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Observations of broadband solar UV-A irradiance at Santa Maria, Brazil (29°S, 53° W)

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RESUMEN

Se llevaron a cabo observaciones de la irradiancia solar en la banda UV-A (320-400 nm) en Santa Maria, Brasil (29° S, 53° W) entre septiembre 1993 y diciembre 1996. Se usaron dos técnicas de medición diferentes: la de Sol directo (DS) con el sensor apuntado directamente al Sol, y la de cenit (ZS), con el sensor señalando hacia el cenit. Se analiza la variación estacional de la irradiancia en UV-A DS y ZS en el mediodía local. Ambas irradiancias UV-A DS y ZS tienen una fuerte variación estacional que está anticorrelacionada con la variación del ángulo cenital. Se muestra que la irradiancia UV-A ZS tiene una variación estacional mayor que la irradiancia UV-A DS, con razones verano/invierno de 3.4 para UV-A ZS y 1.4 para UV-A DS. Esta diferencia se debe al arreglo geométrico de las observaciones; la irradiancia UV-A DS se mide siguiendo al Sol y su variabilidad se debe a la variación del camino óptico atmosférico a lo largo del año. La irradiancia UV-A ZS es la irradiancia difusa medida apuntando a una dirección fija , el cenit, y además de la varaición del camino óptico atmosférico, la componente de la irradiancia directa incidente sobre la superficie horizontal tiene también una variación con el ángulo cenital solar. Analizando las irradiancias UV-A DS y ZS en función el ángulo cenital solar, se observa que UV-A ZS decrece más rápido conforme mayor es el ángulo, en comparación con UV-A DS. Cálculos usando la Ley de Beer a 370 nm, muestran un comportamiento similar para irradiancias en una superficie horizontal al rayo solar incidente, comparados con UV-A ZS, y en una superficie perpendicular al rayo incidente comparados con la irradiancia UV-A DS.

PALABRAS CLAVE: Radiación solar, radiación solar UV, atmósfera, transferencia radiativa atmosférica.

ABSTRACT

Observations of broadband solar UV-A irradiance (320-400 nm) were made at Santa Maria, Brazil (29° S, 53° W) between September 1993 and December 1996. Two different measurement techniques were used, the direct sun (DS) with the sensor pointed directly to the sun, and the zenith sky (ZS), with the sensor pointed to the zenith. The seasonal variation of UV-A DS and ZS irradiances measured at local noon is analysed. Both UV-A DS and ZS irradiances have a strong seasonal variability, anti-correlated to the solar zenith angle variation. It is shown that UV-A ZS irradiance has a larger seasonal variation than UV-A DS irradiance, with summer/winter ratios of 3.4 for UV-A ZS and 1.4 for UV-A DS. This difference is explained because of the geometrical arrangement of the observations; UV-A DS irradiance is measured tracking the sun and its variability is due to the atmospheric optical path variation during the year. UV-A ZS irradiance is diffuse irradiance measured pointing at a fixed direction, the zenith, and besides the atmospheric optical path variability, the component of direct irradiance incident on the horizontal surface has also a variation with solar zenith angle. Analysing UV-A DS and ZS irradiances versus solar zenith angle, it was observed that UV-A ZS decreases faster with higher solar zenith angles than UV-A DS. Calculations using Beer's law at 370 nm were made and show similar behaviour for irradiances at a horizontal surface, compared to UV-A ZS, and at a surface perpendicular to the solar beam, compared to UV-A DS irradiance.

KEY WORDS: Solar radiation, solar UV, atmosphere, atmospheric radiative transfer.

INTRODUCTION

The solar ultraviolet (UV) irradiance corresponds to the radiative output from the sun in the spectral range 10 – 400 nm (1nm = 10^{-9} m). Although UV irradiance accounts for less than 10% of the total solar irradiance (Frederick and Lubin, 1988), it is very important in several atmospheric processes. Solar UV irradiance is a driver of several photochemical reactions, and it is partly responsible by the formation of the ionosphere, the ozone layer and others atmospheric phenomena (Brasseus and Solomon, 1986; Frederick and Lubin, 1988; Blumthaler, 1993; Madronich, 1993; Lenoble, 1993). The UV irradiance has also pernicious effects on the biosphere (Frederick and Lubin, 1988; Blumthaler, 1993; Madronich, 1993).

