Photochemistry and Photobiology, 2006, 82: 1047–1052

UV Index on Tilted Surfaces

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Received 30 November 2005; accepted 3 May 2006; published online 4 May 2006 DOI: 10.1562/2005-11-30-RA-743

ABSTRACT

Solar ultraviolet erythemal irradiance (UVER) has been studied on inclined planes with different orientations in Valencia, Spain. To do this a platform was designed that could turn through 90° on its own axis. The radiometers were inclined at an angle close to the latitude of Valencia (39.5° N). Using two timers the platform could be turned through 90° every 5 min. On clear or partially cloudy days, including those with different turbidity values, it was observed that the UVER showed a maximum at 1200 h GMT, very close to solar noon, in the north and south positions, while the maximum for east and west orientations was found at approximately one hour before and one hour after midday respectively. It was also observed how the irradiance for the south orientation was greater and for the north was less than for the horizontal plane, as well as the opposite performances of the east and west orientations, for four days close to the summer and winter solstices and each equinox. Some experimental results were also compared with the results from the SMARTS2.9 model for the same conditions. It was found that the model frequently overestimated the experimental data.

With respect to the maximum calculated UV Index in the different planes this was always higher for the south orientation than for the north, while it was similar for east and west orientations throughout the year. Finally the accumulated erythemal dosage for the considered period was obtained as a function of phototype and orientation, confirming that the accumulated erythemal dosage decreased by around 37% in the north orientation compared to the horizontal value, while in the south position it was only 6% less and some 20% and 15% less in the east and west positions, respectively.

INTRODUCTION

In 1995 the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in collaboration with the World Health Organization (WHO), the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) drew up a series of recommendations redefining the ultraviolet index (UV Index) (1). In accordance with these directives the WMO (2) recommends that the UV Index should be defined as a physical parameter averaged biologically using the active spectrum defined by the International Commission on Illumination (CIE) (3,4). The UV radiation weighted with the curve representing the response of human skin to erythema or sunburn is called the ultraviolet erythemal radiation (UVER) or the erythemally active radiation.

The UV Index is determined from the integrated UVER expressed in watts per square meter, multiplied by 40. It is expressed as a whole number (the nearest integer) and is always defined on a horizontal surface. (Some international organizations propose calling this the horizontal global UV Index, but this term is not yet officially recognized.) For surfaces with a different inclination, for instance those facing the sun, the UV Index value can be considerably different (5).

The measurement of erythemal irradiance incident on a horizontal surface is not always the most suitable method for estimating the real dosage received by human beings. For this reason knowledge of the irradiance incident on inclined surfaces can be important for dosimetric studies. Webb *et al.* (6) performed a study of spectral UV measurements on vertical planes and for various azimuth angles. Their data have been recently used to validate the results of some simulations using a radiative transfer model (7). Elsewhere Parisi and Kimlin (8) show that the global UVER on a plane perpendicular to the sun can reach up to 27% above that incident on a horizontal plane, while the diffuse UVB and UVER irradiances are less for a plane normal to the sun compared with a horizontal orientation. The influence of topography and soil reflectivity have been studied by Weihs (9), deducing that the UVER on inclined planes increases considerably with altitude.

To study the effects of irradiance on nonhorizontal planes a UVER measurement station has recently been designed and commissioned at the Faculty of Physics by the Solar Radiation Group of Valencia. We present here the first results obtained with this station.

MATERIAL AND METHODS

The measurement station is located on the roof of the Faculty of Physics in Burjassot, Valencia, Spain. It consists of three broad-band YES-UVB-1 radiometers (Yankee Environmental Systems [YES]), one of which includes a shade band for the measurement of diffuse radiation. Two instruments measure global irradiance on planes inclined at 40°, alternating north–south and east–west orientations. The station was conceived for understanding the effects of changing surface orientation on received UV radiation. In order to optimize resources a mechanism was designed consisting of a platform that could turn through 90° on its own axis in such a way that, if the pyranometers face opposite directions, measurements can be made in one position north–south and, in the other, east–west. The radiometers were inclined at an angle close to the latitude of Valencia (39.5°) which, according to various studies, is the optimum angle for

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Table 1. Conversion constants for the reference sensor before and after calibrations.

