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PAPER

Availability of vitamin D photoconversion weighted UV radiation in southern South America

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Ultraviolet radiation (UVR) plays a key role in several biological functions, including human health. Skin exposure to UVR is the main factor in vitamin D photoconversion. There is also evidence relating low levels of vitamin D with certain internal cancers, mainly colon, breast and prostate, as well as other diseases. Several epidemiological studies have shown an inverse relationship between the above-mentioned diseases and latitude, in accordance with the ultraviolet radiation latitudinal gradient. The aim of this study is to determine whether UV irradiance levels in the southern South America are sufficient to produce suitable levels of vitamin D year around. For this purpose, vitamin D photoconversion weighted-irradiance was analyzed between S.S. de Jujuy (24.17°S, 65.02°W) and Ushuaia (54° 50′S, 68° 18′W). In addition to irradiance, skin type and area of body exposed to sunlight are critical factors in vitamin D epidemiology. Due to a broad ethnic variability, it was assumed that the skin type in this region varies between II and V (from the most to the less sensitive). All sites except South Patagonia indicate that skin II under any condition of body area exposure and skin V when exposing head, hands, arms and legs, would produce suitable levels of vitamin D year round (except for some days in winter at North Patagonian sites). At South Patagonian sites, minimum healthy levels of vitamin D year round can be reached only by the more sensitive skin II type, if exposing head, hands, arms and legs, which is not a realistic scenario during winter. At these southern latitudes, healthy vitamin D levels would not be obtained between mid May and beginning of August if exposing only the head. Skin V with head exposure is the most critical situation; with the exception of the tropics, sun exposure would not produce suitable levels of vitamin D around winter, during a time period that varies with latitude. Analyzing the best exposure time during the day in order to obtain a suitable level of vitamin D without risk of sunburn, it was concluded that noon is best during winter, as determined previously. For skin type II when exposing head, exposure period in winter varies between 30 and 130 min, according to latitude, except for South Patagonian sites. During summer, noon seems to be a good time of day for short periods of exposure, while during leisure times, longer periods of exposure without risk of sunburn are possible at mid-morning and mid-afternoon. At 3 h from noon, solar zenith angles are almost the same for sites between the tropics and North Patagonia, and at 4 h from noon, for all sites. Then, in these cases, the necessary exposure periods varied slightly between sites, only due to meteorological differences.

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Introduction

Ultraviolet radiation (UVR) can affect biological systems producing harmful (*i.e.* deoxyribonucleic acid (DNA) damage)[1–6] or beneficial effects (*i.e.* vitamin D production).[5,6] The direct relationship between UVR and skin cancer is well established,[1–6] and the effect of UVR in diminishing internal cancer risk (prostate, breast and colon) was first proposed in 1937.[7] Since then, many studies have shown an inverse relationship between UVR and the incidence of internal cancers. The connection would be vitamin D.[8–21] The evidence of latitudinal dependence for some internal cancers (breast and colon) is strong, and in others is under discussion (prostate).[22] In addition, low serum levels of vitamin D are related to some other diseases: immune suppression, diabetes type I, multiple sclerosis, high blood pressure, cardiovascular diseases and infectious diseases,[23–33] although a recent study showed that, in the case of multiple sclerosis, the effect of UVR could be independent of the production of vitamin D.[34]

Mortality as consequence of some types of cancers has shown a geographical distribution, with an inverse correlation with UVR levels but not with other factors (*e.g.*, dietary or smoking habits).[8,19,35–37] In 1941, Apperly[38] first found this inverse relation between latitude and some internal cancers, which was later verified by others.[39–43] It has been estimated that up to 400 000 people die prematurely in the USA[44] as consequence of an internal cancer caused by insufficient vitamin D.

The level of vitamin D is closely related to UVR as a function of latitude and seasons. Inhabitants of mid to high latitudes experience a seasonal cycle in hydroxyvitamin D (usual measure of vitamin D status) concentration.[45] Studies performed in Norway showed that the levels of 25-hydroxyvitamin D in serum are about 50% higher in late summer than in late winter,[19,46] and, all other conditions remaining the same, annual vitamin D production increases 50% for each 10 degrees of decrease in latitude. Vitamin D deficiencies are then common at higher latitudes, mainly in winter.[20,47,48] A study carried out in Denmark showed that the accumulated summer exposure to solar UVR correlated well with the vitamin D status of the individual, in the summer months and in the following winter months.[49] As a result of determining the vitamin D status of populations in different countries, it has been observed that, in general, people of all ages are below the level considered safe.[50,51]

Since UVR shows an important latitudinal gradient, as the result of changing solar zenith angle (SZA) and total ozone column, and, given the North to South extension of Chile and Argentina, it may be inferred that the populations of these countries present a variety of exposure levels and that population of southern regions could receive a low amount of UVR compared with that received in central and northern areas.[52] Vitamin D deficiencies in Ushuaia (54.5°S) are well documented[53] and supplementation of this vitamin was recommended to avoid rickets in children.

Recently, several studies have focused on the relation between vitamin D weighted and erythema weighted UVR,[54–58] and efforts have also focused on deriving vitamin D weighted irradiance from erythema weighted irradiance, since the last parameter is often available through UV Index (UVI). With the aim of optimizing sun exposure, Webb and Engelsen[58] found that, where solar UVR is sufficient, risk-benefit (sunburn *vs.* vitamin D synthesis) diminishes for brief sun exposure in the middle of the day. They also found that, for large SZA typical of high latitudes during winter, a fine line exists between adequate UVR exposure for vitamin D_3 production and the risk of sunburn. Thus, knowledge of UVR at different latitudes is needed to plan for sufficient but not excess exposure to UVR, in order to maximize vitamin D in the body and avoid harmful effects.

In the present paper, UVR at different sites in the southern tip of South America has been studied to determine the regions with possible risk of vitamin D deficiency. To our knowledge, there is no other study of this extent in this area. Daily maximum and daily integrated irradiances have been analyzed for the irradiance weighted by the action spectrum of vitamin D photoconversion, and compared to the levels necessary for suitable vitamin D production. In addition, time of the day when that condition may be satisfied avoiding sunburn risk, are analyzed for summer and winter. Our results are limited by the variability introduced when considering exposure by horizontal surfaces (as on the radiometer) and the vertical planes of a human body in motion.[59]

Materials and methods

Determination of vitamin D and erythema weighted irradiance

Measurements from the multi-channel instruments of the network IAIRadNet (IAI Radiation Network)[52] in Chile and Argentina have been used to determine UVR levels. The stations considered in this study are presented in Table 1.

The instruments were installed during the 1990s by different national and international efforts and are still in operation, a few of them with temporary gaps. The geographical distribution of the stations provides information on UVR at the regional scale (sub-tropical to sub-Antarctic). Data from 1995 to 2002 are used in this study, since quality and consistency have been checked for that period.[52] The instrument presently at Trelew was originally installed at Puerto Madryn and then, briefly, in Playa Union. These sites are 60 and 25 kilometres, respectively, from Trelew.