In the earth's atmosphere the UV irradiance is classified in terms of its biological effects in: UV-A (320-400 nm), UV-B (280-320 nm) and UV-C (wavelength $\lambda < 280$ nm). The UV-C range is fully absorbed in the atmosphere, while the UV-B range is strongly absorbed by ozone but reaches the terrestrial surface with low intensity, and the UV-A reaches the ground level without much attenuation (Robinson, 1966; Frederick and Lubin, 1988; Blumthaler, 1993).

UV-B range has stronger biological effects and in recent years, the ozone hole phenomenon (Farman *et al.*, 1985; Solomon *et al.*, 1986) and the global ozone decline (Bojkov *et al.*, 1994), have lead to a lot of work to study the UV-B X ozone variations (Frederick and Lubin, 1988; Blumthaler, 1993; Kerr and McElroy, 1993; Madronich, 1993; Frederick and Lubin, 1994). The UV-A range has been less studied (Robinson, 1966; Blumthaler *et al.*, 1996), but it could also have important biological effects (Blumthaler, 1993), and it is important in the tropospheric photochemistry (Madronich, 1993), cloud-irradiance interactions (Lenoble, 1993) and in the solar emission variability studies (Lenoble, 1993). These interactions between UV-A irradiance and the atmosphere indicate the need of more research in this spectral range, which lies between the more studied UV-B and visible ranges.

In this paper, solar UV-A irradiance measurements between September 1993 and December 1996, at Santa Maria, Rio Grande do Sul State, Brazil (29°S, 53°W), are analyzed. UV-A data were obtained with a UV-Meter belonging to the National Institute of Polar Research, that, with others Japanese and Brazilian Institutes and Universities, participates in the Japan-Brazil Joint Cooperation on Basic Space Sciences (Makita *et al.*, 1997; Schuch *et al.*, 1997).

OBSERVATIONS

UV-A observations were made with a hand-held UV-Meter, model 3D, manufactured by Solar Light Co. Inc. The spectral response of this detector is in the 280-320 nm spectral range for the UV-B channel and in the 320-400 nm range for the UV-A. The detector has an estimated cosine response between solar zenith angles 0°-60° of about ±5%. UV-A irradiances are given in units of milliwatts per square centimeter ($mWcm^{-2}$). The UV- Meter resolution is 0.01 $mWcm^{-2}$. The UV-A spectral response of the detector has higher weights in the range 360-380 nm (Solar Light, 2001).

Observations were made only in days when the sun was not obstructed by clouds. Two different techniques were used: the detector was pointed to the zenith, measuring UV irradiance on a horizontal surface - ZS (zenith sky) irradiance; and the detector was pointed to the sun, measuring the UV irradiance on a surface perpendicular to the solar beam – DS (direct sun) irradiance. The UV-A ZS irradiance is composed of diffuse irradiance at the zenith point and the UV-A DS is approximately the direct solar radiation.

The UV data analyzed in this paper is the average of the instantaneous irradiances arriving at ground level. Observations were made four (4) times per day, at 10, 12, 14 and 16 hours, local time, between September 1993 and December 1996. In this work the seasonal variation of the UV-A irradiance measured at 12 hours (local noon) is analyzed.

BEER'S LAW CALCULATIONS

The Beer's law determines the amount of extinction of the direct and monochromatic radiation in a planetary atmosphere (Brasseur and Solomon, 1986; Lenoble, 1993; Echer *et al.*, 2001). It is expressed as:

$$E_\lambda = E^o_\lambda \exp(-\tau_\lambda \sec(\chi)) \ . \quad (1)$$

In the equation (1), E_λ is the irradiance at ground level, E^0_λ is the extraterrestrial irradiance (irradiance at the top of the Earth's atmosphere), τ_λ is the total atmospheric optical depth at wavelength λ and χ is the solar zenith angle.

