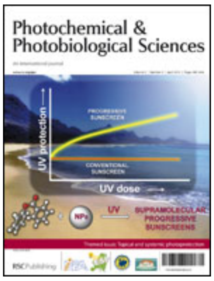

This article is published as part of a themed issue of ***Photochemical & Photobiological Sciences*** on

Topical and systemic photoprotection

Published in **issue 4, 2010**

Behaviour and measurement

Topical photoprotection

Systemic photoprotection

Comparison between UV index measurements performed by research-grade and consumer-products instruments

Marcelo de Paula Corrêa,[a,b] Sophie Godin-Beekmann,[a] Martial Haeffelin,[c] Colette Brogniez,[d] Franck Verschaeve,[a] Philippe Saiag,[e,f] Andrea Pazmiño[a] and Emmanuel Mahé[e,f]

Received 30th November 2009, Accepted 3rd February 2010
First published as an Advance Article on the web 19th March 2010
DOI: 10.1039/b9pp00179d

Ultraviolet radiation (UVR) exposure, skin cancer and other related diseases are not just subjects of scientific literature. Nowadays, these themes are also discussed on television, newspapers and magazines for the general public. Consequently, the interest in prevention of sun overexposure is increasing, as the knowledge of photoprotection methods and UVR levels. The ultraviolet index (UVI) is a well-known tool recommended by the World Health Organization to avoid harmful effects of UV sunlight. UVI forecasts are provided by many national meteorological services, but local UVI measurements can provide a more realistic and appropriate evaluation of UVR levels. Indeed, as scientific instruments are very expensive and difficult to manipulate, several manufacturers and retail shops offer cheap and simple non-scientific instruments for UVI measurements, sometimes included in objects of everyday life, such as watches, outfits and hand-held instruments. In this work, we compare measurements provided by several commercial non-scientific instruments with data provided by a Bentham spectrometer, a very accurate sensor used for UV measurements. Results show that only a few of the instruments analyzed provide trustworthy UVI measurements.

Introduction

Ultraviolet radiation (UVR) overexposure has long been known to be a risk factor for skin cancers, such as malignant melanoma and basal and squamous carcinomas,[1,2] cataracts,[3] immunodepression,[4,5] and other diseases. Sun exposure is important for health, particularly since it helps synthesise the active form of vitamin D_3. It may also induce a feeling of general wellbeing.[6] Moreover, a number of studies published in the scientific literature have shown beneficial effects of UVR exposure in prevention of several types of cancer such as Non-Hodgkin's Lymphoma,[7] prostate,[8] colorectal[9] and breast.[10]

The importance of UVR and its related diseases is not only a subject of scientific literature, but also a common topic of mass communication media due to the significant growing number of new cases of skin cancer around the world.[11–13] For this reason, UVR levels at the Earth's surface are commonly publicised as the Ultraviolet Index (UVI). UVI quantifies the potential of sun exposure for skin damage at any time. One UVI unit is equivalent to 25 mW m^{-2} of erythemal irradiance. Erythemal irradiance is defined as the wavelength-integrated spectral UV irradiance (between 280 and 400 nm) weighted with the CIE action spectrum for the erythema response of the human skin.[14] Nowadays UVI is adopted as a vehicle to raise public awareness and to alert people about the need to adopt protective measures when exposed to UVR.[15]

Due to the growing interest of the general public, non-scientific instruments for UVR measurements, such as watches, meteorological stations, portable dosimeters, are regularly commercialized. However, the accuracy of these instruments is not known. In this work we compare UVR measurements performed by a set of non-scientific instruments with an accurately calibrated UV spectrometer in order to evaluate the reliability of such commercial instruments for the evaluation of personal UV exposure. The paper is organised as follows: after a description of the instruments and the measurements performed in the frame of the present study, the performance of the commercial instruments in terms of UVI measurements is evaluated with respect to that of the UV spectrometer. Conclusion are then drawn from the study.