The GUV-511 is a temperature stabilized multi-channel radiometer, which measures downwelling irradiances with moderately narrow bandwidth (near 10 nm) at approximately 305, 320, 340 and 380 nm, and photosynthetically available radiation (PAR; 400–700 nm).[60] In normal operation, all channels take a measurement every 0.5 s and store an average of 120 readings per minute, 24 h per day, year round. Raw data were processed applying the procedure explained in Diaz *et al.*[52] Between 1995 and 2002, the GUV-511 radiometers were periodically sun calibrated, usually once per year, with a traveling reference GUV (RGUV). During the calibration of the RGUV, output voltage from each channel was related to the calibrated spectral irradiance at the nominal central wavelength of the channel. Then the GUVs were calibrated against the RGUV, and as a result a calibrated monochromatic irradiance was obtained for each channel.[52]

Instantaneous values of vitamin D and erythema weighted irradiance were calculated, applying the methodology described in Vernet *et al.*[61] Coefficients and validation of the derivation for vitamin D photoconversion and erythemally weighted UVR are given in the Appendix. Hourly averaged weighted irradiance were calculated from instantaneous weighted irradiance for each of the IAIRadNet stations (Table 1). From there, vitamin D

Table 1 Stations, describing site, geographical coordinates and altitude above sea level, and the data period included in the present paper

Site	Geographic coordinates and altitude	Time series
San Salvador de Jujuy (Argentina)	24.17°S, 65.02°W, 1300 m	1 Jan 1995–31 Dec 2002
Buenos Aires (Argentina)	34.58°S, 58.47°W, sea level	1 Jan 1995–31 Dec 2002
Santiago de Chile (Chile)	33.41°S, 70.65°W, 543 m	1 Jan 1995–31 Dec 2002 (except 1997)
San Carlos de Bariloche (Argentina)	41.01°S, 71.42°W, 700 m	7 Aug 1998–31 Dec 2002
Valdivia (Chile)	39.81°S, 73.25°W, sea level	1 Jan 1995–31 Dec 2002
Puerto Madryn–Playa Unión–Trelew (Argentina)	P.M: 43.3°S, 65.05°W; Trl.: 43.25°S, 65.31°W, sea level	1 Jan 1995–31 Dec 2002
Punta Arenas (Chile)	53.09°S, 70.55°W, sea level	1 Jan 1995–31 Dec 2002 (except 1997)
Ushuaia (Argentina)	54.50°S, 68.18°W, sea level	1 Jan 1995–31 Dec 2002

Table 2 Skin type classification according to Fitzpatrick, 1988. 1 SED = 100 J m^{-2} of erythema weighted irradiance integrated over continuous time of exposure. SED is Standard Erythemal Dose

Skin type	Description	SED to produce erythema
I	Celtic (always burns)	2–3
II	Pale (burns easily)	2.5–3
III	Caucasian (may burn)	3–5
IV	Mediterranean (rarely burns)	4.5–6
V	South American (rarely burns)	6–20
VI	Negroid (rarely burns)	6–20

daily maximum and daily doses and hourly ratio of vitamin D photoconversion/erythema weighted irradiances were obtained.

Determination of vitamin D and erythemal doses

In addition to ambient radiation, other factors affect vitamin D photoconversion and sunburn. Both processes are inversely related to the skin type, but additionally, vitamin D production is assumed to be directly proportional to the exposed body area.[56]

A relationship between the skin type and the necessary doses to produce erythema was established by Fitzpatrick.[62] Table 2 shows the minimum doses, expressed in SEDs (Standard Erythemal Dose), necessary to produce erythema for different skin types. The SED is a unit of erythema weighted irradiance accumulated in time, being 1 SED = 100 J m^{-2}. The values in the table indicate the doses of erythema weighted irradiance necessary to produce erythema for each skin type (*e.g.* Caucasian between 300 and 500 J m^{-2}). In the calculation of vitamin D doses, we followed the procedure proposed by McKenzie *et al.*,[56] where they applied the values in Table 2 for the correction for skin type, and the "rule of nines", to correct for exposed area. This rule is recommended by St. John's Ambulance to evaluate burns and it establishes that the head constitutes 9% of the body area ($A = 0.09$); head, hands and arms 27% ($A = 0.27$); and head, hands, arms and legs 63% ($A = 0.63$).[63]

Several studies have been carried out in order to determine exposure conditions to obtain suitable vitamin D levels. Webb and Engelsen[64] have modeled the erythema and vitamin D effective solar radiation for all seasons and latitudes to estimate the optimum exposures at different latitudes and skin types. Filetov *et al.*[65] studied the distribution of vitamin D weighted solar UV radiation over the USA and Canada, applying a statistical relationship between UV irradiance and global solar irradiance, total ozone and dew point temperature, validating the method with Brewer spectrophotometer measurements at 12 sites in Canada and 21 sites in the USA. Both studies, based their conclusions on Holick's,[15,16] where it was recommended exposure to $\frac{1}{4}$ of minimal erythemal dose (MED) on $\frac{1}{4}$ of skin area (hands, face and arms) to achieve one standard vitamin D dose (SDD), where 1 SDD corresponds to the UV equivalent of an oral dose of about 1000 IU vitamin D,[65] which is the dose recommended to have all the possible health benefits of vitamin D.[9] Fioletov *et al.*[65] determined that 1 SDD corresponds to 106 J m^{-2} of irradiance weighted by vitamin D action spectrum, for skin type II. From this value, 1 SDD for different skin types and exposed area can be obtained using the following equation:

$$\mathrm{SDD}_{\mathrm{SA}} = \frac{F \times \mathrm{SDD}_{\mathrm{Ref}}}{A_{\mathrm{Ref}}} \tag{1}$$

where $\mathrm{SDD}_{\mathrm{SA}}$ is standard vitamin D dose (SDD) for a given skin type S and exposed area A; $\mathrm{SDD}_{\mathrm{Ref}}$ is the reference SDD (for skin type II and exposure of hands, face and arms), 106 J m^{-2}; F is the skin type correction factor with respect to the reference skin type (type II); A_{Ref} is the exposed area correction factor regarding to the reference area (hands, face and arms). Since in Chile and Argentina there is a broad ethnic variety,[66,67] in our study, it was assumed that the skin type varies between II and V. Then, F, on average, varied between 1 and 5.[62] Regarding the exposed area, the extremes would be head in winter, and head, hands, arms and legs in summer (also trunk or part of it during summer). Following the rule of nines, A_{Ref} varied between 0.33 (exposure only head) and 2.33 (head, hands, arms and legs).[63]

Determination of best time of the day for exposure in order to obtain suitable vitamin D level without producing sunburn

The relation between vitamin D weighted irradiance and erythema weighted irradiance is not linear, being a function of geographic locations and season (mainly driven by ozone and SZA).[54–58,68] Furthermore, vitamin D action spectrum is sensitive to changes in the UV-B, while erythema to both UV-B and UV-A. With the aims of determining the best exposure conditions, Webb and Engelsen[64] studied the ratio vitamin D to erythema weighted irradiance, based on modeled clear sky irradiance, and they found the optimum exposure was at noon for a short time period. Since the necessary exposure period to obtain suitable levels of vitamin D without sunburn at noon during summer were very short, here, we explored also other times during the day, when exposure may be for longer periods, without sunburn risk, which may be of interest mainly during leisure time.

For a given skin type, the time needed to obtain one MED (Minimal Erythemal Dose) is:

$$t_1 = \frac{\mathrm{MED_S}}{I_{\mathrm{Er}}}$$

where t_1 is the time required to obtain one MED for skin type S; and I_{Er} is erythema weighted irradiance.

Also, for a given skin type and area exposed, the time needed to obtain one SDD is:

$$t_2 = \frac{\mathrm{SDD_{SA}}}{I_{\mathrm{VD}}}$$

where t_2 is the time required to obtain one SDD for skin type S and exposed area A; and I_{VD} is vitamin D weighted irradiance.

Then, to obtain a dose of vitamin D weighted irradiance that produces a suitable level of vitamin D without sunburn, t_1 needs to be larger than t_2, then:

$$R > \frac{\mathrm{SDD_{SA}}}{\mathrm{MED_S}} \tag{2}$$

where R is the ratio $I_{\mathrm{VD}}/I_{\mathrm{Er}}$.