In the calculations performed in this work, the Beer's law was applied to the λ = 370 nm, because this wavelength is located in the peak range of the UV Meter response curve (Solar Light, 2001). Only Rayleigh scattering was considered in the atmospheric extinction ($\tau_\lambda = \tau^R_\lambda$). The extraterrestrial irradiance was obtained from the Atlas –3 spectrum (Kaye and Miller, 1996). The irradiance calculated using equation (1) can be applied only as a first approach to the UV-A DS observations, because Beer's law supposes a planar and homogeneous atmosphere, which is not the general case, especially for large solar zenith angles and an atmosphere with clouds and aerosols. For the UV-A ZS irradiance, equation (1) could be used as a proxy multiplying it by the cosine of the solar zenith angle, to obtain the component of the direct solar irradiance on a horizontal surface (equation 2). However, one has to recall that UV-A ZS irradiance is predominantly diffuse, and then eq(2) is only a 'crude' approximation in this case.

$$E_\lambda = E^o_\lambda \exp(-\tau_\lambda \sec(\chi)) \cdot \cos(\chi) \ . \quad (2)$$

RESULTS

Observations of daily UV-A DS and ZS irradiances are shown in Figure 1. The UV-A irradiance clearly shows the seasonal variability, with maximum intensity in the sum-