[a]*LATMOS–Université Pierre et Marie Curie–Centre National de la Recherche Scientifique, 4 place Jussieu, 75252, Paris, France*
[b]*Instituto de Recursos Naturais–Universidade Federal de Itajubá, Av. BPS, 1303–CEP, 37500-903, Itajubá, Brazil. E-mail: mpcorrea@unifei.edu.br*
[c]*Institut Pierre Simon Laplace–École Polytechnique, 91128, Palaiseau, France*
[d]*Laboratoire d'Optique Atmospherique (LOA)–Université des Sciences et Technologies de Lille, F-59655, Villeneuve d'Ascq, France*
[e]*Research unit EA 4339 "Skin cancer and environment"–Ambroise Paré University Hospital–University of Versailles-Saint Quentin en Yvelines, 9 avenue Charles de Gaulle, 92100, Boulogne-Billancourt, France*
[f]*Service de Dermatologie–Ambroise Paré University Hospital–Assistance Publqiue-Hôpitaux de Paris, 9 avenue Charles de Gaulle, 92100, Boulogne-Billancourt, France*

Instrumentation and measurements

In the frame of the RISC-UV project, we conducted an experiment to evaluate the quality of non-scientific instruments for UV radiation measurements. The RISC-UV project aims at establishing a scientific cooperation between the medical community working on diseases related to UV exposure and geophysicists interested in the monitoring of surface UV radiation and its evolution linked to environmental changes.[16] We gathered consumer instruments—handheld sensors, watches and weather stations—all of them equipped with UV radiation sensors. It is important to emphasize that we analyse the comparison of two different, but related

Table 1 Instruments and measurements

Instrument type and make (number of units)	Type	Measurement period	Reference
Solarmeter UVI meter model 6.5* (13#; S/N d1905, d1966–d1977)	Handheld for point measurement	10–17 Sept. 2008, 15–30 May 2009	[a]
Solarmeter Personal UV monitor (1#)	Watch	10–17 Sept. 2008	[b]
Oregon UV RA103 (3#)	Watch	10–17 Sept. 2008	[c]
Décathlon 500 W UV (1#)	Watch	10–17 Sept. 2008	[d]
Oregon Scientific UV BBW213 station (3#)	Compact portable weather station	10–17 Sept. 2008	[e]

[a] http://www.solarmeter.com/model65.html [b] http://www.solarmeter.com/modelPUVM.html. [c] http://www.oregonscientific.be/manuals/RA103_EN.pdf. [d] http://www.decathlon.fr. [e] http://safemanuals.com/314159.php?k=076aa191650ab64922b8e9d7a74fd723&ID=69789&q=OREGON%20SCIENTIFIC%20BBW213.

quantities: the limited solid angle solar UV radiation incident on these non-scientific instruments with respect to the horizontal hemispheric solar UV radiation incident on the spectrometer. Details about the instruments are listed in the Table 1.

These instruments were deployed at the SIRTA observatory, located in Palaiseau, France (48.7°N; 2.2°E; 170 m),[17] a research facility specialized in measurements of atmospheric constituents and solar radiation. The non-scientific sensors were compared against each other and against a Bentham spectrometer that provides an irradiance scan over the 290–650 nm wavelength bands every five minutes. The Bentham spectrometer used in this study is operated by the Laboratoire d'Optique Atmosphérique[18,19] and its calibration is traced to European standards.[20] A first intercomparison exercise was carried out during the period 10–17 September 2008, while a second one, focused on UVI meters, occurred 15–29 May 2009. The instruments were positioned strictly in agreement with the manufacturers' recommendations in order to simulate the conventional use of these instruments by a common user. The watches had the detectors pointed directly at the sun, while the other instruments were positioned in a horizontal plane as shown in Fig. 1. The surface under the instrument supports did not undergo modifications during the experiment.

Fig. 1 Instruments used in the intercomparison experiment. (a) Bentham spectrometer, (b) watches with UV sensors of different brands, (c) weather stations with UV sensors, (d) handheld UV sensor.