Reference instrument	UVB ($W \cdot m^{-2} \cdot V^{-1}$)	UVER ($W \cdot m^{-2} \cdot V^{-1}$)
Manufacturer calibration	1.093	0.141
July 2002 calibration	0.91 ± 0.09	0.117 ± 0.012
February 2005 calibration	0.99 ± 0.10	0.128 ± 0.013

Table 2. Linear fit parameters for the sensors in our measurement apparatus with respect to the reference sensor and conversion constants after the last calibration.

Instrument	Position	Slope	Correlation coeficient	UVB ($W \cdot m^{-2} \cdot V^{-1}$)	UVER ($W \cdot m^{-2} \cdot V^{-1}$)
1	North–east	0.9808 ± 0.0002	0.99993	0.97 ± 0.10	0.126 ± 0.013
2	South–west	1.0729 ± 0.0002	0.99990	1.06 ± 0.11	0.137 ± 0.014

capturing the maximum radiation on inclined planes (10). By means of two timers the platform could be turned every 5 min, alternating both positions. The measurements were taken in the middle of this period, in order to assure that the data were read when the apparatus was in the desired position and not an intermediate position. The database was made up of instantaneous values on inclined planes taken every 10 min.

The YES-UVB-1, whose spectral interval is from 280–400 nm (11), consists of a phosphor that converts UV into visible light which is precisely measured using a solid state photodiode. The direct and diffuse incident solar radiation is transmitted through the YES-UVB-1 quartz dome. The visible light, except for a small fraction in the red part of the spectrum, is absorbed by black glass which transmits only the UV component. The light transmitted by the filter falls on the phosphor which absorbs the UVB component and re-emits visible light by fluorescence, mostly at green wavelengths. The fluorescent light from the phosphor passes through a green glass filter to remove the red light that had passed through the first "black" filter. The intensity of the remaining fluorescent light is measured by a solid state diode (GaAsP), which has a maximum sensitivity in the green spectrum and is not sensitive to red light. All the optical components, the detector and filters are stabilized at a temperature of (45 ± 1)°C for an ambient temperature between –40°C and +40°C.

The radiometers are supplied already calibrated by the manufacturer. Nevertheless it is advisable to recalibrate them periodically, approximately once a year. This calibration is performed by two different procedures: comparison with high resolution spectroradiometers and comparison with a standard radiometer of similar characteristics taken as a reference. The second option, known as intercomparison, is the usual method in UVB networks (12–14). In our case the radiometer used for reference for the global irradiance in the horizontal plane was recalibrated in February 2005 in the Atmospheric Sounding Station "El Arenosillo" belonging to the Spanish National Aerospace Technology Institute (INTA). The standard calibration method consisted of two phases: the first based on measuring the

