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A simple device for the evaluation of the UV radiation index

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The solar ultraviolet radiation (UV) flux density at the earth's surface depends on the incoming solar energy and the transmission properties of the atmosphere. UV radiation is strongly absorbed by ozone in the spectral range 200–310 nm, while the attenuation is increasingly weaker at longer wavelengths. Following the discovery of the Antarctic ozone hole in 1985, the risk of a possible UV increase at ground level, due to the observed stratospheric ozone depletion, has heightened the interest within the scientific community given the potentially harmful effects on terrestrial and aquatic ecosystems. Spectroradiometers, broad-band meters and dosimeters may be used for measurements of solar UV. In addition, radiation transfer models can be used to quantify UV irradiances at various times and locations, provided that the extraterrestrial solar radiation and the state of the atmosphere are known. Information about UV radiation at the earth's surface is given by the ultraviolet index 'UVI', which is defined as the effective integrated irradiance (280–400 nm) weighted by the erythemal action spectrum. The UV Index is widely used by many international weather services as an indicator of UV levels at the earth's surface providing public awareness of the effects of prolonged exposure to the sun's rays.

The aim of this paper is to present a device capable of estimating the UV Index. This device is a compact disc, used as a sundial, and is based on modelled UV irradiances derived from the STAR radiative transfer model (System for Transfer of Atmospheric Radiation). The device was tested in an urban setting under clear sky conditions.

1. Introduction

The ultraviolet radiation (UV) region is the part of the solar spectrum, characterised by wavelengths in the range 200–400 nm, that accounts for a small fraction of the total flux density that reaches the earth's surface. According to the Commission Internationale d'Eclairage (CIE), the UV region is subdivided into UVC (200–280 nm), UVB (280–315 nm) and UVA (315–400 nm). The UVC component is completely absorbed by atmospheric constituents such as oxygen, ozone and trace species. The UVB region is strongly dominated by ozone absorption while the UVA radiation is weakly affected by ozone. The UV radiation relevant to environmental biology is restricted to the combined UVB and UVA ranges (Madronich 1993).

The amount of solar ultraviolet radiation reaching the earth's surface depends on the amount of incoming solar energy, the transmission properties of the atmosphere and the properties of the surface. Astronomic, geometric and atmospheric factors play an important role in controlling the day-to-day changes and seasonal and annual variations. Some of the atmospheric factors in turn may have time-dependent behaviour characterised by trends or long period fluctuations. These factors are studied using measurements and modelled data which indicate that the UV radiation reaching the surface is mainly controlled by the absorptive power of ozone and molecular oxygen in the stratosphere. After the discovery of the Antarctic ozone hole in 1985, solar UV radiation has become an important environmental, ecological and atmospheric parameter to be studied and measured (Webb 1988).

The relationship between UV radiation and biological effects has been well established (UNEP 1998). It is known that exposure to UV radiation can have a detrimental (acute and chronic) effect on unprotected skin and/or eyes with deterministic or stochastic characteristics (Mariutti 2001). The acute reactions consist of sunburn, tanning and snow blindness (when the eyes are exposed to UV radiation coming from unusual directions). Photo-ageing, skin cancer and cataracts represent the chronic reactions caused by prolonged UV exposure. The incidence of skin cancer has increased over recent decades as travel to lower latitudes, fashion and increased leisure time have contributed to changing habits and patterns by humans resulting in increased cumulative exposure to sunlight (UNEP 1998; Webb 1998).

Furthermore, UV radiation can produce deleterious effects in animal, marine and plant life. Several studies have shown that UV radiation is damaging to a variety of aquatic organisms mainly phytoplankton, which represent the base of the aquatic food web (Smith 1995). The effects of UV-B radiation on plants varies widely from species to species, within species and with respect to other conditions of growth (Tevini & Teramura 1989).

It is important to provide relevant information to the public about the potential detrimental effects on health from overexposure to UV radiation. For this purpose, UV levels can be expressed as a dimensionless UV Index used for providing information on UV exposure levels and to help the public adopt suitable sun exposure habits (WMO 1994, 1997).