In order to determine the time period during the day to produce enough vitamin D without sunburn risk, at each site, for different areas exposed, we calculated the mean value of R, for each hour of the day and months of the year, at each of the studied sites and seasons. By calculating the ratio of $I_{\mathrm{VD}}/I_{\mathrm{Er}}$ for each hour of the day and month we can determine when it is possible to produce enough vitamin D without sunburn risk, for different body area exposed and skin type. The R_{lim} is obtained when R equals the ratio $\mathrm{SDD_{SA}}/\mathrm{MED_S}$, or $t_1 = t_2$.[56] For R smaller than R_{lim}, it is not possible to produce a suitable level of vitamin D without sunburn risk. Since both vitamin D and erythema are function of the skin type, the factor for skin type correction (F) disappears when making the ratio, and only the exposed area remains as correcting factor.

Results

Irradiance limit to synthesize vitamin D in southern South America

Webb *et al.*[48] determined the limit level for vitamin D production *in vitro*, performing experiments with human skin. They established that for vitamin D production, the necessary irradiance levels were 0.024, 1.0 and 10 mW m^{-2}, at 300, 306 and 316 nm, respectively. Based on the values at the mentioned wavelengths, Edvardsen *et al.*[69] reconstructed the complete irradiance spectrum with the program LibRadTran (www.libradtran.org).[70] Afterward, they weighted the calculated spectrum with vitamin D action spectrum and integrated in the UV range, obtaining a limit value of 0.917 μW cm^{-2} of vitamin D weighted irradiance, in order to start vitamin D production. At present, this limit is being questioned and should rather be considered as an irradiance below which vitamin D production is too low.[56]

In Fig. 1, we compared the maximum daily value of vitamin D weighted irradiance measured for the sites of the IAIRadNet, in relation with the 0.917 μW cm^{-2} value. Logarithmic scale was used in the *y* axes to better depict the winter values.

In S. S. de Jujuy, all daily maximum values were above the limit, even in winter time. Central (Buenos Aires and Santiago de Chile) and North Patagonian sites (Valdivia, Bariloche and Trelew) were below the limit during a few days in winter. In South Patagonia (Punta Arenas and Ushuaia), maximum daily values did not reach the limit between Julian days 140 and 210 (mid of May to end of July). This implies that, during almost three month of the year the residents in those areas would be unable to produce vitamin D due to low incident UVR. The variability observed in reaching the limit value can be explained by the seasonal variation of minimum SZA for different latitudes (Fig. 2a). The daily minimum SZA observed at summer solstice in Ushuaia is observed in S. S. de Jujuy at the beginning of autumn, and the value at the winter solstice in S. S. de Jujuy is observed in later summer in Ushuaia. Since in this analysis we are considering the maximum daily value of the weighted irradiance, the situation observed here would be the best situation. When exposing at a different time of day, the limit would be reached more seldom since the irradiances would be lower than the observed maximum.

Determination of standard vitamin D dose (SDD)

The existence of a certain irradiance level is a necessary but not sufficient condition to guarantee a suitable level of vitamin D. Based on eqn (1), for skin type II, $\mathrm{SDD_{FA}}$ would be 321 J m^{-2}, when exposing only head and 45 J m^{-2}, when exposing head, hands, arms and legs; while, for skin type V, the corresponding values would be 1606 and 227 J m^{-2}

Daily doses of vitamin D weighted irradiance for each location were calculated from minute data of the IAIRadNet. Fig. 3 shows the daily doses and the calculated limit values for different skin types and exposed body area. For skin II, head, hand, arms and legs (he, ha, a, l), the daily irradiances were above the limit year round, except for a few days at South Patagonian sites; however, it should be pointed out that the clothing necessary to expose arms and legs is not appropriate at Central and Patagonian sites during winter. For skin II he, and skin V he, ha, a, l, daily irradiances were above the limit year round at S. S. de Jujuy. At central sites, only a few sparse days around winter were below the limit; and at North Patagonian sites, some days, also during winter. South Patagonian sites remained under the limit between mid May and beginning of August. Finally, skin V, head, is the most demanding in terms of irradiance daily doses. S. S. de Jujuy showed values above the limit year round, except for a few days, during winter; central sites were below the limit between the beginning of June and mid July; North Patagonian sites between mid May and end of July; and, finally, South Patagonian sites between mid April and end of August.

The ratio (R) between vitamin D weighted irradiance and erythema weighted irradiance

R is a function of geographic locations and season. The resulting values of R_{lim}, to produce vitamin D without sunburn risk, are 1.2, for head exposure, and 0.2, for head, hands, arms and legs, and is independent of the skin type. Time periods for $R < 0.2$, $0.2 \le R \le 1.2$ and $R > 1.2$, as a function of solar time and month, are shown in Fig. 4. In most locations, during summer, it would be possible to produce suitable levels of vitamin D without sunburn risk, exposing for a limited period of time up to 6 h before or after noon, when exposing head, hands, arms and legs ($R > 0.2$), and up to 5 h from noon, when exposing only head ($R > 1.2$). At

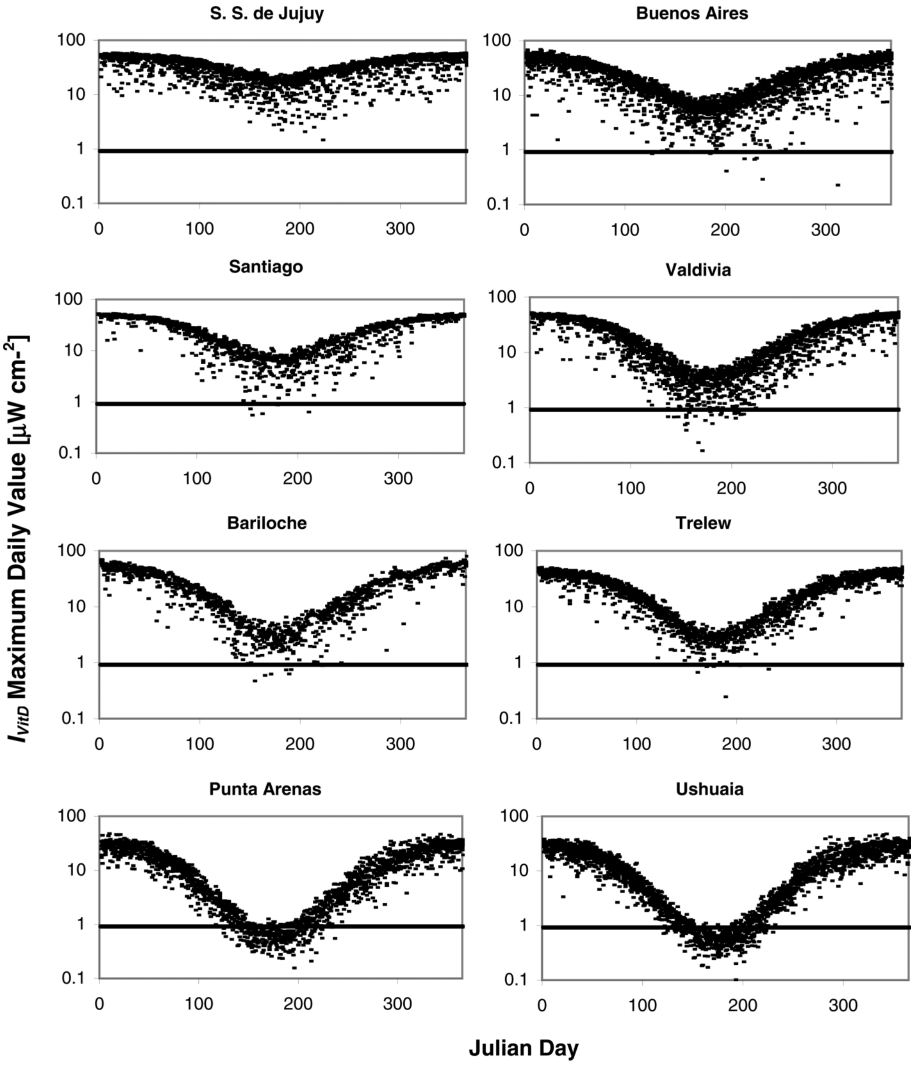

Fig. 1 Maximum daily values of vitamin D production weighted irradiance (I_D). Irradiance below which vitamin D production would not be possible or too low (0.917 μW cm^{-2}),[69] is indicated.