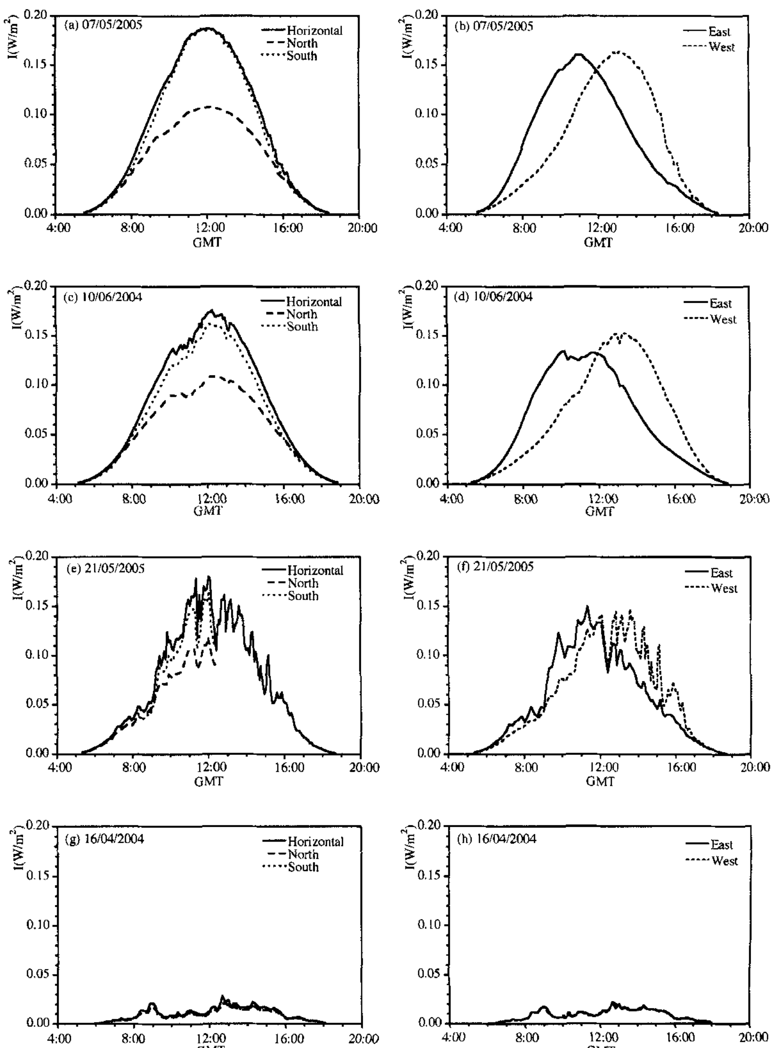

Figure 1. Evolution of UVER for different orientations horizontal, north, south, east and west on a cloud-free day with $\overline{AOD}_{\lambda=500nm} = 0.108$ (a and b), with $\overline{AOD}_{\lambda=500nm} = 0.468$ (c and d), on a partially cloudy day (e and f) and on an overcast day (g and h).

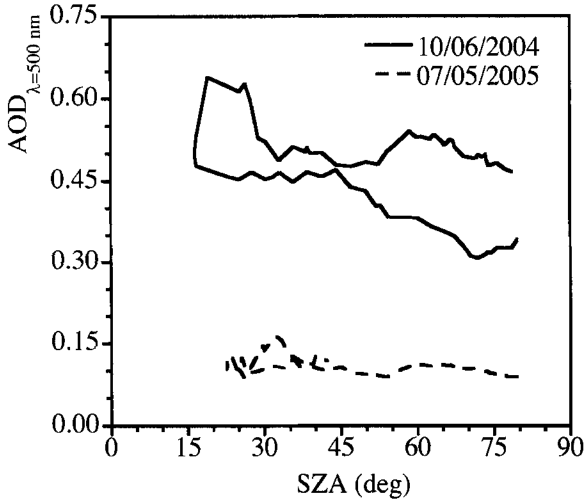

Figure 2. Aerosol optical depth for two clear days: 7 May 2005 (from 0545 to 1823 h GMT) and 10 June 2004 (from 0545 to 1443 h GMT) *vs* Sun Zenith Angle.

radiometer's spectral response and calculating the deviation with respect to the erythemal action spectrum; and the second phase in which it is intercompared with a spectroradiometer, in this case a Brewer. The results of this and a previous calibration, for the conversion constants of our instrument, are shown in Table 1.

Subsequently, between 3 and 14 March 2005 the UVB-1 instruments were intercompared with other radiometers of the UVB measurement network of the Valencian Region, taking for reference the calibration in El Arenosillo. The resulting linear fit values of each of the sensors with respect to the reference are shown in Table 2. The conversion constants for both radiometers were calculated by multiplying the slope of the linear fit by the conversion constants used for the reference sensor. The new values are specified in Table 2. The overall uncertainties are about 10% according to the calibration.

RESULTS AND DISCUSSION

The apparatus described above has allowed us to obtain solar UVB and erythemal radiation data for different orientations. This paper presents an analysis of the UVER measurements made between 16 February 2004 and 31 August 2005.

Figure 1 shows the evolution of UVER (in $W \cdot m^{-2}$) for the different orientations for a pair of cloud-free days with different aerosol optical depth (AOD) and similar total column ozone (7 May 2005, $\overline{AOD}_{\lambda=500nm} = 0.108$, $O_3 = 319$ DU and 10 June 2004, $\overline{AOD}_{\lambda=500nm} = 0.468$, $O_3 = 320$ DU); a partially cloudy day (21 May 2005); and a cloudy day (16 April 2004). It can be seen how for clear days and partially cloudy days the UVER presented a maximum very close to 1200 h GMT (solar noon), in positions north and south, while the maximum for east and west orientations was before and after midday respectively. The time of these maxima for these orientations was 1100 and 1300 h approximately for east and west, respectively. According to this figure the maximum value of UVER for the south orientation was almost twice that for the north orientation, so the erythemal dose received on south-facing planes would be much higher than for north-facing planes. However for the completely cloudy days (Fig. 1g,h), there was no perceivable difference between the maxima of the different orientations.