Many countries have established UV Index programmes for next-day forecasting of the amount of skin damaging UV radiation when the sun is highest in the sky (solar noon). For instance, in 1992 the Atmospheric Environmental Service of Canada (now Meteorological Service of Canada) began issuing the Canadian UV Index based on an empirical relationship between the total UV flux at the surface and total ozone under clear sky conditions (Wilson 1993). The US Environmental Protection Agency along with the National Weather Service issued an ultraviolet index forecast similar to that of Canada in 1992 (Long et al. 1996). In Europe, several forecasting institutions release UV Index values (COST-713, 2000). In the UK, the UV Index is estimated from total ozone prediction (Austin et al. 1994).

In this paper, the UV Index was determined by means of a radiative transfer model, using atmospheric and meteorological parameters characteristic of an urban site. A comparison between modelled and observed UV Indexes was performed at Rome. The modelled index values were used together with a simple device to determine the UV Index under clear sky conditions. The device is a compact disc, which is used to determine the sun's co-ordinates (azimuth, altitude angle and hour angle). It works as an instrument for evaluating the UV Index when a conversion from the sun's co-ordinates into time is performed.

2. The data set

Direct measurements of surface UV radiation and total ozone have been carried out since 1992 at Rome (latitude 41.9°N; longitude 12.5°E; altitude 60 m) using a Brewer spectrophotometer. The Brewer MKIV No.067, located at the Physics Department at Rome University 'La Sapienza' (in the centre of the city), is a single monochromator spectrophotometer designed to measure total ozone, nitrogen dioxide, sulphur dioxide and global spectral irradiance in the ultraviolet region of the solar spectrum (290–325 nm). Daily UV spectral scans are obtained at increments of 5° in the solar zenith angle and near local noon with a spectral resolution of 0.5 nm steps. About 20 scans per day are available spanning the entire year. Regular controls and tests ensure the proper functioning of the instrument. The absolute UV calibration is performed yearly using a 1000 W lamp, traceable to the standards of the National Institute of Standards and Technology (NIST), and the responsivity is checked periodically by the 50 W lamps tests. The accuracy of the UV Brewer measurements have been estimated at close to 5–7% (Casale et al. 2000).

Clear sky UV Indexes determined from UV measurements for the years 1999 and 2000 were included to produce a comparison with the modelled UV Indexes. The UV irradiances were extended to 400 nm using the appropriate Brewer program that provides for the non-measured part of the UVA spectrum (i.e. irradiances at wavelengths longer than 325 nm) (SCI-TEC 1998).

A characterisation of the Rome site in terms of surface type, atmospheric parameters (aerosol load, visibility, vertical aerosol extinction profile, aerosol type, gases such as total ozone and nitrogen dioxide), and meteorological parameters (pressure, temperature and humidity at the surface and their respective vertical profiles) is described in Casale et al. (2000) and Meloni et al. (2000).

The monthly mean ozone (Dobson) time series (1957–1986) of Vigna di Valle (50 km north of Rome) was used as input in the model as a reference series for Rome because, from a climatological point of view, the data record is longer and better represents ozone behaviour in comparison with the Brewer station.

3. Methodology for the evaluation of UV Index

The UV Index is calculated as the biologically weighted irradiance using the CIE erythemal action spectrum (McKinlay & Diffey 1987), integrated up to 400 nm and divided by 25 mWm^{-2} (Cost-713, 2000). Using this approach, the calculated UV Index values can range between 0 (during the night) and 15 or 16 (in the tropics under clear skies at high elevations).

Estimation of the UV Index can be obtained from irradiance measurements made with broad-band instruments that have a spectral response matching skin erythemal or by using spectroradiometers to measure the spectra. Calculations of the UV Index can be also achieved by means of radiative transfer models provided that the extraterrestrial solar radiation and the state of the atmosphere of the site are known (Webb 1998).