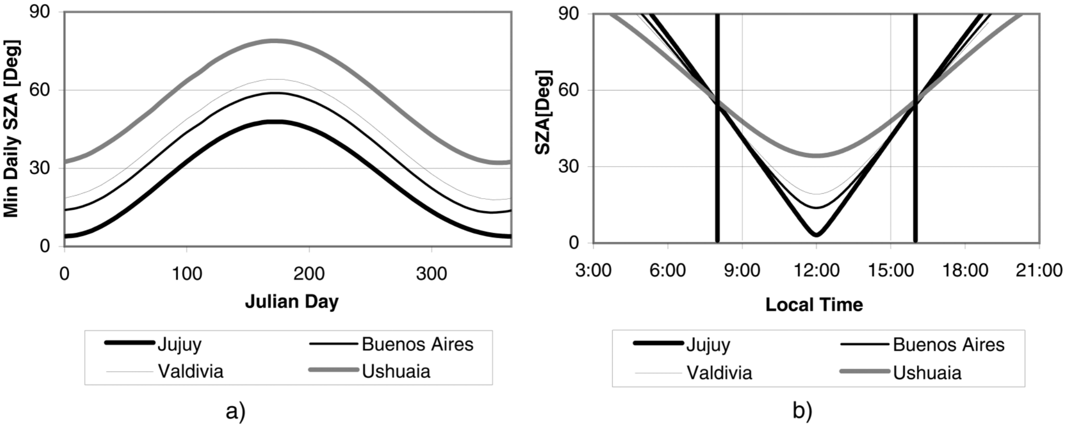

Fig. 2 (a) Seasonal variation of minimum daily (noon) solar zenith angle. (b) Solar zenith angles as function of time of the day for summer (Dec-Jan-Feb) to explain similarity in period of time needed to produce suitable level of vitamin D at different latitudes when exposing at 3 and 4 h from noon. For simplicity, only one site of each region was considered: S.S. Jujuy (tropical), thick black line; Buenos Aires (mid-latitude), mid line; Valdivia (Northern Patagonia), thin line; Ushuaia (Southern Patagonia), thick grey line.

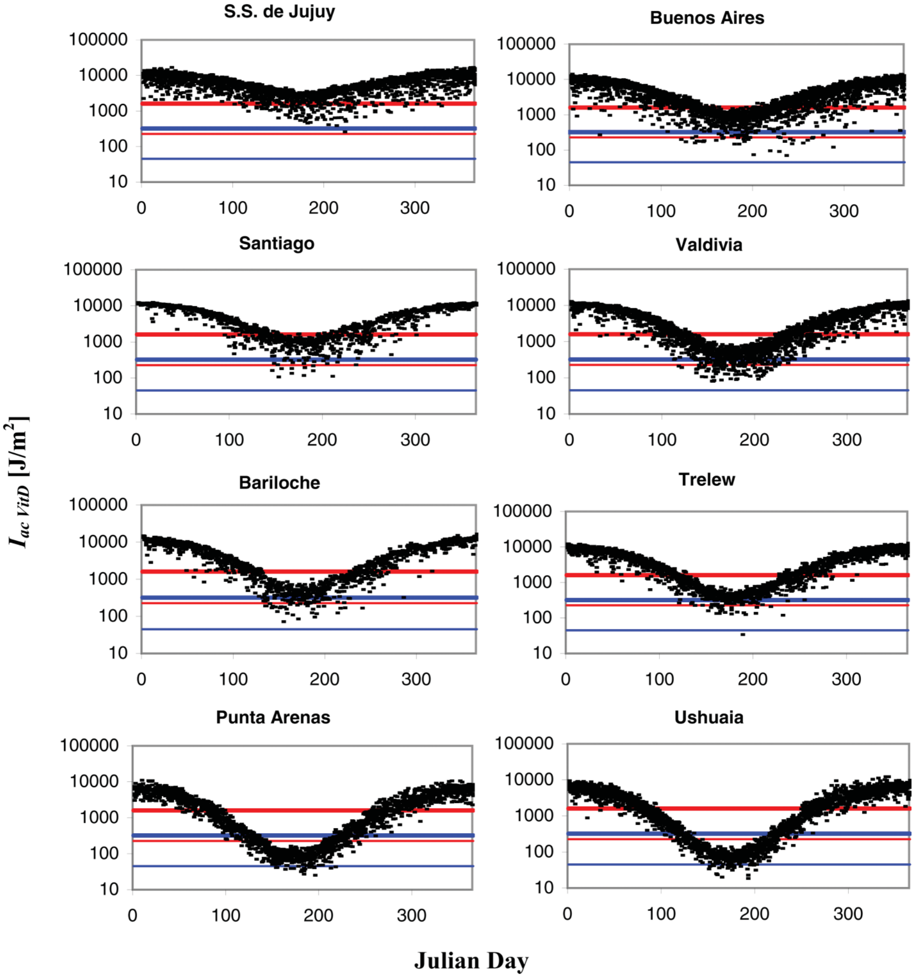

Fig. 3 Daily integrated vitamin D production weighted irradiance (I_{acVitD}) obtained from measurements (dots). Daily dose to produce a suitable level of vitamin D (lines) for (a) skin type II and exposure of head, hand, arms and legs (skin II, he, ha, a, l), thin blue line; (b) skin type II and exposure head (skin II, he), thick blue line; (c) skin type V, exposure head, hands, arms and legs (skin V, he, ha, a, l), thin red line; and (d) skin type V, exposure head (skin V, he), thick red line.

South Patagonian sites, the possibility extended up to 7 and 6 h from noon, respectively, since smaller SZAs are present early in the morning and late in the afternoon. On the other hand, in winter, the hour of the day when vitamin D photoconversion is possible without sunburn risk strongly varied with latitude. At tropical and central sites, the production of vitamin D would be possible up to 4 h before or after noon, when exposing head, hands, arms and leg, or up to 3 h from noon when exposing only head; at the North Patagonian sites, it would be up to 3 and 2, respectively. At Punta Arenas, it would be up to 3 and at Ushuaia, up to 2 h, but only if head, hands, arms and legs are exposed, which is not a realistic scenario for those latitudes in winter.

Exposure period

The necessary exposure period to obtain a suitable level of vitamin D will vary with the time of day. In winter, for skin II, he, at noon, the period necessary to produce a suitable level of vitamin D varied with latitude, from 29 to 131 min, and from 46 and 155 min, to get an erythema, for sites between the tropics and North Patagonia; and it would not be possible to produce suitable levels of vitamin D or sunburn at the South Patagonian sites (Table 3). In summer, for same skin type and exposed area, slight differences were observed in the exposure period necessary to produce suitable levels of vitamin D and erythema, between the tropics and North Patagonian sites (11 to 14 min for vitamin D and 18 to 23 min for erythema), while at the southern sites longer periods were needed (24 min for vitamin D and 37 to 38 min for erythema). The difference observed in the exposure period between sites and seasons is mainly explained by the variation in minimum daily (noon) SZA (Fig. 2a).