Figure 1 also shows the influence of the aerosols on the highest values of the UVER although not on the hourly evolution. Specifically, for the 10 June 2004 (Fig. 1c,d) the maximum UVER value was lower than for 7 May 2005 (Fig. 1a,b), even though the

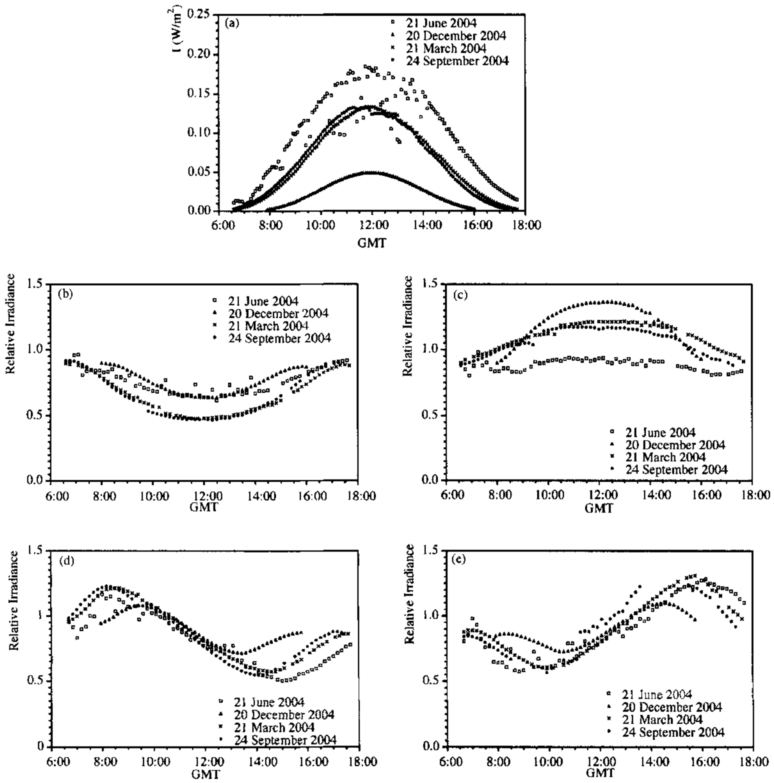

Figure 3. Relative experimental UVER of all orientations over the course of four days: summer solstice (21 June 2004, $\overline{AOD}_{\lambda=500nm} = 0.334$, $O_3 = 357$ DU, $SZA_{12GMT} = 16.07°$), winter solstice (20 December 2004, $\overline{AOD}_{\lambda=500nm} = 0.022$, $O_3 = 212$ DU, $SZA_{12GMT} = 62.94°$), vernal equinox (21 March 2004, $\overline{AOD}_{\lambda=500nm} = 0.134$, $O_3 = 322$ DU, $SZA_{12GMT} = 39.07°$), autumnal equinox (24 September 2004, $\overline{AOD}_{\lambda=500nm} = 0.198$, $O_3 = 270$ DU, $SZA_{12GMT} = 40.24°$) on north (b), south (c), east (d), west (e) and UVER on horizontal incidence (a).

