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Solar ultraviolet irradiance for clear sky days incident at Rosario, Argentina: Measurements and model calculations

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[1] Results of measurements are presented of clear-sky day solar UV irradiance (295–385 nm) in the August 1995 to June 1999 period at the Observatorio Astronómico de Rosario, Argentina, a place typical of the most populated Humid Pampa region of the country. The data give a detailed description of UV variation as a function of time in a given day and for different days of the year. Model calculations for clear-sky days at noon are done, employing the tropospheric ultraviolet visible radiation model (TUV) Madronich radiative transfer code, with the mean monthly ozone and aerosol content of the atmosphere and surface reflectivity provided by the Total Ozone Mapping Spectrometer (TOMS)/NASA instrument on board of the Earth Probe satellite. Two aerosol characteristics are tested in the model, rural-urban and mean urban, with the mean urban giving best agreement with the measurements. A simple mathematical expression is proposed for the “mean” typical curve, which gives a good approximation to the clear sky UV noon data for Rosario. It can be used for extending the results to nearby places and for comparison with other regions of the world having similar atmospheric and albedo conditions. *INDEX TERMS:* 0360

Atmospheric Composition and Structure: Transmission and scattering of radiation; 0399 Atmospheric Composition and Structure: General or miscellaneous; 9360 Information Related to Geographic Region: South America; *KEYWORDS:* ultraviolet, irradiance, ozone, aerosol

1. Introduction

[2] During the last decade, detailed studies of solar UV radiation (280–400 nm) have been undertaken to understand the implications for affecting life and causing degradation of materials. There is additional intrinsic interest for knowing the solar spectral intensity at Earth's surface and its interaction with the atmosphere [see e.g., Jagger, 1985; Zerefos and Bais, 1997]. Rather good knowledge exists for solar global irradiance (UV, Vis, and IR) incident on Argentina [Grossi Gallegos, 1998], but data are very limited for the UV component [Orce, 1990; Frederick et al., 1994]. Several studies of total UV irradiance have been undertaken in different parts of the world: Fairbanks, Alaska, Jungfraujoch, Switzerland [Ambach et al., 1991], Potsdam [Feister and Gwosnick, 1992], and Atlanta, Georgia [Justus and Murphey, 1994], among others. In particular, the UVB and erythemally weighted irradiances are analyzed rather extensively from ground-based measurements, satellite estimates, and model calculations [i.e., Madronich, 1993; Zerefos et al., 1995; Herman et al., 1996; Bodhaine et al.,

1997; Minschwaner, 1999; Herman and McKenzie, 1999; Herman et al., 1999].

[3] Atmospheric components (aerosols, ozone, water vapor, and other gases) reduce the intensities of solar radiation able to reach the Earth's surface by different amounts in different spectral ranges. Because of this, the atmospheric transmittance is strongly dependent on the solar zenith angle (SZA). It is with the help of model calculations that the relative contributions to the UV irradiance from each atmospheric component can be determined.

[4] In what follows, measurements of solar UV irradiance (295–385 nm) on a horizontal plane and calculations are presented for Rosario (32°57'S, 60°37'W, 25 m above sea level (asl)), located in the Argentina Humid Pampa, the largest populated region of the country. A comparison between clear-sky measurements at noon and calculations with the tropospheric ultraviolet visible radiation model (TUV) Madronich model was performed. On the basis of the measurements, a simple mathematical expression for the typical solar UV irradiance at noon as a function of the day of the year is proposed.

2. Instrument and Measurements

[5] Measurements were made at the Observatorio Astronómico de Rosario, Argentina. For this work, only clear-sky data (cloudiness less than or equal to 15% with uncovered Sun, following the conventional meteorological criteria through visual observations) were selected.

[6] The employed instrument is a Kahl Precision Pyranometer (Model TUVR, serial number 30076). Their relative

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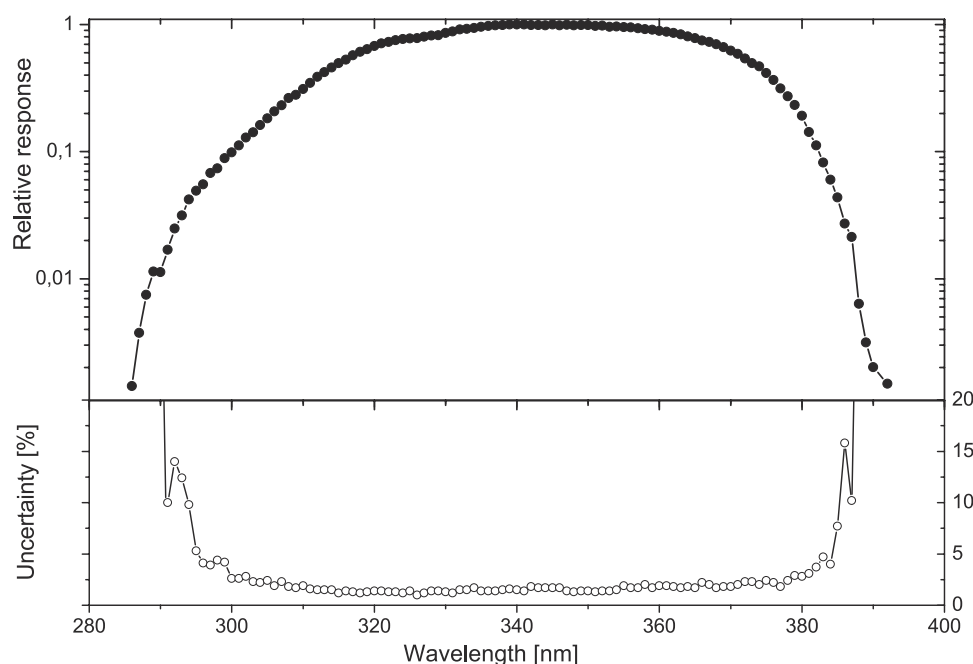