As the periods necessary to produce a suitable level of vitamin D and erythema were very short at noon and very closed, in summer, we explored other exposure conditions that may allow a longer stay outside without risk of erythema, which is more appropriate during leisure times. The necessary exposure time for 3 and 4 h before or after noon were obtained. In these cases, the difference between the time necessary to produce a suitable level of vitamin D and to produce a sunburn varied between 15 and 25 min (at 3 h from noon) and between 24 and 38 min (at 4 h from noon) (Table 3). It may be observed that for exposure at 3 or 4 h from noon, time variation did not show a marked

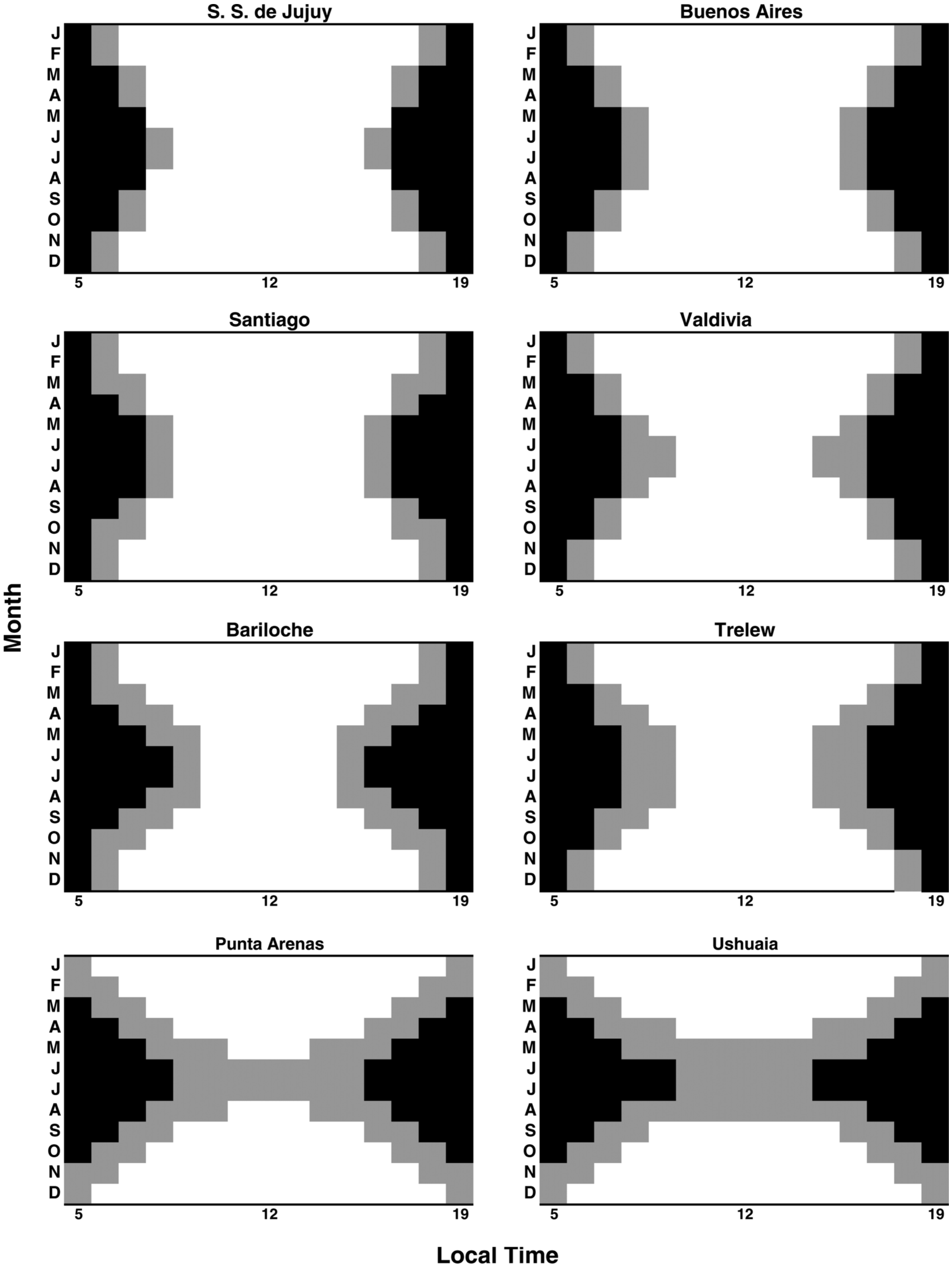

Fig. 4 Ratio of vitamin D production weighted irradiance to erythema weighted irradiance, mean value for each hour and month calculated from averaged hourly values of time series 1995–2002. The shades indicate the possibility of producing a suitable level of vitamin D without sunburn risk. Black, $R < 0.2$, indicates times of the day when it is not possible to produce suitable levels of vitamin D without sunburn; grey, $0.2 \leq R \leq 1.2$, it is possible to produce suitable levels of vitamin D, only exposing head, hands, arms and legs; and white, $R > 1.2$, it is possible to produce suitable levels of vitamin D exposing just the head.

latitudinal variation, with even longer times for S.S. of Jujuy than sites at North Patagonia. This result is explained also by SZAs. At 3 h from noon, SZAs are about the same for sites between the tropics and North Patagonia (near 40°), and at 4 h from noon, SZAs for all sites are about the same (near 55°) (Fig. 2b). In consequence, the observed differences in the period of exposure between the sites, at these times of the day, are related to local meteorological conditions, and not to its latitude. The longer time periods observed at S.S. de Jujuy are a consequence of the presence of the wet season in that region during summer. On the other hand, South Patagonian sites are overcast most of the year. It should be pointed out that values in Table 3 were calculated

Table 3 Exposure period, in minutes, necessary to produce a suitable level of vitamin D and erythema (sunburn), at different sites and time of the day, for summer months (DJF) and winter months (JJA). The values in the table were calculated from minute average for summer months or winter months. Also, the exposure period indicated in the table means half of that period before and half after the time under consideration; for example, 12 min at noon means 6 min before and 6 after solar noon

	Noon mid-summer		Noon mid-winter		3 h from noon summer		4 h from noon summer	
Site	Vit D	Eryth	Vit D	Eryth	Vit D	Eryth	Vit D	Eryth
S. S. de Jujuy	11	18	29	46	31	53	67	105
Buenos Aires	13	21	75	113	27	45	57	85
Santiago	12	21	73	119	25	40	51	77
Valdivia	13	20	135	173	25	40	49	73
Bariloche	12	19	131	163	25	41	51	77
Trelew	14	23	131	155	28	45	53	77
Punta Arenas	24	37	n. p.	n. p.	42	65	75	103
Ushuaia	24	38	n. p.	n. p.	42	67	76	107

from minute average for summer months (Dec-Jan-Feb) or winter months (Jun-Jul-Aug). Also, the exposure period indicated in the table means half of that period before and half after the time under consideration; for example, 12 min at noon means 6 min before and 6 after solar noon.

These results correspond to skin type II and head exposure. For skin type V exposure periods may be approximated by multiplying by 5 the values in the table; and for exposure of head, hands, arms and legs, by dividing by 7, but in this latter case, only for vitamin D, since no correction is necessary for erythema.