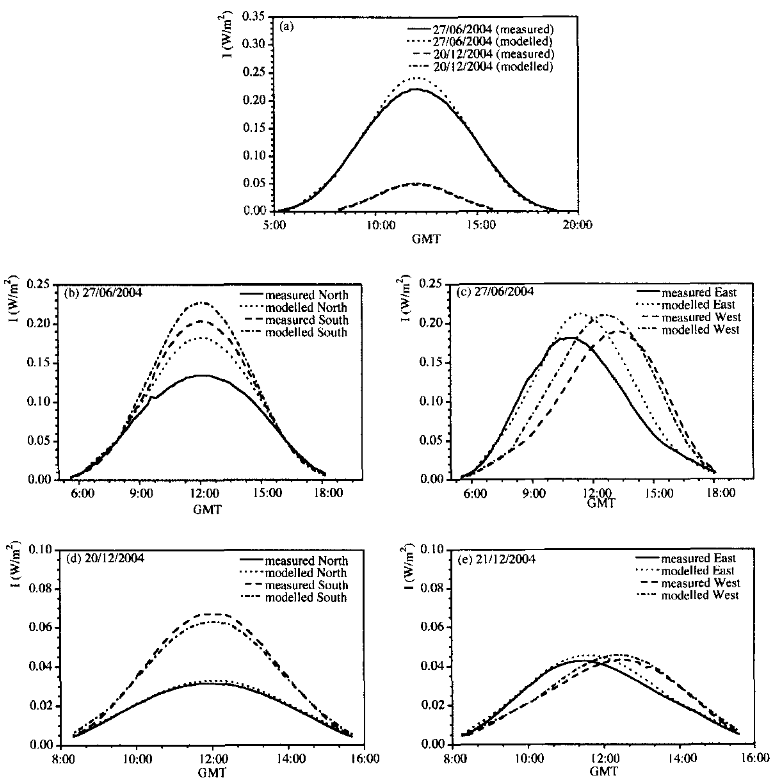

Figure 4. Experimental and modeled with SMARTS2.9 UVER of all orientations. Summer (27 June 2004, $\overline{AOD}_{\lambda=500nm}$ = 0.136, O_3 = 302 DU, SZA_{12GMT} = 16.23°) north and south (b), east and west (c). Winter (20 December 2004, $\overline{AOD}_{\lambda=500nm}$ = 0.022, O_3 = 212 DU, SZA_{12GMT} = 62.94°) north and south (d), east and west (e) and horizontal plane in both days (a).

solar elevation was higher and the ozone amounts were similar. This was because on the first date the turbidity was higher than on the second, as can be seen in Fig. 2 where the AOD for both dates obtained with a Cimel photometer in Valencia is shown. The total column ozone data are provided by TOMS (http://toms.gsfc.nasa.gov/teacher/ozone_overhead.html).

Figure 3 shows ratios of all readings with respect to horizontal incidence over the course of four clear days close to the summer and winter solstices and each equinox. For ease of comparison, the figure also includes the irradiance on horizontal orientation and relevant data such as the minimum sun zenith angle, the daily mean AOD and the total column ozone. It can be seen how the relative irradiance is greater than unity for the south orientation, while it is less for the north orientation. This is because the irradiance was greater and less for the south and north respectively than for the horizontal plane for the considered days. It can also be seen that the east and west orientations have opposite performances for their relative irradiances due to the fact that the sun rises in the east and sets in the west.

As a first approximation for modeling UVER on inclined planes a parameterized transmittance model has been implemented, SMARTS2.9 (15), that provides spectral irradiance on inclined planes directly. Once the UVER was calculated for each direction the results were compared with the experimentally measured results for two clear days, one in winter, the other one in summer. The aerosol model used was the urban one by Shettle and Fenn (16). This model is appropriated for this location (17) and for mean relative humidity in these days, about 50%, and for ultraviolet wavelength range, the simple scattering albedo is about 0.65. Moreover we have considered an average broadband surface albedo equal to 0.2.

The comparison between the measurements and the modeled results is shown in Fig. 4. It can be seen how for the 20 December 2004 the daily root mean square (RMS) difference between the modeled results and the measured ones was about 10% for the east and south, 8% for west and north, and 9% for the horizontal orientation. However this difference was greater for the 27 June 2004, the daily RMS was about 19% for east, west and north and 12% for the south plane. In horizontal orientation the difference was about 10%. This model frequently overestimated the experimental data.

Given the interest that the UV Index has as an indicator of UVER at ground level and as a parameter for informing the public,

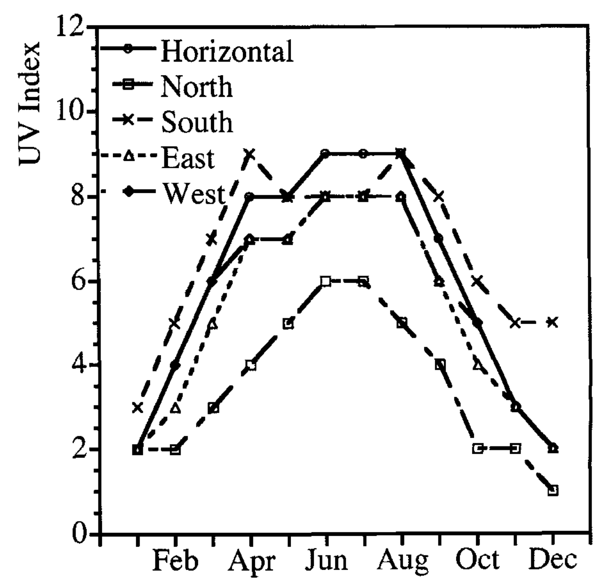

Figure 5. Monthly maximum UV Index for different orientations from February 2004 to August 2005.

