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UVER and UV index at high altitude in Northwestern Argentina

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ABSTRACT

Measurements of ultraviolet erythemal radiation (UVER) made during two years at three sites located at altitudes over 1000 m a.s.l. in Northwestern Argentina (Salta, San Carlos, and El Rosal) have been used to estimate and analyze the UV Index (UVI) and the cumulative doses at these locations. For the UVER irradiance, data of January (maximum values) and June (minimum values) have been analyzed as representative of the year for all locations. The UVI reaches extreme (>11) values in >20% of the analyzed days in Salta (1190 m a.s.l.), while these are reached in San Carlos (1611 m a.s.l.) and El Rosal (3355 m a.s.l.) in >40% of the analyzed days. Finally, the cumulative doses over an average year have also been studied for each location. The doses received during austral summer and autumn are of the same order, and represent one third of the annual dose, while the doses received during austral winter and spring represent one sixth of the annual dose approximately.

1. Introduction

Solar UV radiation, and particularly UVB, has an important influence in terrestrial and marine ecosystems, being in many cases an indicator of their development due to its impact over the physical and chemical conditions that allow the ecosystems to evolve [1–3].

The effects of UV solar radiation on human beings are mostly observed over the skin [4,5], the eyes [6,7] and the immune system [8,9]. The effects over the skin depend on the duration of the exposure to sunlight. Chronic skin overexposure produces morphological changes: the epidermis turns thicker, disorganized, parakeratotic, and acanthotic [10]. Severe skin overexposure produces prostaglandins generation, which is associated with severe sunburn that causes heat, erythema and other symptoms approximately 16 h after exposure to natural sunlight [11–13]. Epidemiological evidence also exits of the direct influence of sunlight over skin cancer in human beings [14–18].

The most common effect of overexposure to solar radiation, sunburn or erythema, is studied through the ultraviolet erythemal radiation (UVER), which is determined as the spectrally integrated weighted solar irradiance at ground level with the spectral standard erythema action curve adopted by the CIE (Commission Internationale de l'Éclairage) in 1987 [19]. The study of the influence of the UV erythemal radiation over the skin is usually based on the minimum dose of UVER that produces a noticeable reddening of human skin which has not been previously exposed to solar radiation. This dose is known as MED (Minimum Erythemal Dose) [20,21], and is always related to a specific skin type (phototype). Nowadays, most countries have adopted a skin classification which considers four phototypes [22]. Table 1 shows the main characteristics of these four skin types as well as the dose needed to produce one MED. However, a Standard Erythemal Dose (SED), which does not depend on the skin type and corresponds to 100 J/m^2, should be used instead of the MED [22].

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 Environmental Program (UNEP), recommended the use of the global solar UV Index in order to forecast and to inform general public in a simple way about the levels of UV irradiance that reach the ground [23]. The UVI is quantitatively obtained by multiplying the UVER value (expressed in W/m^2) by 40, and it should be reported as a value rounded to the nearest integer.

Most UVER and UVI measurements are made in the Northern Hemisphere, and thus, those made in the Southern Hemisphere are of great importance for describing and understanding the levels of UV radiation all over the Earth [24]. In the literature we can find several works which present measurements made in Southern America: measurements of total UV radiation in Puna de Atacama (Argentina) [25,26], UVB measurements in Chile [27] and Argentina [28,29], and UVER measurements in Chile [30], Brasil [31] and Argentina [32–34]. The values registered in the Southern Hemisphere are usually higher than those found at similar latitudes and altitudes in the Northern Hemisphere mainly because the distance Sun-Earth is minimal in early January, i.e., in summer, when

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Table 1
Skin types defined by ISO 17166 CIE S 007/E [23].

Skin type	Tanning ability	Sunburn susceptibility	Hair colour	Eye colour	MED (J/m^2)
I	None	High	Blond/red	Blue	200
II	Poor	Moderate	Blond	Blue/green	250
III	Good	Low	Brown	Grey/brown	350
IV	Very good	Very low	Black	Brown	450

UVER values are high [35]. There are also some other reasons that depend on the location like the absence of cloudiness or its high altitude (e.g. the Andes mountains) [36].