Our estimates of exposure time (Table 3) are similar to those by McKenzie *et al.* (Table 2),[56] who estimated vitamin D photoconversion and exposure time as a function of the UV Index (UVI = 40 × I_{Er}). In general, values are in good agreement for UVI larger than 4. For example, for UVI = 10, the time for erythema is 18 min, while for vitamin D, it is 10 min for McKenzie *et al.*,[56] and 11 min in our calculation. For small UVI, some of the values agree but others show a difference of several minutes. Particularly, for UVI smaller than 2, differences can be as large as 50 min. For example, in Table 3, at noon in mid-winter, in Valdivia, the mean UVI value would be slightly larger than 1, with 173 min necessary to produce erythema and 135 min to produce a suitable level of vitamin D. Interpolating in Table 2 of McKenzie *et al.*,[56] the corresponding time for vitamin D would be 185 min. The difference in time of exposure between studies relates to the method used. For small UVIs, the exposure time needed could be even half of the value obtained[56] by McKenzie *et al.*, given that for each UVI value, there is a range of possible $I_{\mathrm{VD}}/I_{\mathrm{Er}}$ ratios, and the range is larger as UVI becomes smaller.[56] In their calculations, McKenzie *et al.* considered the worst scenario, which is given by the lower limit of the envelope of the ratio, while in Table 3, we used the mean value.

The irradiance used in this study, and in many of the referenced studies, is the ambient solar UVR, measured as the radiation incident on a flat, horizontal surface. In consequence, the results presented here may differ from those in real life. The human body presents surfaces with different orientations, which change with the motion of the person relative to the position of the sun in the sky. Webb *at al*[59] performed a study modelling the solar radiation incident on vertical surfaces, at different positions with respect to the sun, and compared with the incidence on a horizontal surface. The time necessary to obtain a given dose at both exposure situations (*i.e.* horizontal and vertical) varied by a factor that ranged from 1.4 to 4, being function of the position of the vertical surface with respect to the sun and the SZA.[59]

4. Discussion and conclusions

The aim of this study was to determine whether the irradiance level in the southern part of South America is sufficient to obtain suitable levels of vitamin D for all months of the year, and to determine time of the day when that is possible without sunburn risk.

The analysis of instantaneous irradiance showed that the southernmost sites (Ushuaia and Punta Arenas) would not reach the limit for vitamin D production during almost three months of the year, while for S. S. de Jujuy the values were always above the this limit. For the other sites, the limit level was reached most of the time, except for a few days during winter.

When analyzing the necessary dose to obtain suitable serum levels of vitamin D, additional parameters, skin type and exposed area were introduced. For all sites, except South Patagonian stations, skin II, under any condition of area of the body exposed and skin V, exposing head, hands, arms and legs, would not have problems in producing suitable levels of vitamin D (except for some days in winter at North Patagonian sites). For South Patagonian sites, it would only be possible to obtain acceptable levels of vitamin D year round for skin II, if exposing head, hands, arms and legs, which is not realistic clothing due to low temperatures at those sites. Exposing only head, the suitable level would not be obtained between mid May and beginning of August. The same considerations as skin II, head, apply to skin V, head, hands, arms and legs. Finally, skin V, exposing head, is the most demanding situation, and, with the exception of the tropical station (S. S. de Jujuy), the doses would not reach a level to allow acceptable levels of vitamin D for a period around winter. This period varied with latitude, from beginning of June to mid July for central sites; between mid May and end of July for North Patagonian sites; and between mid April and end of August for South Patagonian sites (Table 4).

Analyzing the best the time of the day to expose in order to obtain a suitable level of vitamin D without sunburn risk, it was concluded that noon is the best moment during winter, in agreement with Webb and Engelsen.[64] The necessary exposure period, for skin type II, exposing head, varies between 30 and 130 min, according to latitude, except for South Patagonian sites,

Table 4 Availability of daily accumulated irradiance for photoproduction of a suitable level of vitamin D, for skin type II and V and two different exposure situations

	Skin Type	Part of the Body Exposed	Month											
			J	F	M	A	M	J	J	A	S	O	N	D
Jujuy	II	he,ha, a and l	░	░	░	░	░	░	░	░	░	░	░	░
		he	░	░	░	░	░	░	░	░	░	░	░	░
	V	he,ha, a and l	░	░	░	░	░	░	░	░	░	░	░	░
		he	░	░	░	░	░	░	░	░	░	░	░	░
Buenos Aires Santiago	II	he,ha, a and l	░	░	░	░	░	░	░	░	░	░	░	░
		he	░	░	░	░	░	░	░	░	░	░	░	░
	V	he,ha, a and l	░	░	░	░	░	░	░	░	░	░	░	░
		he	░	░	░	░	░	█	█░	░	░	░	░	░
Valdivia Bariloche P. Madryn	II	he,ha, a and l	░	░	░	░	░	░	░	░	░	░	░	░
		he	░	░	░	░	░▒	▒	▒	░	░	░	░	░
	V	he,ha, a and l	░	░	░	░	░▒	▒	▒	░	░	░	░	░
		he	░	░	░	░	░█	█	█	░	░	░	░	░
P. Arenas Ushuaia	II	he,ha, a and l	░	░	░	░	░	░	░	░	░	░	░	░
		he	░	░	░	░	░█	█	█	░	░	░	░	░
	V	he,ha, a and l	░	░	░	░	░█	█	█	░	░	░	░	░
		he	░	░	░	░█	█	█	█	█	░	░	░	░

░ Daily Integrated Irradiance is enough to produce Vitamin D levels considered sufficient, with the indicated part of the body exposed.

▒ Daily Integrated Irradiance is not enough, for some days, to produce Vitamin D levels considered sufficient, with the indicated part of the body exposed.

█ Daily Integrated Irradiance is not enough to produce Vitamin D levels considered sufficient, with the indicated part of the body exposed.

Where: he, ha, a and l: is head, hands, arms and legs; and he, head

where it would not be possible to obtain a suitable dose. During summer, noon seems to be a good option for short periods of exposure, while larger difference between the periods to obtain an acceptable level of vitamin D and to get a sunburn, and longer periods of exposure, are possible at 3 or 4 h before or after noon (see Table 3). The exposure during these times is particularly beneficial, during leisure times at summer, taking into account that it is usual to expose more than the head, then the periods to obtain vitamin D would be even shorter than shown at Table 3. For skin type V, values in the table should be multiplied by approximately 5; and for exposure of head, hands, arms and legs, dividing by approximately 7, but in this last case only for vitamin D, since no correction is necessary for erythema.

Our results may need to be affected by a factor of 1.4 to 4 to account for the difference between irradiance on a flat surface (as measured by ground instruments) and the incidence on vertical surfaces, as shown by a body in motion.[59]

Appendix

When spectral measurements are available, the procedure to obtain biologically-weighted irradiances is to convolute the irradiance spectrum with the action spectrum under consideration, and then to integrate in the UV band (290–400 nm). When measurements are obtained from multi-channel radiometers, then the procedure is not direct. Here, we derived the biologically weighted irradiance applying the method explained in Vernet *et al.*[61] The equation proposed to calculate the biologically weighted irradiances was:

$$I_w = Af(x_1) + Bf(x_2) + Cf(x_3) + Df(x_4) + Ef(x_5) \qquad \text{(A1)}$$

where I_w is the weighted irradiance, A, B, C, D and E are the regression coefficients determined with least square methods and $f(x_i)$ is a function of the irradiance measured by channel i, except $f(x_5)$, which was a function of (90 – SZA), where SZA is the solar zenith angle.

The function that affects each channel was determined as the best fit of the scatter plot of the biologically-weighted irradiance obtained from the spectral data, obtained with spectroradiometers SUV-100 (Biospherical Instruments, NSF Network, http://www.biospherical.com[71]) against the irradiance measured by the GUV-511 channel under consideration.