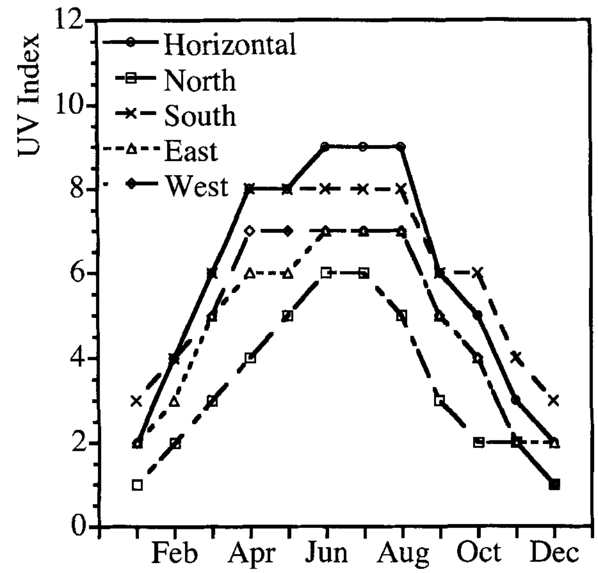

Figure 6. Monthly maximum UV Index at noon for different orientations from February 2004 to August 2005.

we carried out a monthly study of the maximum value for all the hours as well as the maximum value for 1200 h GMT, corresponding to solar noon. Figures 5 and 6 show the monthly maximum values of the UV Index for all data and for 1200 h GMT only respectively for the different orientations throughout 2004 and the months from January to August 2005.

We can see that the monthly maximum UV Index, as would be expected, was always greater for the south-facing than for the north-facing orientation while it was approximately equal for the east- and west-facing orientations for all the months of the year. For the south-facing orientation the UV Index was greater than on the horizontal plane for the months January to April and from September to December, it was lower than on the horizontal plane in June and July, and it was the same as on the horizontal plane for the months of May and August.

All of these comments are also valid for the 1200 h GMT maximum UV Index, which in 97% of cases was equal or differed by less than one unit from the maximum value of the UV Index. These results for monthly maximum values coincide with those found for horizontal UVER and at different stations for daily values (18,19).

In Table 3 we can see the UV Index values at 1200 h GMT for each orientation, and their recurrence (in %) during the considered observation period. We can see that the highest values of the UV Index were only reached on the horizontal plane and for the south-facing plane. We can also see that the lowest values were obtained for the north-facing plane. The percentages in the east and west orientations were fairly similar; indicating that the annual energy received in both directions was of the same order although with a different hourly evolution (Fig. 1).

Table 4. Erythemal dosage for a whole year (the period between 16 February 2004 and 15 February 2005) for the different orientations and phototypes.

MEDs	Horizontal	North	South	East	West
Phototype I	4019	2481	3782	3157	3381
Phototype II	3215	1985	3026	2525	2702
Phototype III	2296	1418	2161	1804	1930
Phototype IV	1786	1102	1681	1403	1501
SED	8039	5055	7565	6428	6830

The accumulated erythemal dosage during the period between 16 February 2004 and 15 February 2005 has been obtained as a function of phototype and orientation. We can see in Table 4 how the accumulated erythemal dosage decreased by 37% in the north orientation with respect to the horizontal plane while in the south position it was only 6% less. Considering the east and west positions, the decrease was 20% and 15% respectively. Nevertheless a great quantity of the erythemal dosage is accumulated in the summer months. Specifically 55% of the total erythemal dosage was received in the four summer months from June to September on the horizontal plane, east, west and north planes while for the south orientation it was 52%.

Furthermore it was observed how the erythemal dosage accumulated over the whole measurement period was much greater for a south-facing plane than that accumulated on the north-facing plane. Figure 7 shows the standard erythemal dose (SED) for each orientation illustrating that the accumulated erythemal dosage in the south-facing plane was much greater that for the north-facing plane and greater than the accumulated doses in the east- and west-facing planes, which were similar to each other as detailed above in Table 4. Differences between west and east orientations could be due to the use of a pair of cross-calibrated instruments in order to obtain simultaneous values in both planes. Moreover the horizon is quite different in the two orientations. Because the sea is close to this location the east plane is more influenced by the seawater, whereas the west plane is more affected by the city and the pollution.