UVI measurements provided by the non-scientific instruments were compared against the Bentham spectrometer data (Fig. 2). This spectrometer performs irradiance scans over the 290–650 nm wavelength bands in five minutes. Each measurement was convoluted by the CIE erythemal spectral response for human skin to provide UVI measurements.[15]

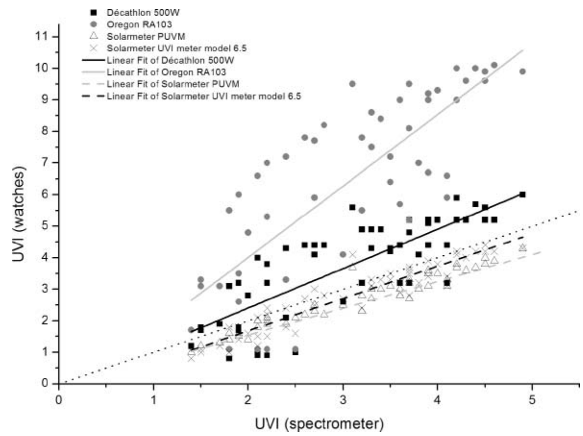

Fig. 2 Scatterplot of UVI measurements—watches *versus* spectrometer.

These comparisons were performed under heterogeneous atmospheric conditions, *e.g.* cloudy or cloudless skies. According to the SIRTA database, we did not observe significant changes in the aerosol optical properties or in the total ozone content during the experiment. Measurements provided by the spectrometer showed a range between 1.4 and 7.0 UVI, as shown in Fig. 2, which represents the evolution of UVI at the SIRTA location from 10 to 17 September. The average UVI measured during this period was 4.3 ± 1.5 (one sigma standard deviation).

Evaluation of the "non-scientific" instruments

The results will be shown for each set of instruments: (a) watches; (b) UV meteorological stations; and (c) handheld dosimeters. Fig. 2 shows the comparison between 53 simultaneous UVI measurements performed by the UV watches and the spectrometer.

The three Oregon RA103 watches tested in this work provided very similar results. For this reason, just the results of one of them is showed in Fig. 2. The Solarmeter instruments, PUVM watch and handheld UVI meter model 6.5, provided good correlations with the spectrometer (linear fits: $y = 0.87x - 0.07$, adjusted-r^2 = 0.94; $y = 1.03x - 0.38$, adjusted-r^2 = 0.88, respectively). Despite the good correlation, PUVM watch provided underestimated UVI values for a limited UV index range. Décathlon 500 W ($y = 1.25x - 0.10$, $r^2 = 0.63$) and Oregon RA103 ($y = 2.26x - 0.52$, $r^2 = 0.61$) watches showed a poorer correlation and a larger variability. These two watches revealed a high sensitivity, several times providing results two or three times greater values than the true UVI values. We observed that this undesirable variability was related to small movements that can be naturally done by a common user using a watch. In such a case, as the main purpose of these non-scientific instruments is to provide important information for the health care for the general public, we caution potential users of these devices for UVI measurements.

According to the manufacturer's advertisement, the Oregon Scientific UV comfort meteorological station (UV-station) is ideal for outdoor activities and vacations and is designed to protect a family's sensitive skin, mainly that of babies. We compare three such UV-stations against the Bentham spectrometer. The UV-station measurements overestimated the UVI in most of the tests. Besides, UVI figures presented as integer values decrease the possibility of comparison with scientific instruments. Fig. 3 shows the comparison between the UV-station data with coincident measurements of the Bentham spectrometer. (Linear fits and adjusted-r^2 are, respectively, $y = 1.29x + 0.90$ and $r^2 = 0.70$ for UV-station 1; $y = 0.96x + 1.61$ and $r^2 = 0.79$, for UV-station 2; and, $y = 1.10x + 1.24$ and $r^2 = 0.78$, for UV-station 3) It is important to note that UV stations were positioned on a horizontal plane, according to manufacturer recommendations.