In this study, the System for Transfer of Atmospheric Radiation (STAR) model (Ruggaber 1994) was used to calculate spectral irradiances from 280 to 400 nm with 1 nm wavelength steps (in the spectral range from 280 to 325.5 nm) and with 2 nm wavelength steps (in the spectral range from 327 to 400 nm). The irradiances were then weighted by the erythemal action spectrum, so that the UV Index was estimated, at the Rome site, under cloud-free conditions. The STAR model is a multiple scattering model based on matrix operator theory. The inhomogeneity of the atmosphere is taken into account by considering 33 layers in which scattering and absorption are described by optical depth and mixed phase functions of molecules, droplets and particles. Results of previous testing and verification of the STAR model are presented in Casale et al. (2000) and Meloni et al. (2000).

In order to build up the series of UV Index values as a function of solar zenith angles (SZA), the model was run through the spring and summer months (from April to September) with the SZA ranging between 18.4° (summer solstice in June) and 90°. As input, all climatological, atmospheric and meteorological parameters available for the selected months were considered.

When data such as vertical profiles of pressure, temperature, relative humidity and atmospheric constituents were not available, the STAR model was used with the US Standard profiles as input. According to d'Almeida et al. (1991), on the basis of the atmospheric pollutant content, the Rome site was classified as an urban area, i.e. highly polluted. Ground albedo was computed as the mean value for a mixture of asphalt, concrete and vegetation.

In order to model the highest UV levels, the STAR code was run using the minimum monthly ozone mean values from the Dobson time series of the Vigna di Valle station as input.

The uncertainties on modelled irradiances were first estimated as a function of SZA following Schwander et al. (1997) and then at double these values to determine a more accurate error on the final UV Indexes. This was done because the calculation was made by varying the ozone mean content and the solar zenith angle, but ignoring the different aerosol conditions that could be expected to be predominant in summer, when clear sky days are more frequent. In fact, it was shown that using only the aerosol amount variations in the calculation of the UV Index can produce similar results as in the small ozone changes (Koepke et al. 1998).

Table 1 reports the modelled UV Indexes as a function of solar zenith angles at Rome. Clear sky modelled UV Indexes were compared with those obtained by the Brewer UV measurements. This comparison was obtained for the years 1999 and 2000 when more UV observations were available. Typical values of the UV Index for the Rome site range between 3 and 8 during summer. The average percentage differences (measured-modelled)/measured, were calculated at the following zenith angles (Table 1 below):

20° (May–July); 25° (May–August); 30° (April–August) and from 35° to 70° (April–September). The results are shown in Table 2. For SZA above 30° the percentage differences are positive (ranging from 1.54% to 10.27%). Below SZA = 30° the percentage differences are negative reaching –9.31 at 25° SZA. The modelled UV Index is greater than the measured value (+1 UV Index unit) at low SZA, while it decreases by 1 UV Index unit at high SZA. This discrepancy between modelled and measured indexes could be partly due to the aerosol loading and its vertical profile that are not correctly quantified in the model (Meloni et al., 2000). The effect of an enhanced aerosol amount is strong absorption of the solar direct radiation at high zenith angles (hence the model underestimates the measured amount). At high SZA the longer solar path through the atmosphere could explain the underestimation by the model, which does not accurately describe the structure of the lower troposphere.

Table 1. *Monthly distribution of UV Index as a function of Solar Zenith Angle (SZA) and solar altitude angle (h) at Rome*

SZA	h	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
20°	70°					6.46	6.50	6.82					
25°	65°					5.88	5.92	6.21	6.39				
30°	60°				5.00	5.23	5.26	5.52	5.68				
35°	55°				4.34	4.53	4.56	4.78	4.92	5.01			
40°	50°			3.92	3.76	3.92	3.95	4.13	4.25	4.33			
45°	45°			3.11	2.99	3.11	3.13	3.28	3.37	3.43	3.58		
50°	40°		2.62	2.52	2.42	2.52	2.54	2.65	2.72	2.77	2.89		
55°	35°		1.98	1.91	1.83	1.91	1.92	2.00	2.06	2.09	2.18	2.19	
60°	30°	1.48	1.45	1.42	1.36	1.42	1.42	1.48	1.52	1.55	1.61	1.61	
65°	25°	1.01	1.00	0.97	0.94	0.97	0.98	1.01	1.03	1.05	1.09	1.10	1.08
70°	20°	0.65	0.64	0.63	0.61	0.63	0.63	0.65	0.66	0.67	0.70	0.70	0.70