CONCLUSIONS

Firstly we studied the hourly evolution of UVER for planes oriented towards the north, south, east and west. We were able to check that the UVER has a maximum at 1200 h GMT

Table 3. UV Index at 1200 h GMT and their recurrence (%) for the different orientations.

	UV Index (1200 h GMT)									
Orientation	0	1	2	3	4	5	6	7	8	9
Horizontal	27716 (37)	12958 (17)	8292 (11)	6327 (9)	5225 (7)	4692 (6)	4168 (6)	3535 (5)	883 (1)	13 (1)
North	12071 (45)	6063 (22)	3844 (14)	2744 (10)	2173 (8)	343 (1)	—	—	—	—
South	10731 (39)	4397 (16)	3181 (12)	2311 (8)	1927 (7)	1814 (7)	1774 (6)	966 (4)	78 (1)	—
East	15185 (39)	7712 (20)	4656 (12)	3623 (9)	3078 (8)	2813 (7)	1844 (4)	212 (1)	—	—
West	13259 (39)	6758 (19)	4539 (12)	3438 (9)	3046 (8)	2744 (8)	2221 (6)	491 (1)	2 (1)	—

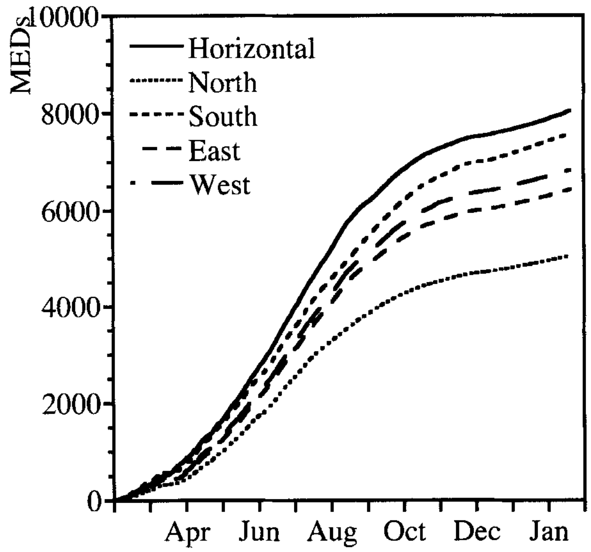

Figure 7. Evolution over time from 16 February 2004 to 15 February 2005 of the accumulated erythemal dosage as a function of the SED for different orientations.

corresponding to solar noon for the north and south positions while the maxima for the east and west orientations were located before and after midday respectively. Analyzing the days for which we had data we found that these maxima occurred around 1100 and 1300 h for east and west respectively.

It was also observed how the irradiance for the south orientation was greater and for the north was less than for the horizontal plane, as well as how the east and west orientations have opposite performances for their relative irradiances, for four days close to the summer and winter solstices and each equinox. Some measured results were compared with the modeled results with SMARTS2.9. For the winter day the daily RMS difference was about 8–10% whilst for the summer day the RMS discrepancy was about 10–19%. The model usually overestimates the experimental data.

We carried out a monthly study of the UV Index, concentrating on the maximum and 1200 h GMT UV Index values. This analysis showed that in both cases the UV Index was systematically higher for the South orientation than for the North, while it was equal or very similar for the east and west orientations. We also observed how in 97% of cases the maximum value and the 1200 h GMT value were the same within one unit for all orientations.

The accumulated erythemal dosage for the period of a whole year was obtained as a function of phototype and orientation, from which it was observed that the accumulated erythemal dosage decreased by 37% in the north orientation with respect to the horizontal plane while for the south orientation the decrease was only 6%. Considering the east and west orientations the decrease was 20% and 15% respectively. More than a half of the accumulated dosage is received from June to September for all the orientations except north.

Acknowledgements—This work is the result of the collaboration between the Valencian Autonomous Government and the Solar Radiation Group of the University of Valencia. A. R. Esteve received a grant subsidized for this collaboration. The collaboration of M. J. Marín was possible thanks to a grant CTBPRB/2003/93. This work was also financed by the CICYT (Spanish Commission of Science and Technology) through the Project REN2002-00749 and the Valencian Autonomous Government through the Project CTIDIB/2002/113. We want to thank V. Estellés for his collaboration.

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