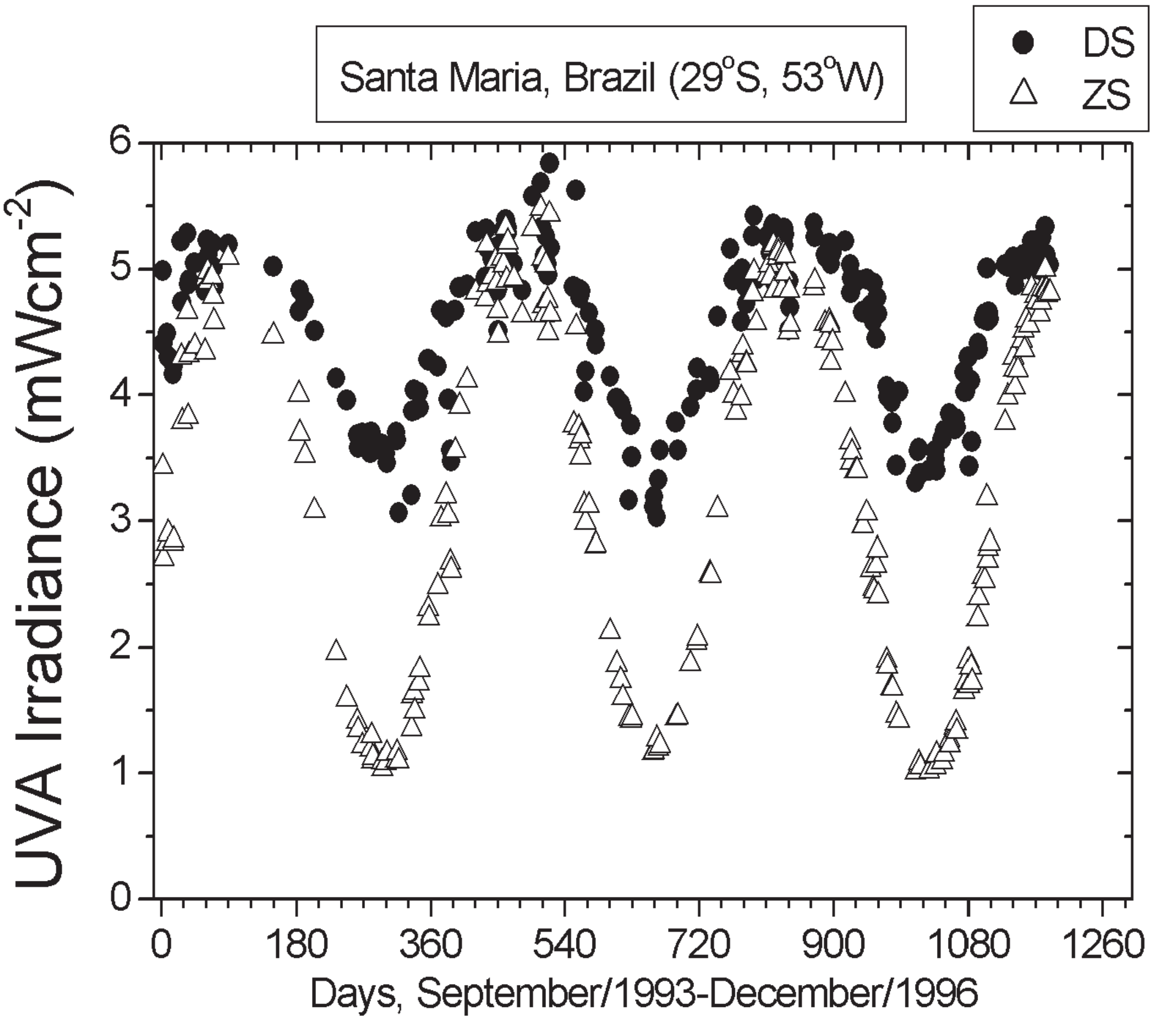

Fig. 1. UV-A DS (full circles) and ZS (open triangles) irradiances daily observations at 12 hours local time at Santa Maria, September/1993-December/1996.

mer period and minimum intensity in the winter period, as expected. It is also seen that UV-A ZS has a higher annual variation than UV-A DS.

Monthly means were calculated and an average seasonal curve was obtained for UV-A DS and ZS irradiances and for the solar zenith angle. These seasonal curves are seen in Figure 2. Again, it is easily seen the strong annual cycle of UV-A DS and ZS irradiances, and that the solar zenith angle variation is 180° (in anti-phase) with UV-A variation.

UV-A data were separeted in four seasons: summer (Dec, Jan, Feb), spring (Sep, Oct, Nov), autumn (Mar, Apr, May) and winter (Jun, Jul, Aug), and seasonal averages, seasonal rations and UV-A DS/ZS ratios were calculated. In Table 1 the seasonal averages are shown. Seasonal rations are shown in Table 2 and in Table 3 the UV-A DS/ZS irradiance ratios are presented.

Average irradiances are higher in summer and spring, as expected. UV-A DS values are always higher than UV-A ZS. The UV-A DS seasonal variation is lower than UV-A ZS. The summer/winter ratio is about 1.4 for UV-A DS and 3.4 for UV-A ZS. They have nearly the same intensity in the summer (DSZS ratio = 1.1), but in winter UV-A DS is much higher (DS/ZS ratio = 2.6) than UV-A ZS (see Table 3).

Figure 3 shows normalized UV-A DS and ZS irradiances versus solar zenith angle. It is seen that for low solar zenith angles (< 15°), both irradiances show similar intensities, as it is normally observed during summer, but as the solar zenith angle increases, ZS irradiances decrease faster than DS irradiances.

Using Beer's law (eq. 1 and eq. 2), direct and horizontal irradiances were calculated at 370 nm. Figure 4 shows the normalized calculated irradiances versus solar zenith