Figure 1. Relative spectral response of the Kahl precision pyranometer model TUVR, serial number 30076 used in this work, together with the uncertainty of its measurement.

spectral and cosine responses were measured at the U.S. Central UV Calibration Facility (USCF/NOAA), Boulder, Colorado. Relative response is shown in Figure 1 normalized to 1 at maximum (339 nm) together with the response uncertainty. As can be seen, it has a high response for most of UVB (280–320 nm) and UVA (320–400 nm) ranges. However, in order to select a practical reference

range that permits comparison with similar data, a conversion factor is included in the calibration constant, obtained in the present case from the field calibration. The factor transforms its measurements to the nominal 295- to 385-nm range such that the relative spectral response of the instrument would be equal to 1 in this range. To illustrate this, Figure 2 shows a reference-

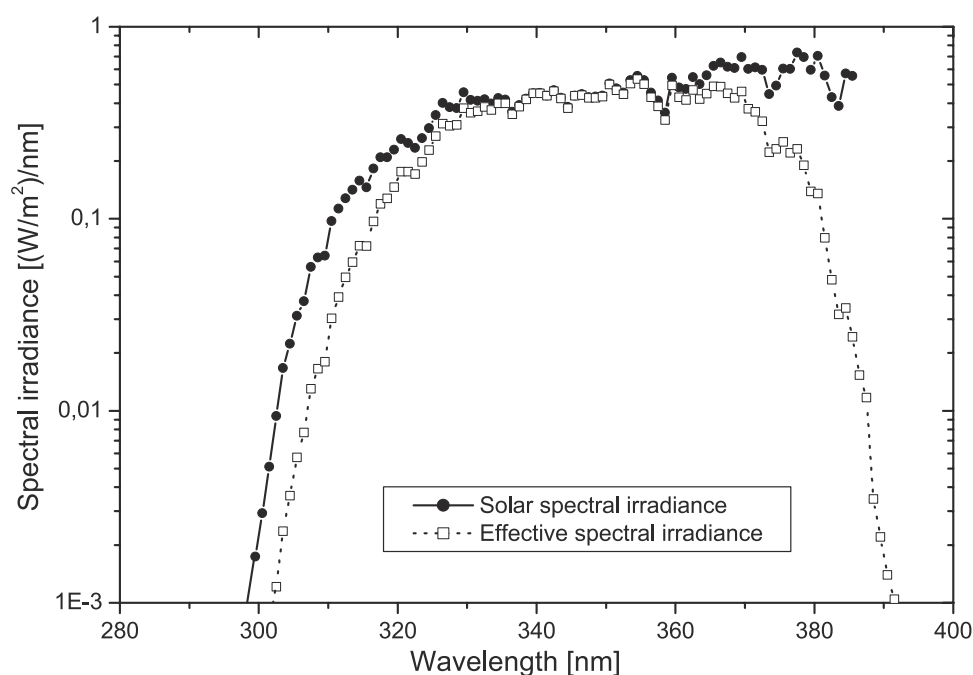


Figure 2. Solar spectral irradiance at ground for a typical condition ($\text{SZA} = 45^\circ$, ozone column = 300 DU, $\text{AOT}_{360} = 0.25$, and albedo = 0.06) in the wavelength interest range, and effective irradiance (weighted with the spectral response of the Kahl instrument).