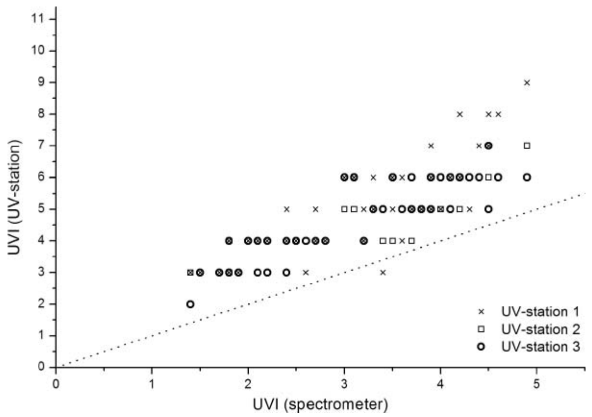

Fig. 3 Scatterplot of UVI measurements—UV-stations *versus* spectrometer.

We compared 53 samples of each non-scientific instrument measurement with the spectrometer data. Table 2 shows the results of a two-sided hypothesis test for independent means with a significance level of 0.05 and critical-*t* around 1.98 for 135 degrees of freedom (reference). The results showed in Table 2 provide evidence to reject the hypothesis of equal means in comparisons between non-scientific instruments and the spectrometer (*p*-value < significant level), except for the UVI Solarmeter Model 6.5 (*p*-value ≫ significance level).

Moreover, UVI measurements performed by most of the non-scientific instruments showed large discrepancies compared to the spectrometer data. Fig. 4 show histograms of the relative differences observed between the spectrometer, handheld dosimeters and watches (Fig. 4a) and the UV stations (Fig. 4b). We consider positive differences, *e.g.* UVI non-scientific measurements larger than those derived from a scientific instrument ("true UVI"), as a pseudo-protective effect. On the other side, UVI underestimations can induce sun overexposure and consequently

Table 2 Test statistics for a two-sided hypothesis tests for independent means:[a] non-scientific instruments *vs.* spectrometer

	Instrument	Test statistic, *t*	*p*-value
Watches	Décathlon 500W	−2.72	0.0079
	Oregon RA103	−7.84	<0.0001
	Oregon RA103	−8.30	<0.0001
	Oregon RA103	−8.23	<0.0001
	Solarmeter PUVM	2.56	0.01
Compact portable weather stations	UV-station #1	−7.36	<0.0001
	UV-station #2	−7.58	<0.0001
	UV-station #3	−7.33	<0.0001
Handheld dosimeter	UVI Solarmeter Model 6.5–SN 1905	1.48	0.142

[a] $\alpha = 0.05$, critical-*t*: ~1.98.

harmful effects for human beings. However, very large differences, positive or negative, could affect negatively the knowledge on photoprotection.

Fig. 4a shows that the Solarmeter PUVM watch and the handheld Solarmeter UVI meter model 6.5 provided most UVI measurements with relative differences between 0 and −20%. The Decathlon 500 W watch showed a larger range of discrepancies with very unstable results, and the Oregon RA103 watch overestimated UVI values in more than 90% of the measurements. In 80% of the cases, Oregon relative difference overestimation is larger than 50%. In spite of the pseudo-protective effect observed in most of the Oregon and Decathlon results, these instruments cannot be considered as trustworty equipment due to the strong variability and relative differences above 20%. In addition, note that in spite of their stability, Solarmeter instruments generally underestimated UVI values and consequently should be used with caution with regard to human health protection. In the same way, Fig. 4b shows that all the measurements accomplished by the UV-stations provided significant overestimates compared to the spectrometer data. Only less than 10% of the compared UV-station data showed relative differences below 20%. Even though UV-stations do not underestimate the UVI and consequently do not bring risks of sun overexposure, the differences are significantly larger than those expected for an instrument developed for health care.

During the first test period, we found the handheld Solarmeter UVI model 6.5 (serial number 1905) to be easy to manipulate, to provide good correlations with the spectrometer (Table 2) and stable performances (Fig. 4). Consequently we decided to perform a second test using 12 additional handheld Solarmeter UVI model 6.5 (serial numbers 1966–1977). Fig. 5 shows the relative differences between the UVI measurements performed by the handhelds and the spectrometer. We considered 55 samples collected under sunny and cloudy conditions.