Table 2. *The average percentage differences (measured-modelled)/measured, at different zenith angles (1999–2000) for clear sky conditions.*

SZA	h	Average percentage differences (%)
20°	70°	–6.51
25°	65°	–9.31
30°	60°	–2.31
35°	55°	1.54
40°	50°	4.19
45°	45°	7.08
50°	40°	5.61
55°	35°	10.27
60°	30°	9.68
65°	25°	8.76
70°	20°	8.60

In addition, a comparison of daily maximum index values was also made on a monthly basis under cloud-free conditions. The modelled UV Index underestimates the UV Indexes obtained by the Brewer measurements. For each month the average percentage difference over the whole period is +7.2% meaning that the modelled UV Indexes are +1 unit lower than the measured values.

4. A device to estimate UV Index

A compact disc (CD) is an excellent and inexpensive reflective diffraction grating if the sun is used as a source of light because it shows thin radial lines when illuminated. As explained by Catamo & Lucarini (1999), using the CD allows the sun's co-ordinates (azimuth, altitude angle and hour angle) to be measured, and it can work as a sundial if a conversion into time is then operated. The azimuth was chosen, among the sun's co-ordinates, and it is precisely read on the CD's graduated edge when:

(a) it is used in the horizontal position;
(b) the zero of the azimuth is in the south direction;
(c) the observer's eye is perpendicular to the centre of the compact disc.

Conditions (a) and (b) can be easily met using a circular level and a simple compass, while the third condition needs a mirror, located in the centre of the compact disc, where the operator's eye is exactly reflected.

A spherical trigonometry relationship allows the transformation of the sun's azimuth into altitude angle at a fixed latitude (i.e. a parallel on the earth's surface is