This article presents an analysis of UVER measurements performed during the years 2013 and 2014 at three different sites in Northwestern Argentina (Salta, San Carlos, and El Rosal), located at altitudes between 1.200 and 3.400 m above sea level (a.s.l.). These measurements have been used to estimate the UVI and the cumulative doses, which are also analyzed here. Although this kind of analysis has been previously performed by the authors using 10 years of measurements in 14 stations of the Spanish UVB Radiometric Network [37,38], the novelty of this work resides in this kind of analysis being performed now at measurement sites located at high altitudes in the Southern Hemisphere.

2. Materials and Methods

The UVER measurements presented in this study were made using UVS-*E*-T radiometers manufactured by Kipp & Zonen, which measure ultraviolet erythemal irradiance to the ISO 17166:1999, CIE S 007/E-1998 response function [39]. The radiometers were acquired at the beginning of the measurement period (December 2012), and although they had been calibrated by the manufacturer, they were compared at the University of Valencia against a YES UVB-1 radiometer, calibrated previously in the National Institute for Aerospace Technology (INTA) in Spain. The calibration of the YES UVB-1 radiometer consists in the measurement of the spectral response and the cosine response indoors as well as a comparison with a reference spectroradiometer outdoors. The result is a double input matrix that depends on the zenith angle and total column ozone [40]. However, the calibration of the UVS-E-T radiometers by direct comparison with the YES UVB-1 does not include the cosine factor of these instruments.

Data were registered every 5 s using Campbell Scientific CR1000 dataloggers, and 1 min averages of those measurements were saved and used to obtain the hourly and daily averages presented in this study. Due to the significant cosine errors of the measurement instruments, especially for high solar zenith angles [41], only UVER measurements obtained for SZA < 60° have been used here.

The measurements presented in this study were made during the years 2013 and 2014 at three different sites located in the Salta Province in Northwestern Argentina. The Salta Province borders to the north with Bolivia and Paraguay and to the west with Chile. The measurement sites of Salta, San Carlos, and El Rosal are located at altitudes between 1.200 and 3.400 m a.s.l. Due to technical problems, measurements in San Carlos were only available from 1 January 2013 to 18 March 2014. Table 2 shows the geographical coordinates and altitudes above sea level of the three stations, as well as the number of available measurements made every minute, hourly and daily in each of them.

3. Results and Discussion

3.1. UV Erythemal Radiation

3.1.1. Daily Values

The annual evolution of the cumulative daily values and the monthly mean cumulative daily values of UVER (in kJ/m^2) at Salta, San Carlos, and El Rosal is shown in Fig. 1. It is observed that the curves of the monthly mean values follow a sinusoidal evolution, with a minimum in June (1.75 kJ/m^2 in Salta, 2.07 kJ/m^2 in San Carlos and 2.48 kJ/m^2 in El Rosal), and a maximum in January (6.24 kJ/m^2 in Salta, 7.31 kJ/m^2 in San Carlos and 7.82 kJ/m^2 in El Rosal). The values obtained in El Rosal are slightly lower than those obtained for the high-altitude station of La Quiaca (Jujuy, Argentina) (22.11° S 65.67° W, 3459 m a.s.l.) in the Andean Plateau, where values of 8.3 kJ/m^2 and 3.05 kJ/m^2 were obtained in January and July, respectively [34]. Besides, there are some strong fluctuations of the cumulative daily values of UVER during January and February in all the measurement stations which could be explained by the "Bolivian winter", which is a meteorological event of the Puna de Atacama region that makes the cloud cover higher in summer (January and February) than in the rest of the year [33]. Moreover, these fluctuations decrease as the altitude increases, which could be explained by the increasing possibility of clouds remaining below the measurement site with altitude.

3.1.2. Hourly Values

The daily evolution of the hourly mean values of the UVER for each month at the three measurement sites is shown in Fig. 2. The maximum values in El Rosal are always obtained at 12:00 SLT. However, in Salta and San Carlos, they are obtained at 12:00 SLT for each month except in December, when they are obtained at 11:00 SLT, although the hourly mean values obtained in December at 11:00 SLT are only slightly higher than those obtained at 12:00 SLT (e.g. 0.290 W/m^2 at 11:00 SLT vs. 0.285 W/m^2 at 12:00 SLT in December in San Carlos). The lowest maximum values are obtained in June: 0.096, 0.114 and 0.129 W/m^2 in Salta, San Carlos and El Rosal, respectively. The highest maximum values are obtained in February: 0.266, 0.292 and 0.315 W/m^2 in Salta, San Carlos and El Rosal, respectively.

