne for the period 1986 to the end of 1993. Over the period shown the average annual total MEDs was 4240±240. Trend analysis will be attempted on deseasonalised data (Bodeker 1995) when the archive is up to date for all sites. Lubin and Jensen (1995) have predicted that based on current ozone depletion rates and the fact that interannual cloud variability is small then trends in erythemal UVR should be statistically significant with respect to cloud cover by the year 2000.

Conclusions

Australia has high ambient levels of solar UVR due to its location, relatively clear and unpolluted skies and lower levels of stratospheric ozone (compared with central Europe and parts of North America). Accurate quantification of these ambient levels and subsequent trend analyses depends crucially on the characterisation and calibration of the detectors used for measurement. Intercomparisons of spectroradiometers and broadband detectors allow direct comparison of datasets from National networks.

Acknowledgments

We gratefully acknowledge the cooperation of the following organisations in the maintenance of monitoring equipment at locations outside of Melbourne: The Australian Antarctic Division, Bureau of Meteorology, Cancer Council of NSW, James Cook University, National Science and Technology Centre, South Australian Health Commission, Sugar Research Institute, Telecom, University of Southern Queensland and the University of Tasmania.

References

Björn, L.O. 1989. Computer programs for estimating ultraviolet radiation in daylight. In *Radiation Measurement in Photobiology* (B.L. Diffey, editor), Biological Techniques Series, Academic Press, London.

Bodeker, G.E. 1995. Trends in total column ozone over Australia and New Zealand and its influence on clear-sky surface erythemal irradiance. *Radiation Protection in Australia, 13*, 39- 49.

CIE 1987. CIE Research Note. A reference action spectrum for ultraviolet induced erythema in human skin. *CIE J., 6*, 17-22.

DeLuisi, J., Wendell, J. and Kreiner, F. 1992. An examination of the spectral response characteristics of seven Robertson-Berger meters after long-term field use. *Photochem. Photobiol., 56*, 115-22.

Diffey, B.L. 1992. Stratospheric ozone depletion and the risk of non-melanoma skin cancer in a British population. *Physics in Medicine and Biology, 37*, 2267-79.

Frederick, J.E. and Weatherhead, E.C. 1992. Temporal changes in surface ultraviolet radiation: A study of the Robertson-Berger meter and Dobson data records. *Photochem. Photobiol., 56*, 123-31.

Gies, H.P., Roy, C.R., Toomey, S., Maclennan, R. and Watson, M. 1995. Solar UVR exposures of three groups of outdoor workers on the Sunshine Coast, Queensland. *Photochem. Photobiol., 62*, 1015-21.

Gies, H.P., Roy, C.R., Toomey, S. and Tomlinson, D. 1994. The ARL solar UVR measurement network: Calibration and results. *Ultraviolet Technology V, SPIE, 2282*, 274-84.

Herlihy, E., Gies, H.P., Roy, C.R. and Jones, M. 1994. Personal dosimetry of solar UVR for different outdoor activities. *Photochem. Photobiol., 60,* 288-94.

ICNIRP (International Commission on Non-Ionizing Radiation Protection) 1995. *Global Solar UV Index.* ICNIRP, Germany.

Kennedy, B.C. and Sharp, W.E. 1992. A validation study of the Robertson-Berger meter. *Photochem. Photobiol., 56,* 133-41.

Lubin, D. and Jensen, E.H. 1995. Effects of clouds and stratospheric ozone depletion on ultraviolet radiation trends. *Nature, 377,* 710-13.

McKenzie, R.L., Kotkamp, M., Seckmeyer, G., Erb, R., Roy, C.R. Gies, H.P. and Toomey, S.J. 1993. First Southern Hemisphere intercomparison of measured solar UV spectra. *Geophys. Res. Lett., 20,* 2223-6.

Mims, F.M. and Frederick, J.E. 1994. Cumulus clouds and UV-B. *Nature, 371,* 291.

Nunez, M., Forgan, B. and Roy, C. 1994. Estimating ultraviolet radiation at the earth's surface. *Int. J. Biometeorol., 38,* 5-17.

Seckmeyer, G. and Bernhard, G. 1993. Cosine error correction of spectral-irradiances. In: *Atmospheric Radiation. SPIE, 2049,* 140-51.

Seckmeyer, G., Mayer, B., Bernhard, G., McKenzie, R.L., Johnston, P.V., Kotkamp, M., Booth, C.R., Lucas, T., Mestechkina, T., Roy, C.R., Gies, H.P. and Tomlinson, D. 1995. Geographical differences in the UV measured by intercompared spectroradiometers. *Geophys. Res. Lett., 22,* 1889-92.