For larger SZAs, we used the logarithm of the irradiance to improve the quality of the fitting, increasing the influence of smaller irradiance value when solving the equation by least squares. Then, for large SZAs, the applied equation was:

$$\ln(I_w) = K\ln(x_1) + L\ln(x_2) + M\ln(x_3) + N\ln(x_4) + O\ln(x_5) + P \qquad \text{(A2)}$$

where K, L, M, N, O and P are the coefficients of the multi-regressive equation determined with least square methods.

Table A1 Fitting functions for each channel and for the complement of the SZA applying the action spectrum for the conversion of 7-dehydrocholesterol to pre-vitamin D_3 (vitamin D production) in human skin[72]

		Ushuaia (June 6th, 2000 to December 31st, 2000)				
		Ch 305 (x_1)	Ch 320 (x_2)	Ch 340 (x_3)	Ch 380 (x_4)	90 – SZA (x_5)
Vit. D	SZA ≤ 70	$a_{1VD}x_1^3 + b_{1VD}x_1^2 + c_{1VD}x_1$	$a_{2VD}x_2^2 + b_{2VD}x_2$	$a_{3VD}x_3^2 + b_{3VD}x_3$	$a_{4VD}x_4^2 + b_{4VD}x_4$	$a_{5VD}x_5^2 + b_{5VD}x_5$
	SZA > 70	$\ln x_1$	$\ln x_2$	$\ln x_3$	$\ln x_4$	$k_{5VD}x_5^3 + l_{5VD}x_5^2 + m_{5VD}x_5 + n_{5VD}$

$a_{1VD} = 0.044800438$, $b_{1VD} = -0.654864616$, $c_{1VD} = 9.303873387$, $a_{2VD} = 0.015086780$, $b_{2VD} = 0.605828461$, $a_{3VD} = 0.003791411$, $b_{3VD} = 0.287506349$, $a_{4VD} = 0.001953577$, $b_{4VD} = 0.273925295$, $a_{5VD} = -0.000566028$, $b_{5VD} = 0.026981726$, $k_{5VD} = 0.000006645$, $l_{5VD} = -0.000371698$,, $m_{5VD} = -0.0163680971$, $n_{5VD} = 2.966111969$

In order to develop and test the proposed method, we used simultaneous spectral and multichannel data from Ushuaia (54.49°S, 68.19°W) and San Diego (32.45°N, 117.11°W). The selected sites show important differences in the patterns of ozone, cloud variability and solar zenith angles. Ushuaia experiences large daily ozone variations during the spring because of the presence of the "ozone hole", and is under rather cloudy skies. San Diego presents a smaller variation in ozone and smaller SZAs in the summer than Ushuaia and preponderance of clear skies, although with more influence of aerosols as consequence of its larger population (about 3 million *versus* ~50 000 for Ushuaia). At both sites, the spectral data was obtained with spectroradiometers SUV-100 (Biospherical Instruments, NSF Network, http://www.biospherical.com[71]) and the multichannel data with a GUV-511 radiometer. Measurements at both sites were performed under all weather conditions, which included different cloud cover, large SZAs, extreme ozone conditions and various albedo situations.

In the present study, our interest was the action spectra for the conversion of 7-dehydrocholesterol to pre-vitamin D3 (vitamin D production) in human skin[72] and for erythema (sunburn).[73] Then, the model was solved for Ushuaia, combining instantaneous spectral data weighted by each action spectrum and multichannel data, for the period July 1st to December 31st, 2000, for SZA smaller than 85°. Data for the radiometers GUV were obtained each minute, while the spectroradiometer SUV-100 performed one scan each 15 min. Thus, four concurrent values per hour could be obtained. Once the equations and coefficients were determined, the model was tested for San Diego, using data for the period July 9th to December 20th, 1999.

For vitamin D action spectrum (VD), the fitting functions for each channel and SZA are shown in Table A1.

The regression coefficients obtained when solving eqn (A1) and (A2) are shown in Table A2.

Table A2 Regression coefficients resulting from solving equations (A1) and (A2) for vitamin D action spectrum

Coefficient	Vitamin D photoconversion (CIE)
A	0.886005
B	−0.054007
C	0.642766
D	−0.469521
E	0.635787
K	0.601831
L	0.697208
M	−0.387344
N	0.077334
O	−0.044072
P	1.539869

Fig. A1a and A1c show the values obtained from the spectroradiometer and derived from the multichannel instrument for San Diego, for the period July 14 to 24, and December 4 to 14, respectively. In Fig. A1b and A1d the normalized residuals (residuals divided by the spectroradiometer values) are shown. It may be observed that values corresponding to larger SZA show larger normalized residuals (time in the figure is in GMT, to obtain local time 7.8 h should be subtracted). Values of the residuals varied between −0.05 and +0.14 for values near the winter solstice, and between −0.03 and +0.15 near the summer solstice. A tendency to overestimation in the radiometer-derived values is observed. Over the periods used to solve and test eqn (A1) and (A2), the difference between the values obtained by the spectroradiometer and the values derived from the multifilter instrument were bellow 7.50%, for SZA smaller than 50 degrees (RMS value).

For erythema action spectrum (Er), the fitting functions for each channel and SZA are shown in Table A3.

The regression coefficients obtained when solving eqn (A1) and (A2) are shown in Table A4.

Table A3 Fitting functions for each channel and for the complement of the SZA for erythema[73]

		Ushuaia (June 28th, 2000 to December 31st, 2000)				
		Ch 305 (x_1)	Ch 320 (x_2)	Ch 340 (x_3)	Ch 380 (x_4)	90 – SZA (x_5)
Eryth.	SZA ≤ 65	x_1	$a_{2Er}x_2^2 + b_{2Er}x_2$	x_3	x_4	$a_{5Er}x_5^3 + b_{5Er}x_5^2 + c_{5Er}x_5$
	SZA > 65	$\ln x_1$	$\ln x_2$	$\ln x_3$	$\ln x_4$	$k_{5Er}x_5^3 + l_{5Er}x_5^2 + m_{5Er}x_5 + n_{5Er}$

$a_{2Er} = 0.005287744$, $b_{2Er} = 0.390850307$, $a_{5Er} = 0.000007492$, $b_{5Er} = 0.000239944$, $c_{5Er} = -0.024427194$, $k_{5Er} = -0.000037153$, $l_{5Er} = 0.005950209$, $m_{5Er} = -0.340310649$, $n_{5Er} = 5.409441294$