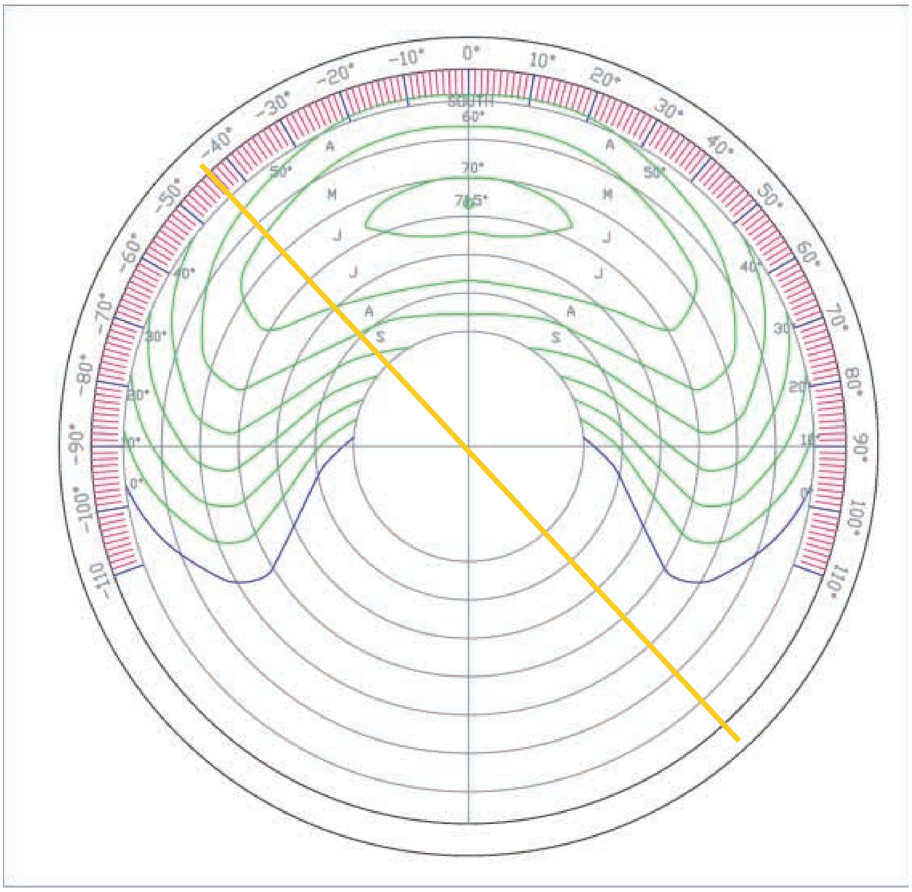

Figure 1. *The CD used a sundial for measuring the sun's co-ordinates at a fixed latitude (42°). The azimuth is read at the edge and each corona corresponds to a different month (in this application six months, i.e. from April, A, to September, S). Each green line represents the 'isogone' of each altitude angle of the sun (10°, 20° and so on). The minimum value of altitude angle is 0° (blue line) while the maximum is about 72° (summer solstice). The orange line represents an example of the diffraction trace ray due to the sun's light. In the figure the diffraction line indicates –43° as azimuth and 60° as altitude angle on 1 August (chosen as an example).*

chosen) and solar declination angle (i.e. a date is selected) as given in Equation 1:

$$\cos Az = \pm \frac{\sin(h)\sin\phi - \sin\delta}{\cos(h)\cos\phi} \qquad (1)$$

where Az is the azimuth, h is the altitude angle of the sun, ϕ is the latitude of the site and δ the declination angle of the sun.

Using the CD, the sun's azimuth reading can be converted into the sun's altitude angle reading in the following way (Figure 1):

1. The CD surface was divided into coronas, each corresponding to a different month (in this case six months, i.e. from April to September). Each day is represented by a coronal radius that is related to the declination angle of the sun (Catamo & Lucarini 1999).
2. Predetermined values of altitude angle, for example 10°, 20° and so on, were introduced into the formula until the maximum summer solstice altitude angle was achieved for the selected latitude and suitable δ values – a series of azimuth angular values – were obtained.
3. With the polar co-ordinates defined (that is, the distance from the CD centre and the azimuthal angular values), these values were transferred onto the CD. The computed points referring to the same altitude angle were joined with a continuous curve, which is the 'isogone' of each altitude angle of the sun (10°, 20° and so on).

The diffraction line, indicating the sun's azimuth at the same time, refers the sun's altitude angle at the observation instant. The altitude angle is given by reading the curve intersected by the diffraction line at the observation date.

If this parameter were the only factor in determining the risk of sunburn, the CD with the indication of solar altitude angle could be considered as a helpful personal advisory instrument during solar exposure. In fact, several factors influence the transmission of the sun's radiation through the atmosphere in addition to the geometrical ones (latitude, longitude, altitude and the sun's altitude angle). The atmospheric contributions from ozone, trace gases, aerosols, albedo and clouds also need to be considered.

In order to take into account the dependence of ultraviolet radiation on different atmospheric conditions,