In order to understand the behaviour of the maximum values of UVER, which will be later used to estimate the UV Index, a study of the most representative statistical indices of the UVER obtained at local noon has been performed for the three measurement sites. As an example, Tables 3 and 4 show the results obtained during January and June, respectively. These months usually present the highest and lowest records of UVER in the Southern Hemisphere, following the annual evolution of the total ozone column, which shows a minimum at the end of the summer in this hemisphere (February – April) [28].

In January, the absolute maxima of the UVER measured at local noon vary from 0.339 W/m^2 in San Carlos to 0.372 W/m^2 in El Rosal, whereas the absolute minima range between 0.065 W/m^2 in Salta and 0.190 W/m^2 in San Carlos. The difference (in percentage) between the absolute maxima and the P_{95} percentiles ranges from 0% (San Carlos and El Rosal) to 1.2% (Salta). These values are systematically lower than the difference observed between the absolute minima and the P_5 percentiles, which varies between 0% (San Carlos) and 37% (Salta). The absolute extreme values (maximum and minimum) have been also compared with their corresponding quartile values (Q_3 and Q_1, respectively) to verify if they are representative of the

Table 2
Geographical coordinates and number of available data of the measurement sites used in this study.

	Latitude (°S)	Longitude (°W)	Altitude (m a.s.l.)	1-minute data	Hourly data	Daily data
Salta	24.729	64.409	1190	440,783	8085	644
San Carlos	25.890	65.923	1611	313,971	5541	434
El Rosal	24.392	65.767	3355	429,733	7906	699

UVER records for all the measurement sites. The difference between the Q_1 quartiles and the absolute minima ranges from 36% (San Carlos) to 79% (Salta), whereas the difference between the Q_3 quartiles and the absolute maxima varies between 4.3% (San Carlos) and 9.8% (Salta). Therefore, although the maximum values can be considered representative of the

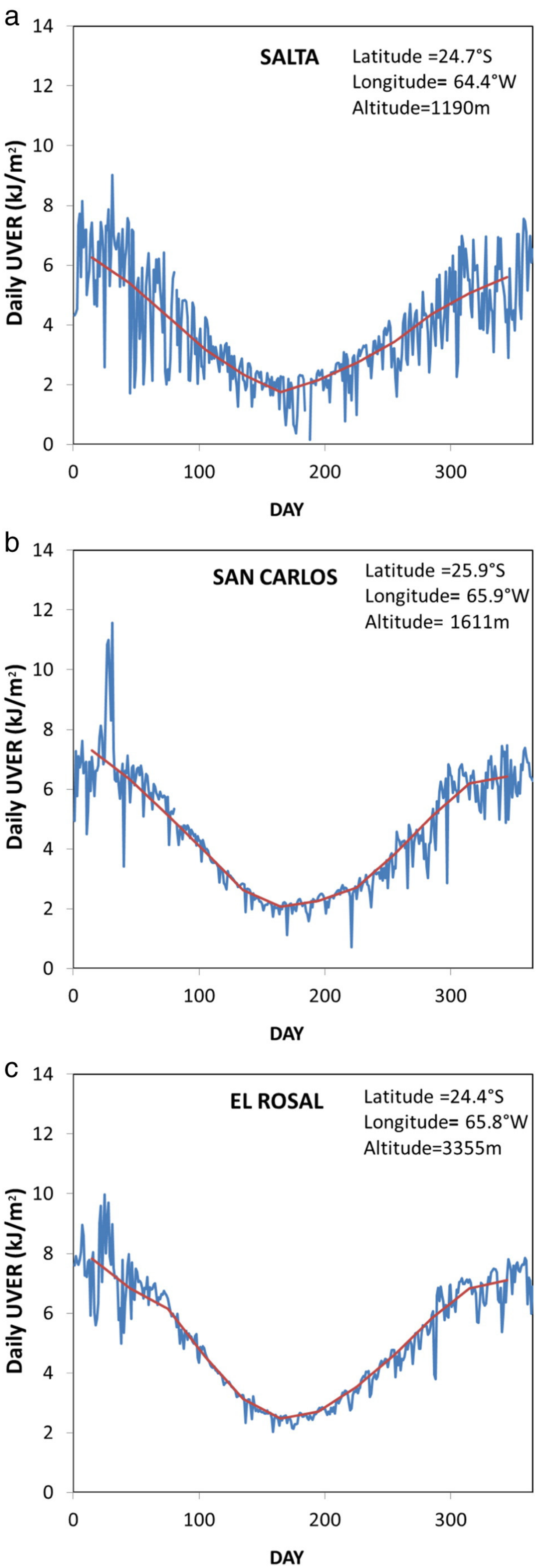

Fig. 1. Annual evolution of cumulative daily values and monthly mean daily values of UVER at: (a) Salta, (b) San Carlos, and (c) El Rosal. The observed fluctuations in summer may be caused by the “Bolivian winter”. The stronger fluctuations throughout the year in Salta may be explained by the possibility, which increases with altitude, of clouds remaining below the measurement site.