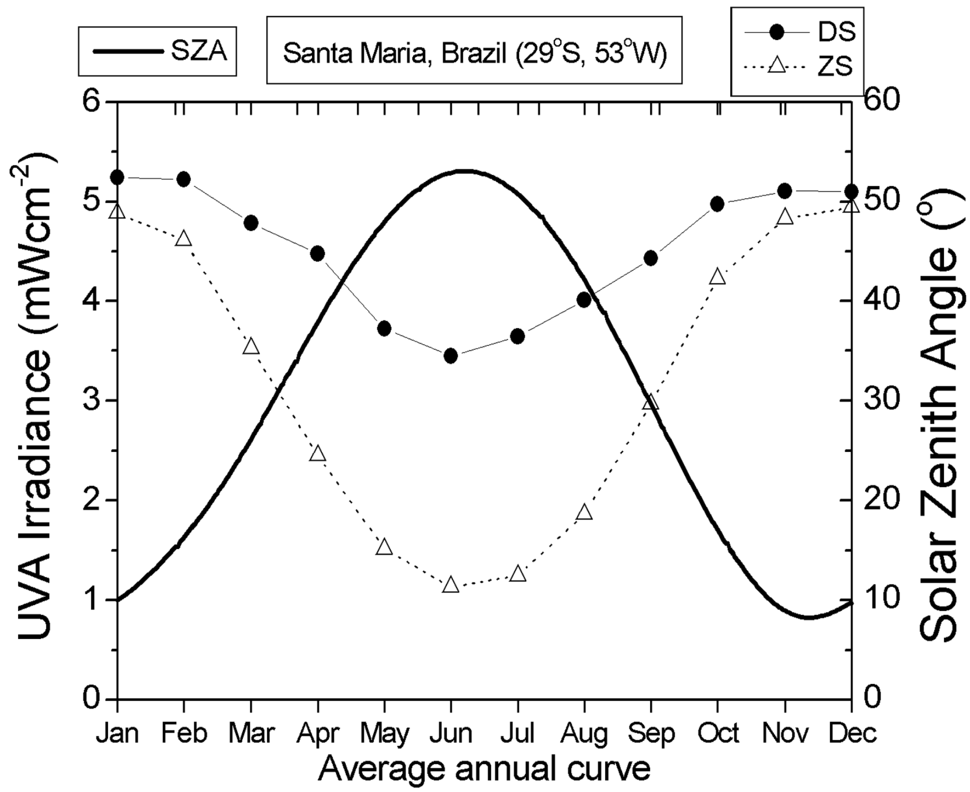

Fig. 2. UV-A DS (full circles) and ZS (open triangles) irradiance monthly means at Santa Maria, September/1993-December/1996. The continuous line is solar zenith angle.