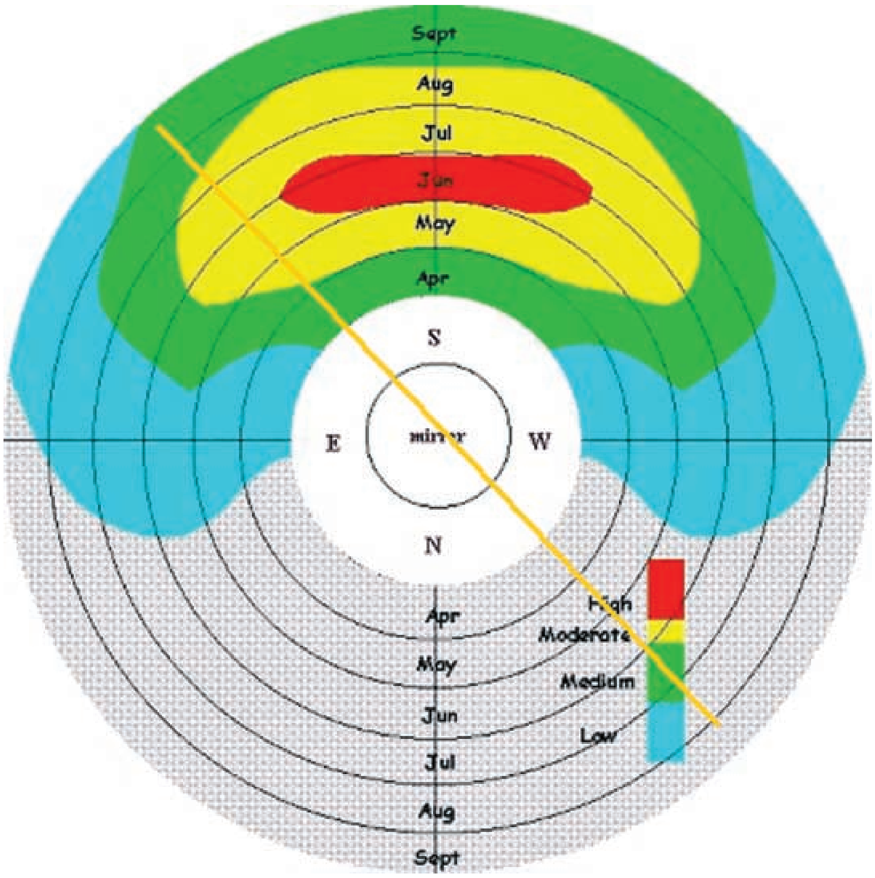

Figure 2. *The CD on which the 'isoUVI' were plotted. The UV Index distribution was divided into four classes for average photosensitivity (COST-713, 2000): low (0–2), medium (3–4), moderate (5–6), and high (>7). The orange line represents an example of the diffraction trace ray due to the sun's light. In the figure the same diffraction line from Figure 1 is reported, showing a moderate UV Index value for 1 August (see also Table 1 for h = 60° and the month of August). In this example, the discrepancy with the Brewer measured UVI is around 2 % (see Table 2).*

the isogones were corrected and converted into similar lines of UV Index values, named 'isoUVI' (see Table 1). This can be performed if each point of the isogones, giving the sun's altitude angle for any day of the month, yields a proper value of the UV Index obtained by means of the STAR model.

Figure 2 shows the CD on which the 'isoUVI' values were plotted. Due to the direct relationship between the sun's altitude angle and the UV Index, the six months from April to September now proceed from the centre to the edge of the CD. The UV Index distribution was divided into four classes for average skin photosensitivity (COST-713, 2000): low (0–2), medium (3–4), moderate (5–6), and high (>7). Each class is characterised by a different colour: light blue (low), green (medium), yellow (moderate) and red (high). Maximum values are reached during the summer owing to the combination of geometrical (Figure 1) and atmospheric factors.

5. Conclusions

The purpose of this study was to propose the use of a commonly available device such as a compact disc (CD) to estimate UV levels at the earth's surface under clear sky conditions. A sophisticated radiative transfer model (the STAR model), with climatological atmospheric parameters of a Rome site as input, was used to provide a series of UV Indexes as a function of solar zenith angles under clear sky conditions. The next step was to create a sundial by using a CD to estimate the value of the UV Index at a given time. The most important limitation is that each CD is linked to a fixed site (or, at most, to a narrow range of latitudes and altitudes). In this case the choice of latitude 42°N (Rome) was taken as the reference value for the Italian peninsula and it can be used in all Italian urban sites below 100 m. The advantage of the device is twofold: (i) the sun's altitude angle is directly determined, and (ii) the observation does not depend on the local time.

It is important to note that the sundial should not be considered as an instrument yielding absolute UV values. This would require a thorough validation and more input parameters in the model, which was not contemplated by this research.

From the point of view of radiation, the device is intended as a tool for personal use with the aim of informing people about UV intensity, hoping to induce change in their solar exposure habits. Moreover, there are no foreseen difficulties in providing different CDs suited to each skin phototype.

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References

Austin, J., Barwell, B. R., Cox, S. J., Hughes, P. A., Knight, J. R., Ross, G., Sinclair, P. & Webb, A. R. (1994) The diagnosis and forecast of clear sky ultraviolet levels at the earth's surface. *Meteorol. Appl.* **1**: 321–336.

Casale, G. R., Meloni, D., Miano, S., Siani, A. M., Palmieri, S. & Cappellani, F. (2000) Solar UV-B irradiance and total ozone in Italy: fluctuations and trends. *J. Geophys. Res.* **105**: 4895–4901.