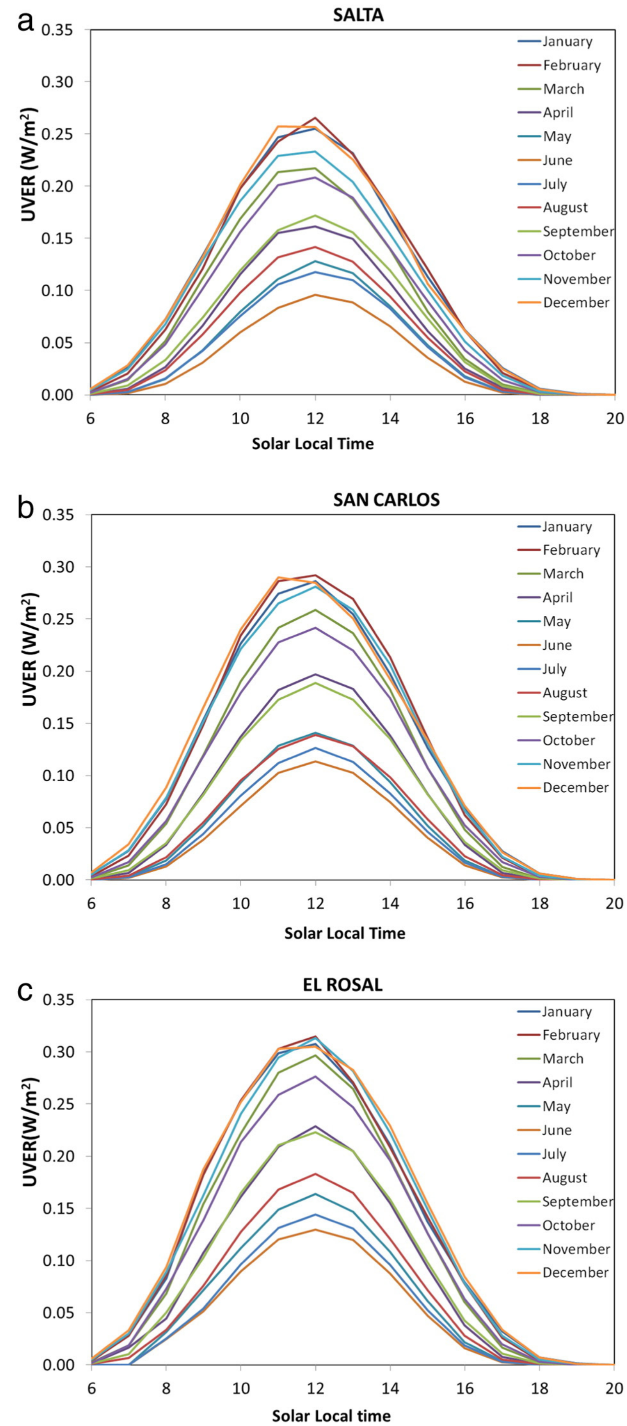

Fig. 2. Daily evolution of the hourly mean values of UVER for each month at: (a) Salta, (b) San Carlos, and (c) El Rosal.

Table 3
Statistical indices of the hourly UVER irradiance, in January, at solar noon for each location.

	Mean	SD	Median	Mx	Mn	Q_1	Q_3	P_5	P_{95}
Salta	0.255	0.070	0.281	0.345	0.065	0.281	0.311	0.104	0.341
San Carlos	0.286	0.042	0.299	0.339	0.190	0.299	0.323	0.190	0.339
El Rosal	0.308	0.049	0.321	0.372	0.160	0.321	0.340	0.195	0.372

UVER at local noon in January, the minimum values represent unusual extreme values for this month.