Fig. 5 shows that only the oldest handheld (serial number d1905) provided negative differences. Since this instrument was bought one year before the others, this result could be representative of its aging. However, two positive aspects can be emphasized: (a) all instruments provided small deviations (±3%) on the order of what can be expected by scientific instruments (Moris and Berger, 1993; Kipp and Zonen, 2007); and (b) the pseudo-protective effect due to the observed positive differences. A one-way ANOVA test (significance: 0.05; *p*-value = 0.376) indicates that there

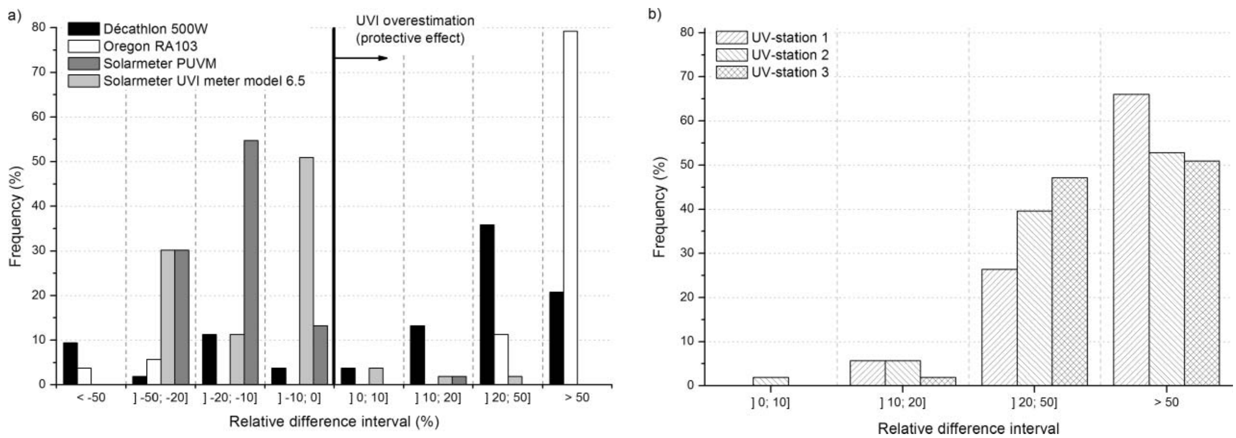

Fig. 4 Histogram of the relative differences intervals observed between the scientific (Bentham spectrometer) and the non-scientific measurements: (a) watches; (b) UV-stations.

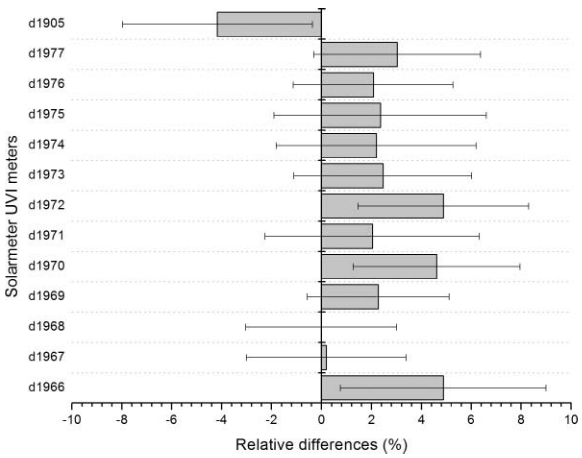

Fig. 5 Mean relative differences (%) between 55 UVI measurements performed by Solarmeter UVI meters and a Bentham spectrometer. The vertical axis shows the serial number of the handheld, gray bars show the mean relative differences, and black lines are the standard deviation of these differences.

is not sufficient evidence to reject the equality of UVI means collected by this set of handheld instruments. For that reason, these instruments were selected for further investigation of UV exposure at different tourist locations within the Paris area, conducted during the RISC-UV2 experiment.[16]

Conclusions

This paper examined non-scientific instruments used to obtain relative measurements of UVI. To accomplish this objective, we compared watches, compact portable weather stations and handheld UV meters with a recently calibrated Bentham UV spectrometer. These instruments were used strictly according to manufacturer's recommendations.