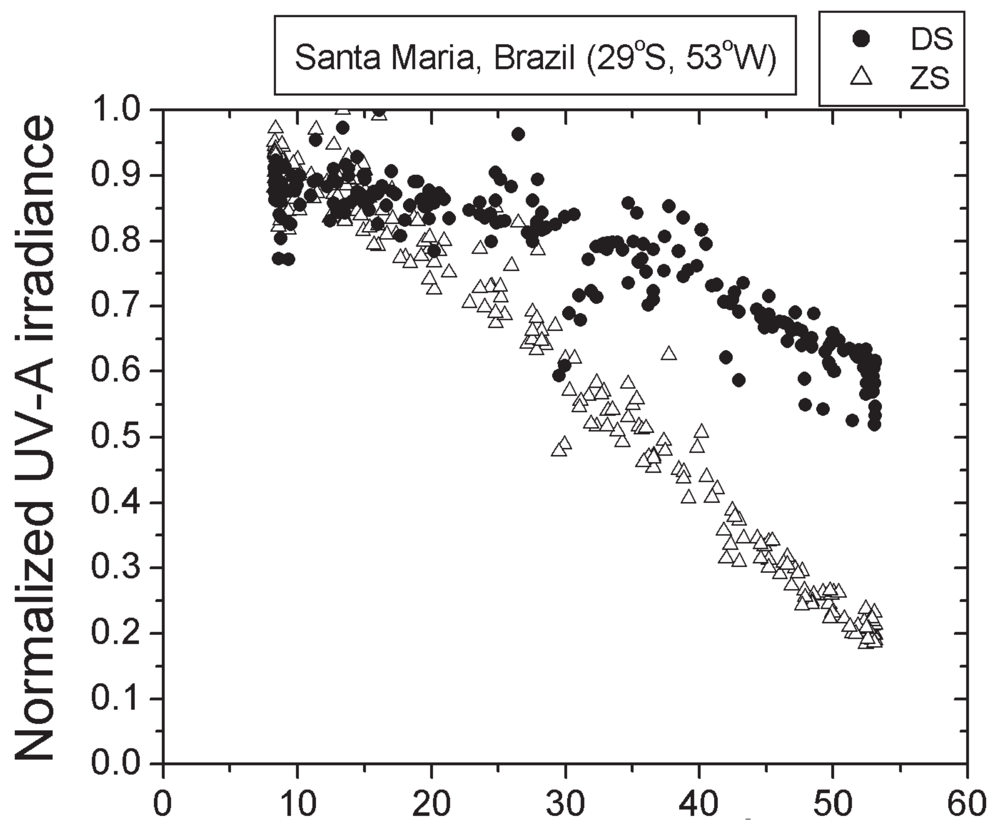

Fig. 3. UV-A DS (full circles) and ZS (open triangles) irradiances, daily observations at 12 hours local time versus solar zenith angle.

Table 1

Seasonal averages (± standard deviation) of UV-A DS and ZS irradiances (mWcm2)

Period	UV-A - DS	UV-A - ZS
Summer	5.2 ± 0.1	4.8 ± 0.2
Autumn	4.3 ± 0.5	2.5 ± 1.0
Spring	4.8 ± 0.4	4.0 ± 0.9
Winter	3.7 ± 0.3	1.4 ± 0.4

Table 2

Seasonal ratios of UV-A DS and ZS irradiances

Period	UV-A DS	UV-A ZS
Summer/Winter	1.4	3.4
Summer/Spring	1.1	1.2
Summer/Autumn	1.2	1.9
Spring/Winter	1.3	2.8
Spring/Autumn	1.2	1.9
Autumn/Winter	1.2	1.8

Table 3

UV-A DS/ZS Ratio

Period	UV-A DS/ZS ratio
Summer	1.1
Autumn	1.7
Spring	1.2
Winter	2.6

angle. It can be observed that both irradiances have similar relative intensities for solar zenith angles lower than 10°, but for larger values the horizontal irradiance decreases more than the direct one. Thus the Beer's law results are in qualitative agreement with observations, showing that irradiances on horizontal surfaces (ZS) decreases more with the solar zenith angle than direct irradiances (DS). The results in Figures 3 and 4 also show the strong dependency of the solar irradiance in relation to the solar zenith angle.

DISCUSSION

A large difference in the amplitude of annual variation was observed between UV-A DS and ZS irradiances. From Table 2, it is observed that summer/winter ratios are 1.4 for DS and 3.4 for ZS. From Figure 2, it is observed that minimum solar zenith angle is about 10° during summer, and about 50° during winter. Beer's law calculations for UV-A ratios using these solar zenith angles have resulted in ratios of about 1.3 for DS and 2.0 for ZS (horizontal surface), reproducing very well the DS observational results, and only approximately the ZS results, as expected.

These results indicate that the difference is mainly caused by the geometrical arrangement of the observations. In the UV-A DS observations, the atmospheric optical path varies during the year, depending on the solar zenith angle, and this variation causes the observed annual variation. For UV-A ZS, besides this variation of the atmospheric optical path (optical thickness), the component of the direct solar beam that reaches the horizontal surface also decreases with the solar zenith angle, as a function of the cosine. Thus, in summer, when the sun is near the zenith, the difference between DS and ZS is smaller than in the winter, because UV-A DS and ZS have almost the same direct component. This explains the difference between calculated DS and ZS irradiances. But UV-A ZS is mainly diffuse irradiance, and the large difference between UV-A ZS summer/winter ratio as calculated by Beer's law (2.0) and experimental (3.4) may be explained because of this UV-A ZS feature. UV-A ZS measures the photons that were scattered from the direct solar beam by the atmosphere. The amount of scattered light depends of the optical path in atmosphere. In summer, the sun is close to the zenith, and the optical path that photons have to cross in order to propagate from sun's position to zenith position is small, and the difference between direct and ZS diffuse irradiances is low. In winter, the sun is far from zenith, photons have to cross a much larger optical path and less photons than calculated only by the geometrical factor are available on the zenith. Thus in winter the UV-A ZS would be much lower, relatively to the summer, than UV-A DS. This difference in optical thickness also explains the higher decrease of observed UV-A ZS with zenith angle (Figure 3) as compared to the decrease of calculated horizontal irradiance (Figure 4).