The maximum values obtained in the Southern Hemisphere are higher than those obtained in the Northern Hemisphere for similar latitudes and altitudes [35,36]. For example, the absolute UVB maximum for ten years in Spain was 1.855 W/m^2 in Ciudad Real (38.98° N, 3.92° W, 620 m a.s.l.) [38], while the highest irradiance measured in Córdoba (Argentina) (31.44° S, 64.19° W, 400 m a.s.l.) was 2.650 W/m^2 [28]. The maximum UVER values obtained at solar noon in El Rosal and San Carlos (Table 3) are of the same order than those estimated for two stations in the Northern Hemisphere located at higher altitudes in the western Himalayas: the maximum UVER at local noon at Hanle (32.78° N, 78.97E, 4517 m a.s.l.) was 0.375 W/m^2 and at Leh (34.15° N, 77.57°E, 3441 m a.s.l.) was 0.333 W/m^2 [42].

In June, the values of the absolute maximum range from 0.126 W/m^2 in San Carlos to 0.145 W/m^2 in El Rosal, whereas the values of the absolute minimum vary between 0.021 W/m^2 in Salta and 0.081 W/m^2 in El Rosal. As it happened for January, the difference between the absolute maxima and the P_{95} percentiles is systematically lower than that observed between the absolute minima and the P_5 percentiles. These differences vary between 0.7% (El Rosal) and 0.8% (Salta) for the absolute maxima and P_{95} percentiles, and between 0.8% (Salta) and 34% (San Carlos) for the absolute minima and P_5 percentiles. The comparison of the extreme values with their corresponding quartiles shows a variation between 40% (El Rosal) and 82% (Salta) for the difference between the Q_1 quartiles and the absolute minima, whereas the difference between the Q_3 quartiles and the absolute maxima ranges from 2.8% (El Rosal) to 6.1% (Salta). Thus, as it happened for January, the maximum values can be considered representative of the UVER at local noon in June, while the minimum values cannot.

3.2. UV Index

The UV Index has been determined from the UVER measurements using two different criteria: a) the value at solar noon, which was the criterion used up to 1998; b) the maximum daily value, currently recommended by all the international organisations [23]. Thus, an elementary statistical analysis of the differences between the UVI values obtained with each criterion at each location has been performed (Fig. 3). The coincidence percentage for Salta was of 75.4%, whereas in 12.2% of the cases there was a difference of one UVI unit and in 12.4% of the cases the difference was two or more UVI units. However, in San Carlos and El Rosal, the coincidence percentage was of 89.5% and 90.5%, with differences of one UVI unit in 4.4% and 3.7% of the cases, respectively, and differences of two or more UVI units in 5.6% and 6.3% of the cases, respectively. Therefore, the value of the UV Index at solar noon disagreed with the daily maximum value by one or less in 87.6%, 93.9% and 94.2% of the cases considered for Salta, San Carlos and El Rosal, respectively. It is observed that the level of agreement between

Table 4
Statistical indices of the hourly UVER irradiance, in June, at solar noon for each location.

	Mean	SD	Median	Mx	Mn	Q_1	Q_3	P_5	P_{95}
Salta	0.096	0.034	0.111	0.131	0.021	0.111	0.123	0.022	0.130
San Carlos	0.114	0.014	0.117	0.126	0.050	0.117	0.120	0.075	0.125
El Rosal	0.129	0.015	0.135	0.145	0.081	0.135	0.140	0.090	0.144

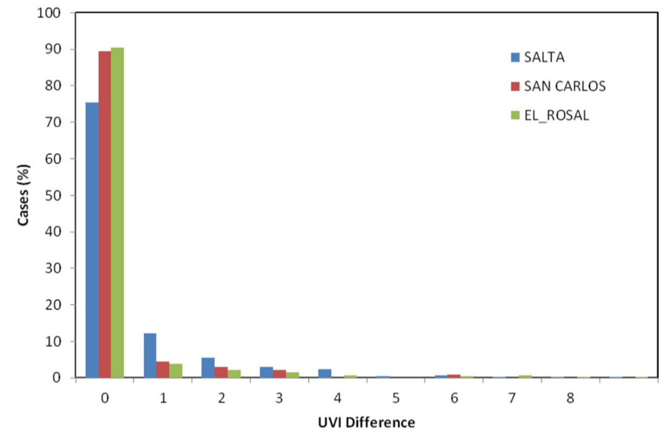

Fig. 3. Differences between the values of the UV Index at solar noon and the maximum daily UVI (in integer UVI units) at: (a) Salta, (b) San Carlos, and (c) El Rosal.

the two criteria increases with the location's altitude, which could be explained by the possibility of clouds remaining below the altitude of the measurement site, also observed in Fig. 1. These results are comparable to those obtained by Utrillas et al. [37], who analyzed 10 years of measurements in 14 stations of the Spanish UVB Radiometric Network, and found that the percentage of cases for which the difference between the two criteria was zero or one UVI unit varied between 89% (A Coruña) and 95% (El Arenosillo, Huelva), with an average value of 92%.