Comparisons showed significant discrepancies between commercial and scientific instruments. Differences were naturally expected, but portable weather stations and Decathlon and Oregon watches showed UVI measurements larger than 50% when compared to spectrometer data. Some of those measurements overestimate the measured UVI two or three times. Solarmeter instruments, watch and handheld meter, showed stability and smaller differences. However, most of Solarmeter measurements underestimate UVI by 10 to 20%. Therefore, these instruments can induce sun overexposure with harmful effects for human beings.

We also perform an intercomparison with 13 Solarmeter UVI meters model 6.5. We chose this instrument because of its easy manipulation and stability. The instrument acquired one year before showed negative differences around –4%, while the 12 others showed differences between 0 and +5%. These deviations (±5%) are commonly expected for scientific instruments. For that reason, we decided to use UVI 6.5 meters for further investigation in the RISC-UV2 experiment.[16]

In conclusion, the present study shows that most of the non-scientific instruments analyzed in this work do not provide trustworthy results. Since these instruments are freely commercialized, we consider that the trade of these instruments should be inspected by governmental agencies of health. For a more detailed analysis we recommend other comparisons with larger sets of instruments and under different conditions, such as higher UVI levels, seasonal variability and instrumentation aging.

Moreover it is to be expected that the broadband filter radiometers will show dependencies on total column ozone and solar zenith angle, the two main parameters affecting the spectral shape of the solar spectrum on the ground. We do not know the behaviour of these instruments when submitted to high UV levels, as commonly observed in tropical countries or high mountains. We intend to perform analyses under these different situations.

Acknowledgements

This work was performed in the frame of the RISC-UV project funded by the Climate-Environment-Society consortium (GIS CES, France). We specially thank the SIRTA and LOA/Lille Team for the technical support. The first author would like to thank The State of Minas Gerais Research Foundation (Fapemig, Brazil), The National Council for Scientific and Technological Development (CNPq, Brazil) and the National Center for Scientific Research (CNRS, France).

Notes and references

1 J. M. Elwood and J. Jopson, Melanoma and sun exposure: An overview of published studies, *Int. J. Cancer*, 1997, **73**, 198–203.

2 Ferrari Junior, N. M., H. Muller and M. Ribeiro, (2008) Cutaneous melanoma: Descriptive epidemiological study, *Sao Paulo Med. J.*, 2008, **126**(1), 41–47, DOI: 10.1590/S1516-31802008000100008.

3 C. A. McCarty and H. R. Taylor, A review of the epidemiologic evidence linking ultraviolet radiation and cataracts, *Prog. Lens Cataract Res. Dev. Ophthalmol.*, 2002, **35**, 21–31.

4 F. R. De Gruijl, UV-induced immunosuppression in thebalance, *Photochem. Photobiol.*, 2008, **84**, 2–9.

5 M. Norval, P. McLoonel, A. Lesiak and J. Narbutt, The effect of chronic ultraviolet radiation on the human immune system, *Photochem. Photobiol.*, 2008, **84**, 19–28.

6 M. F. Holick, The vitamin D epidemic and its health consequences, *J. Nutr.*, 2005, **135**, 2739–2748.

7 K. Kricker, B. K. Armstrong, A. M. Hughes, C. Goumas, K. E. Smedby, T. Zheng, J. J. Spinelli, S. De Sanjosé, P. Hartge, M. Melbye, E. V. Willett, N. Becker, B. C. Chiu, J. R. Cerhan, M. Maynadié, A. Staines, P. Cocco and P. Boffeta, and Interlymph Consortium. Personal sun exposure and risk of non Hodgkin lymphoma: A pooled analysis from the Interlymph Consortium, *Int. J. Cancer*, 2008, **122**, 144–154.

8 W. B. Grant, A multicountry ecologic study of risk and risk reduction factors for prostate cancer mortality, *Eur. Urol.*, 2004, **45**, 271–279.

9 E. D. Gorham, C. F. Garland, F. C. Garland, W. B. Grant, S. B. Mohr, M. Lipkin, H. L. Newmark, E. Giovannucci, M. Wei and M. F. Holick, Optimal vitamin D status for colorectal cancer prevention: A quantitative meta analysis, *Am. J. Prev. Med.*, 2007, **32**(3), 210–216.