Absolute values of UV-A DS irradiance at Santa Maria are lower than UV-A DS irradiances measured in similar conditions at 23° S, 45° W, at Taubaté and São José dos Campos, neighbour cities in São Paulo State, Brasil (Echer and Kirchhoff, 2001). Although the observation period is different (1996-1999 at 23° S and 1993-1996 in this work), it is not observed that UV-A varies much with solar cycle or that it could have a large trend during a few years (Lenoble, 1993). The irradiances are higher at 23° S than at 29° S, as expected, because of the difference in geographical latitudes. UV-A DS irradiance averages in summer are 5.6 mWcm^{-2} for 23° S and 5.2 mWcm^{-2} for 29° S. In winter, UV-A DS irradiance averages are 4.0 mWcm^{-2} for 23° S and

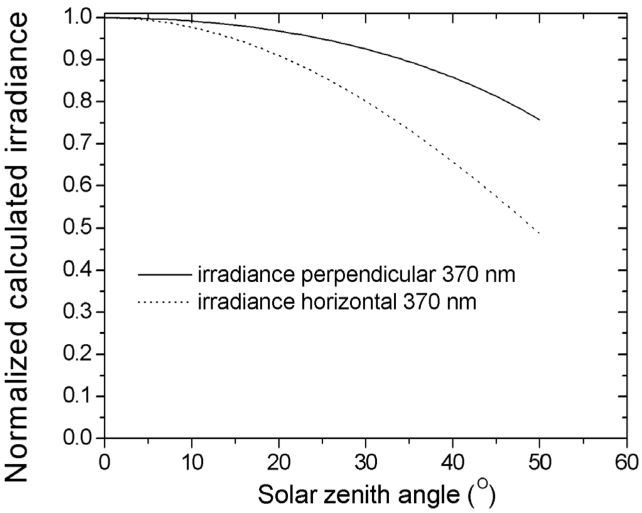

Fig. 4. Normalized calculated irradiances at 370 nm, using the Beer's law versus the solar zenith angle. Solid line, direct irradiance; dotted line, irradiance at a horizontal surface.

3.7 mWcm^{-2} for 29° S. The UV-A DS irradiance ratios between both latitudes (29° S/23° S) is 0.93 in summer and 0.92 in winter. Beer's law calculations (eq. 1) were made considering only the variation of solar zenith angle between 10° – 50° for 29° S, and between 1°–45° for 23°S. UV-A DS irradiance ratio 29°S/23° S calculated is 0.99 for summer and 0.93 for winter, in good agreement with observations.

The observed seasonal variation is strong for UV-A (about 40% for DS irradiance at 29° S and 23° S), but it is not as strong as in the UV-B range. Echer and Kirchhoff (2001) have determined a summer/winter ratio of 2.3 for UV-B DS at 23° S. This larger variation in UV-B occurs because the Rayleigh scattering is higher for the shorter UV-B wavelenghts than for UV-A wavelenghts. Furthermore there is a strong absorption by ozone in UV-B range. Thus when solar zenith angles are larger, more atmospheric absorbing and scattering particles are on the path of photons, and as in UV-B the efficiency of absorption and scattering is higher than in UV-A, the UV-B range will be more attenuated than UV-A.

CONCLUSIONS

The seasonal variation of UV-A DS and ZS irradiances was analyzed at Santa Maria, Brazil, for the observations made between September 1993 and December 1996. A strong annual variation of UV-A irradiance was found, anticorrelated with the solar zenith angle, as expected. It was also observed that UV-A ZS irradiances have a larger seasonal variation (about 3.4) than UV-A DS (1.4). This occurs because UV-A ZS measures diffuse radiation, and the atmospheric optical path between the sun and zenith positions is much higher in winter than in summer, causing a larger optical thickness and scattering for photons in winter. Consequently the UV-A DS/ZS ratio would be much higher in winter than in summer, as observed in this work.

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