Table 5 shows the recurrence, in percentage (%), of the daily maximum values of the UV Index for the three measurement stations classified according to the exposition categories and using the colour code recommended by the WHO [23]. The UVI reaches high (6–7), very high (8–10) or extreme (>11) values in 67.4% of the cases in Salta, whereas in San Carlos and El Rosal these values are reached in 76.8% and 88.8% of the cases, respectively. The extreme values account for 33.4% and 41.6% in San Carlos and El Rosal, but in Salta these values only represent 24.7%. Since the measurement period in San Carlos is from 1 January 2013 to 18 March 2014, i.e., a complete year and a second summer, the percentage of very high or extreme UVI values could be higher than expected if two complete years had been considered as in the other two measurement sites. Extreme values are obtained at stations with similar high altitudes as well. For example, a maximum UV Index of 20 was obtained at Mauna Loa (Hawai) (19.5°N, 3400 m a.s.l.) [43], and of 18 at Lhasa in the Tibet region (29.63°N, 3698 m a.s.l.) [44]. In the Southern Hemisphere, a maximum UV Index of 20 was also obtained in La Quiaca in the Andean Antiplano (22.11°S, 3459 m a.s.l.) [33].

Low (<2) values of the UV Index are reached in 6.2% of the cases in Salta and very rarely (0.8%) in San Carlos and El Rosal (0.4%), Table 5. Maximum protection must be adopted against the extreme values reached in these three locations by wearing long-sleeved shirts, sunglasses, hats, total sunscreen of SPF 50 + and avoid sunbathing between 10 and 14 GMT [23].

Table 5
Days (in %, during the two years considered) in which the indicated maximum value of the UV Index is reached in each measurement site. The UVI has been classified according to the exposition categories and the colour code recommended by the WHO [23].

Station	UV index (%)				
	<2 low	3–5 moderate	6–7 high	8–10 very high	>11 extreme
Salta	6.2	26.4	21.7	21.0	24.7
San Carlos*	0.8	22.4	20.2	23.2	33.4
El Rosal	0.4	10.8	22.4	24.8	41.6

*Period from 1 January 2013 to 18 March 2014.