10 T. Gissel, L. Rejnmark, L. Mosekilde and P. Vestergaard, Intake of vitamin D and risk of breast cancer—A meta-analysis, *J. Steroid Biochem. Mol. Biol.*, 2008, **111**, 195–199.

11 Cancer in Australia: an overview, 2006, *Cancer series*, AIHW (Australian Institute of Health and Welfare) & AACR (Australasian Association of Cancer Registries), Canberra, 2007, vol. 37, Cat. no. CAN 32.

12 M. Garcia, A. Jemal, E. M. Ward, M. M. Center, Y. Hao, R. L. Siegel and M. J. Thun, *Global Cancer Facts & Figures*, American Cancer Society, Atlanta, GA, 2007.

13 National Cancer Institute (INCA), Estimates 2008: Incidence of Cancer in Brazil, Ministry of Health, General Office of Attention to the Health, Coordination of Prevention and Surveillance of Cancer, 2007, 1–94, available at: http://www.inca.gov.br/english/, accessed on 19 November 2008 [in Portuguese].

14 A. F. McKinlay and B. L. Diffey, A reference action spectrum for ultra-violet induced erythema in human skin, in *Human Exposure to Ultraviolet Radiation: Risks and Regulations*, ed. W. F. Passchier and B. F. M. Bosnajakovic, Elsevier, Amsterdam, 1987, pp. 83–87.

15 World Health Organization (WHO), *The Global Burden of Disease: 2004 Update*, Library Cataloguing-in-Publication Data, Geneva, 2008.

16 M. P. Corrêa, S. Godin-Beekmann, M. Haeffelin, P. Saiag, E. Mahé, C. Brogniez, J. C. Dupont, A. Pazmino, F. Auriol and B. Bonnel, RISC-UV: A multidisciplinary research project on UV radiation, in 15th International Congress of Photobiology, 2009, Düsseldorf, *Annals of 15th International Congress of Photobiology*, Düsseldorf: Institut für umweltmedizinische Forschung, 2009.

17 M. Haeffelin, L. Barthès, O. Bock, C. Boitel, S. Bony, D. Bouniol, H. Chepfer, M. Chiriaco, J. Cuesta, J. Delanoë, P. Drobinski, J.-L. Dufresne, C. Flamant, M. Grall, A. Hodzic, F. Hourdin, F. Lapouge, Y. Lemaître, A. Mathieu, Y. Morille, C. Naud, V. Noël, W. O'Hirok, J. Pelon, C. Pietras, A. Protat, B. Romand, G. Scialom and R. Vautard, SIRTA, a ground-based atmospheric observatory for cloud and aerosol research, *Ann. Geophys.*, 2005, **23**, 253–275.

18 C. Brogniez, M. Houët, A. M. Siani, P. Weihs, M. Allaart, J. Lenoble, T. Cabot, A. de la Casinière and E. Kyrö, Ozone column retrieval from solar UV measurements at ground level: Effects of clouds and results from six European sites, *J. Geophys. Res.*, 2005, **110**(d24), D24202, DOI: 10.1029/2005JD005992.

19 A. F. Bais, B. G. Gardiner, H. Slaper, M. Blumthaler, G. Bernhard, R. McKenzie, A. R. Webb, G. Seckmeyer, B. Kjeldstad, T. Koskela, P. J. Kirsch, J. Gröbner, J. B. Kerr, S. Kazadzis, K. Leszczynski, D. Wardle, W. Josefsson, C. Brogniez, D. Gillotay, H. Reinen, P. Weihs, T. Svenoe, P. Eriksen, F. Kuik and A. Redondas, SUSPEN intercomparison of ultraviolet spectroradiometers, *J. Geophys. Res.*, 2001, **106**(d12), 12509–12525.

20 J. Gröbner, M. Blumthaler, S. Kazadzis, A. Bais, A. Webb, J. Schreder, G. Seckmeyer and D. Rembges, Quality assurance of spectral solar UV measurements: results from 25 UV monitoring sites in Europe, 2002 to 2004, *Metrologia*, 2006, **43**, S66–71.