Catamo, M. & Lucarini, C. (1999) Light as shadow – sundials without gnomons. *Compendium, J. N. Am. Sundial Society* **3**: 19–23.

COST-713 Action (2000) *UV Index for the Public*. European Communities, Brussels, 27 pp.

d'Almeida, G. A., Koepke, P., Shettle, E. P. (1991) *Atmospheric Aerosols: Global Climatology and Radiative Characteristics*. Deepak, Hampton, Virginia.

Koepke, P., Bais, A., Balis, D., Buchwitz, M., De Backer, H., De Cabo, X., Eckert, P., Eriksen, P., Heikkila, A., Koskela, T., Lapeta, B., Litynska, Z., Lorente, J., Mayer B., Renaud, A., Ruggaber, A., Schauberger, G., Seckmeyer, G., Seifert, P., Schmalwieser, A., Schwander, H., Vanicek, K. & Weber, M. (1998) Comparison of models used for UV Index Calculations. *Photochem. Photobiol.* **67(6)**: 657–662.

Long, C. S., Miller, A. J., Lee, H. T., Wild, D. J., Przywarty, R. C. & Hufford, D. (1996) Ultraviolet index forecasts issued by the National Weather Service. *Bull. Am. Met Soc.* **77(4)**: 729–748.

Madronich, S. (1993) The atmosphere and UV-B radiation at ground level. In: *Environmental UV Photobiology*, ed. A. R. Young et al., Plenum Press, New York, pp. 1–39.

Mariutti, G. (2001) Come si affronta il problema della protezione dalla radiazione ultravioletta. In: *La radiazione solare ultravioletta,* ed. S. Palmieri. Cuen, Napoli, Italy pp. 146–158.

McKinlay, A. F. & Diffey, B. L. (1987) A reference action spectrum for ultraviolet induced erythema in human skin. In: *Human Exposure to Ultraviolet radiation: Risks and Regulations*, ed. W. R. Passchler & B. F. M. Bosnajokovic, Elsevier Publishers, Amsterdam.

Meloni, D., Casale, G. R., Siani, A. M., Palmieri, S. & Cappellani, F. (2000) Solar UV dose patterns in Italy. *Photochem. Photobiol.* **71(6)**: 681–690

Ruggaber, A., Dlugi, R. & Nakajima., T. (1994) Modelling radiation quantities and photolysis frequencies in the troposphere. *J. Atmos. Chem.* **18**: 171–210.

Schwander, H., Koepke, P. & Ruggaber, A. (1997) Uncertainties in modelled UV irradiances due to limited accuracy and availability of input data. *J. Geophys. Res.* **102**: 9419–9429.

SCI-TEC (1998) *Brewer MKIV Spectrophotometer*. Operator's Manual, SCI-TEC Instruments Inc.

Smith, R. C. (1995). Ozone, middle ultraviolet radiation and the aquatic environment. *Photochem. Photobiol*. **50**: 459–468.

Tevini, M. & Teramura, A. H. (1989) UV-B effects on terrestrial plants. *Photochem. Photobiol*. **50**: 479–488.

US Government (1976) *US Standard Atmosphere*. US Government Printing Office, Washington DC, NOAA-S/T 76–1952.

UNEP (United Nations Environment Programme) (1998) *Environmental Effects of Ozone Depletion: 1998 Assessment*. Elsevier, 103pp.

Webb, A. (1998) *Solar UVB Instrumentation and Applications*. Gordon and Breach Science Publishers, Amsterdam, 104pp.

Wilson, L. J. (1993) *Canada's UV Index: How It Is Computed and Disseminated*. Environment Canada, Atmospheric Environment Service, 3pp.

WMO (1994) *Report of the WMO Meeting of Experts on UV-B Measurements, Data Quality and Standardization of UV Indices*, Les Diablerets, 25–28 July, 1994, GAW, Report no. 95, Geneva.

WMO (1997) *Report of the WMO-WHO Meeting of Experts on Standardization of UV Indices and their Dissemination to the Public*, Les Diablerets, 21–24 July, 1997, GAW, Report no. 1997, Geneva.