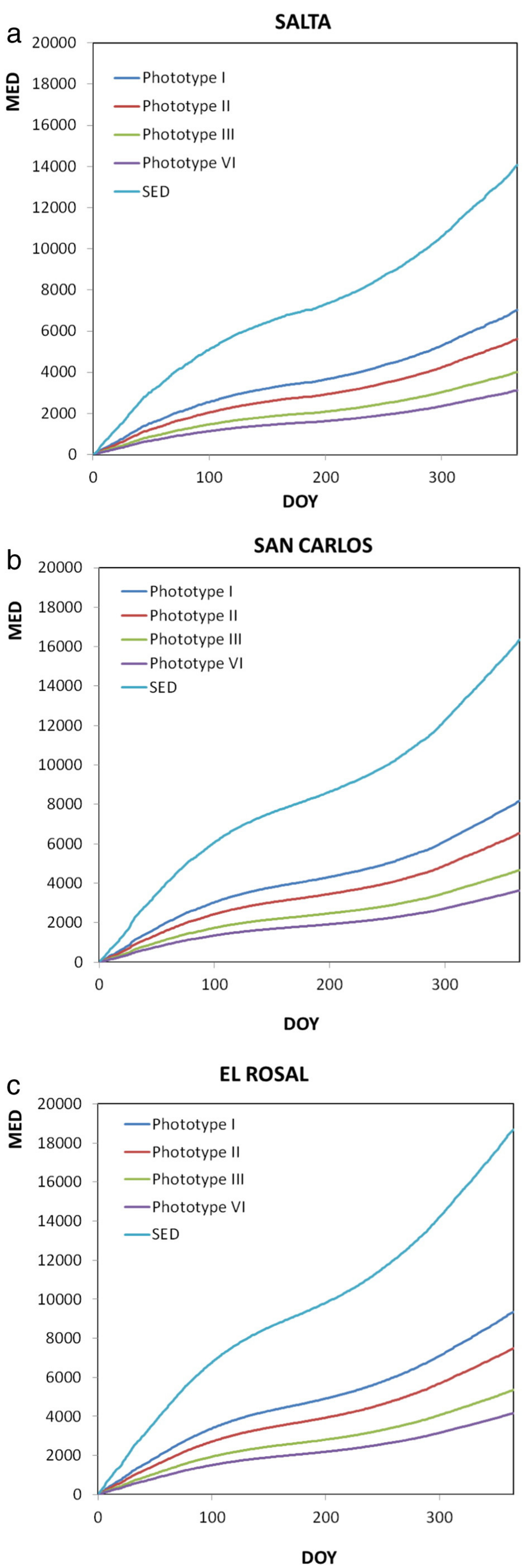

Fig. 4. Annual cumulative dose for the skin types defined by ISO 17166 CIE S 007/E [23] and the Standard Erythemal Dose at: (a) Salta, (b) San Carlos, and (c) El Rosal.

3.3. Cumulative Doses

Fig. 4 shows the annual cumulative dose for each phototype and for the Standard Erythemal Dose obtained dividing the daily UVER values by the corresponding MED and SED values over an average year at the three measurement sites. These values correspond to a continuous and uninterrupted exposure to the sun, on a horizontal position, throughout the year. It is observed that the cumulative doses during an average year range from 14062 SEDs in Salta to 18,678 SEDs in El Rosal, with the highest value being reached in the measurement site located at the highest altitude (3355 m a.s.l.). The most common skin type in Argentina, phototype III, could receive an annual cumulative dose between 4018 in Salta and 5337 in El Rosal. These curves also show a clear change of slope during the austral summer (December, January, and February). If we estimate the cumulative doses for each season, we observe that 34% of the annual cumulative dose is received in summer, 32% in autumn, 18% in winter, and 16% in spring. The large difference found between the autumn and spring contributions to the annual dose is due to the combined effect of the Earth orbit around the sun (producing maximum broadband radiation in December in the Southern Hemisphere) and the annual evolution of the ozone layer (showing a minimum in the total ozone column in February–April in the Southern Hemisphere). Therefore, the UVER values in the Southern Hemisphere are much higher in summer and autumn than spring and winter, being the summer values also slightly higher than autumn.

4. Conclusions

Measurements of ultraviolet erythemal radiation (UVER) made during two years at three sites located at altitudes over 1000 m a.s.l. in Northwestern Argentina (Salta, San Carlos, and El Rosal) have been analyzed. These measurements have been used to estimate the UV Index (UVI) and the cumulative doses, which have been analyzed as well. The novelty of this work resides in the fact that it is the first thorough analysis of this type performed in this region of the Southern Hemisphere.

The annual evolution of the UVER at the three measurement sites follows a sinusoidal evolution, with a minimum in June (austral winter) and a maximum in January (austral summer). UVER data obtained in January (maximum values) and June (minimum values) have been analyzed as representative of the year for all locations. Since the difference between the Q_1 quartile and the absolute minima is high (36–79%), whereas the difference between the Q_3 quartile and the absolute maxima is small (4.3–9.8%), the maximum values can be considered representative of the UVER at local noon, but the minimum values represent unusual extreme values.

The UV Index shows minimum differences between the value at solar noon and the maximum daily value, with >90% of the cases showing differences of one or less UVI units for the three measurement sites. It has also been observed that the UVI reached high (6–7), very high (8–10) or extreme (>11) values in 67.4% of the cases in Salta, whereas in San Carlos and El Rosal these values were reached in 76.8% and 88.8% of the cases, respectively. The extreme values represent 33.4% and 41.6% in San Carlos and El Rosal, but only 24.7% of the cases in Salta.

Finally, the cumulative doses for each phototype and for the Standard Erythemal Dose over an average year have also been studied for each location. The doses received during austral summer and autumn are of the same order, and represent one third of the annual dose, while the doses received during austral winter and spring represent one sixth of the annual dose approximately.

Therefore, this study shows that the UVER values obtained in Northwestern Argentina are of the same order than those obtained in other regions of the Southern Hemisphere with similar latitudes and altitudes, although these are higher than those obtained for the Northern Hemisphere. Moreover, very extreme values of UV Index have been measured in both hemispheres for stations located at very high altitudes (above 3000 m a.s.l.).

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