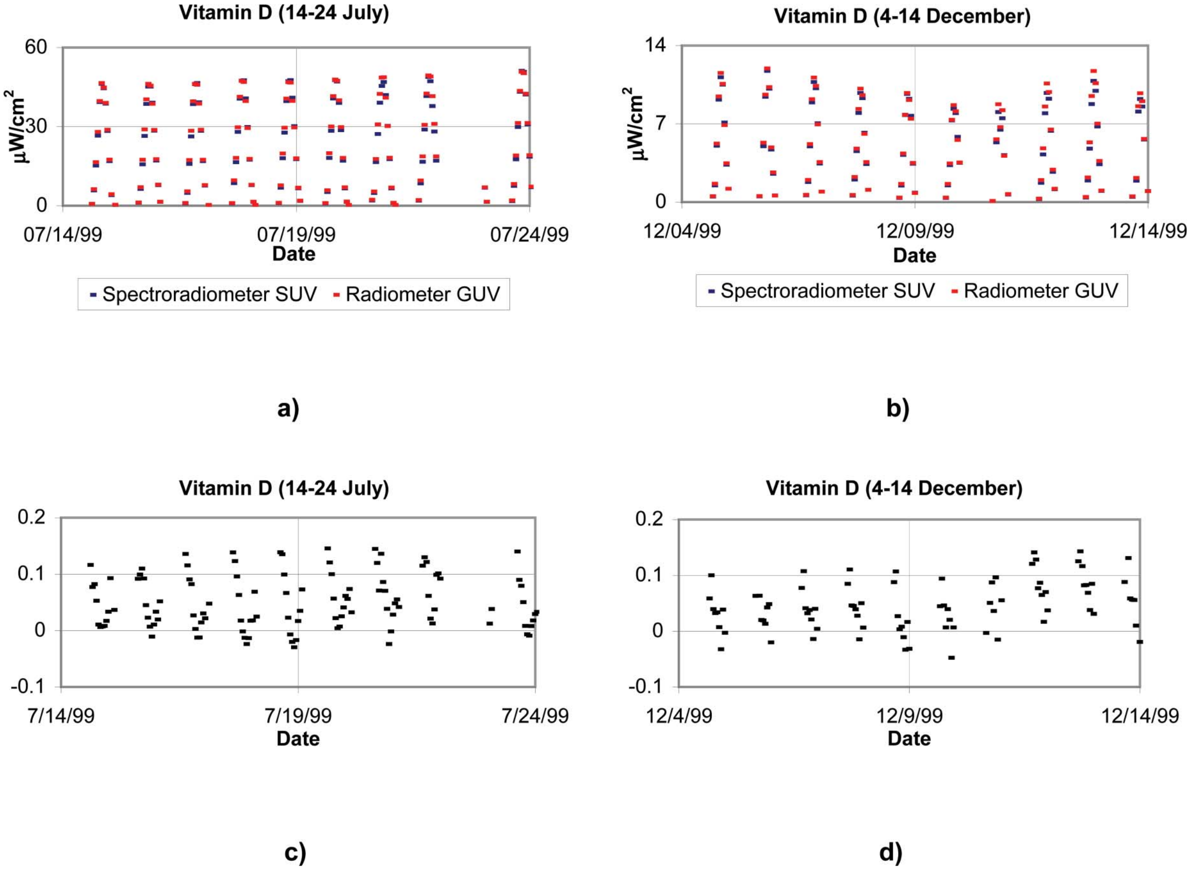

Fig. A1 a) and c) show the values for irradiance weighted by the action spectra for the conversion of 7-dehydrocholesterol to pre-vitamin D3 in human skin (Bouillon *et al.*, 2006),[72] obtained from the spectroradiometer SUV-100 and derived from the multichannel instrument GUV 511 for summer and winter time, respectively. The normalized residuals are shown in b) and d).

Fig. A2a and A2c show obtained values from the spectroradiometer and derived from the multichannel instrument for the same period as vitamin D (July 14–24 and December 4–14), and Fig. A2b and A2d, the normalized residuals. As observed for vitamin D, values corresponding to larger SZA show larger normalized residuals, but in this case the values of the normalized residuals varied between –0.07 and +0.14 near winter solstice, and between –0.01 and +0.15 near the summer solstice. Also, a tendency to overestimation in the radiometer-derived values was observed. Over the periods used to solve and test eqn (A1) and (A2), the difference between the values obtained by the spectroradiometer and the values derived from the multifilter instrument were below 6.60% for SZA smaller than 50° (RMS value).

It should be pointed out that, since the output voltage from each channel of the radiometers was related to the calibrated irradiance at the nominal central wavelength of the channel, a calibrated monochromatic irradiance was obtained for each channel, and then the obtained coefficients and equations are not instrument dependant.

Table A4 Regression coefficients resulting from solving equations (A1) and (A2) for erythema action spectrum

Coefficient	Erythema
A	2.761597
B	–0.122665
C	0.232263
D	–0.094852
E	–0.098034
K	0.473879
L	–0.435139
M	1.078051
N	–0.160834
O	–0.027122
P	–0.185785

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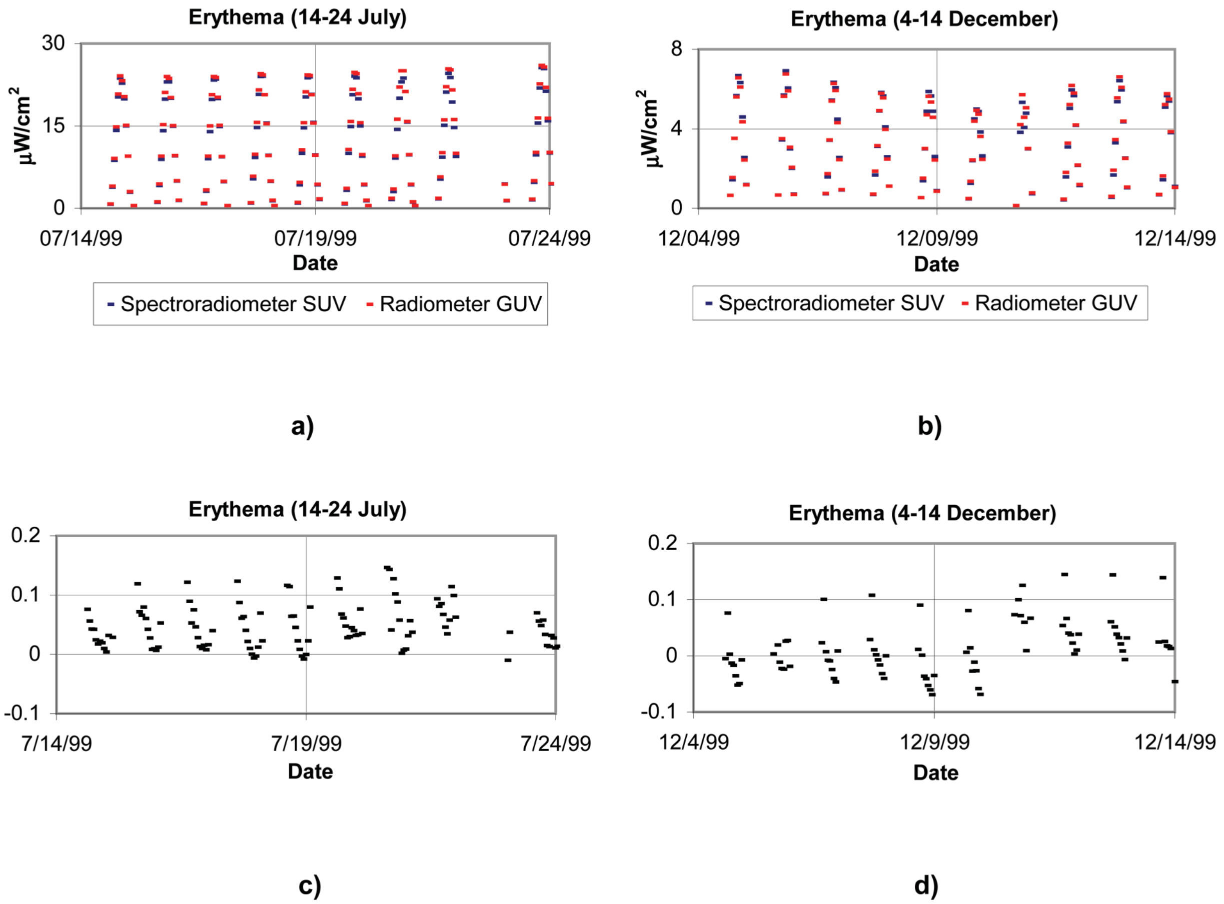

Fig. A2 a) and c) show the values for irradiance weighted by the action spectra for erythema (McKinlay and Diffey, 1987),[73] obtained from the spectroradiometer SUV-100 and derived from the multichannel instrument GUV 511 for summer and winter time, respectively. The normalized residuals are shown in b) and d).

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