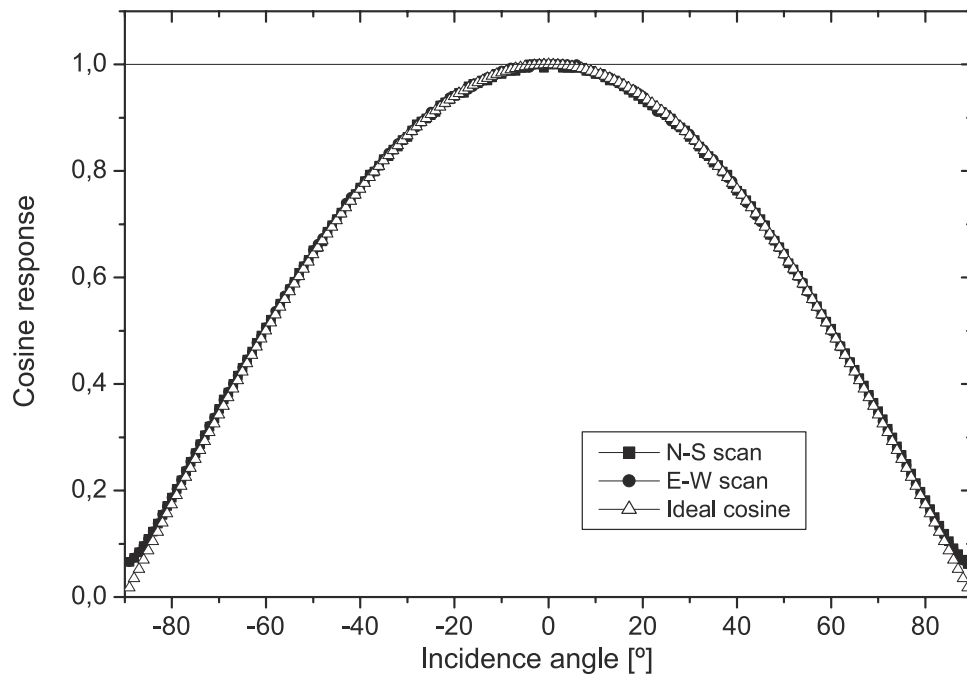


Figure 3. Cosine response of the Kahl instrument for two perpendicular scans (namely north-south and east-west) and “ideal” cosine response.

modeled solar spectral irradiance in the wavelength range of interest for a typical atmospheric condition at the place (see section 2) and the effective spectral irradiance (i.e., filtered with the instrument’s spectral response from Figure 1). The voltage output of the instrument corresponds to the wavelength-integrated effective irradiance, so the calibration constant relates this voltage output to the equivalent wavelength-integrated solar UV spectral irradiance in the 295- to 385-nm range. The field calibration was made during the European Intercomparison Campaign at Thessaloniki, Greece, in July 1997, against the University of Innsbruck/Austria spectroradiometer. The calibration constant for the 295- to 385-nm range was determined to be $4.37(\text{W/m}^2)/\text{mV}$, within a 5% uncertainty. The cosine response is seen in Figure 3. It follows the “ideal cosine response” very

closely even at large incidence angles and, as expected, is without azimuthal dependence.

[7] In order to avoid rapid degradation of the instrument, it was used each day for only a few minutes around noon (typically, three measurements separated by half an hour). On particularly clear-sky days during the year, additional measurements were made. The “effective” time of use of the instrument is no more than 10 months, lower than that generally suggested for recalibration of this type of instrument (about every 12 months of continuous use). Also, comparisons with simultaneous solar global measurements made with a solarimeter, calibrated against the Argentine national standard, show no relative trends. Therefore the calibration constant was considered unchanged for the whole period.

3. Model

[8] Calculations were done with the TUV Madronich code (available at <http://acd.ucar.edu/models/UV/TUV/index.html>), using the pseudospherical two-stream algorithm for solving the radiative transfer equations and with the SUSIM solar extraterrestrial spectrum included in the code as input.

[9] In order to achieve a rather smooth representation of the clear-sky UV irradiance, model calculations were performed for solar noon for the fifteenth of each month of the year. Monthly average values of ozone total column and aerosol optical thickness at 360 nm (AOT_{360}), shown in Figure 4, were taken from the measurements of the TOMS (Total Ozone Mapping Spectrometer)/NASA instrument on board of the Earth Probe satellite (data are available from Goddard Space Flight Center Distributed Active Archive Center (GSFC/DAAC), Greenbelt, Maryland, USA).

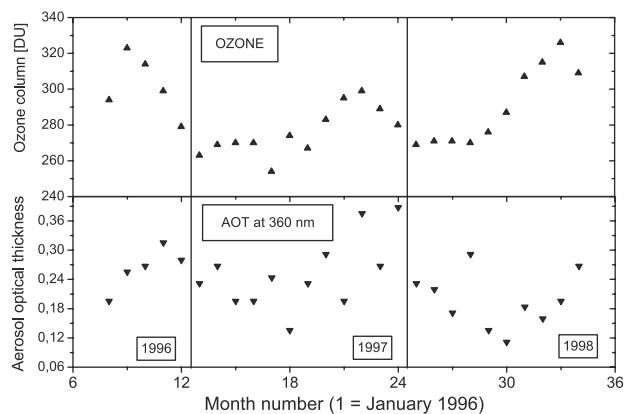


Figure 4. Ozone and aerosol optical thickness at 360 nm from TOMS/EP satellite data used in the model calculations.

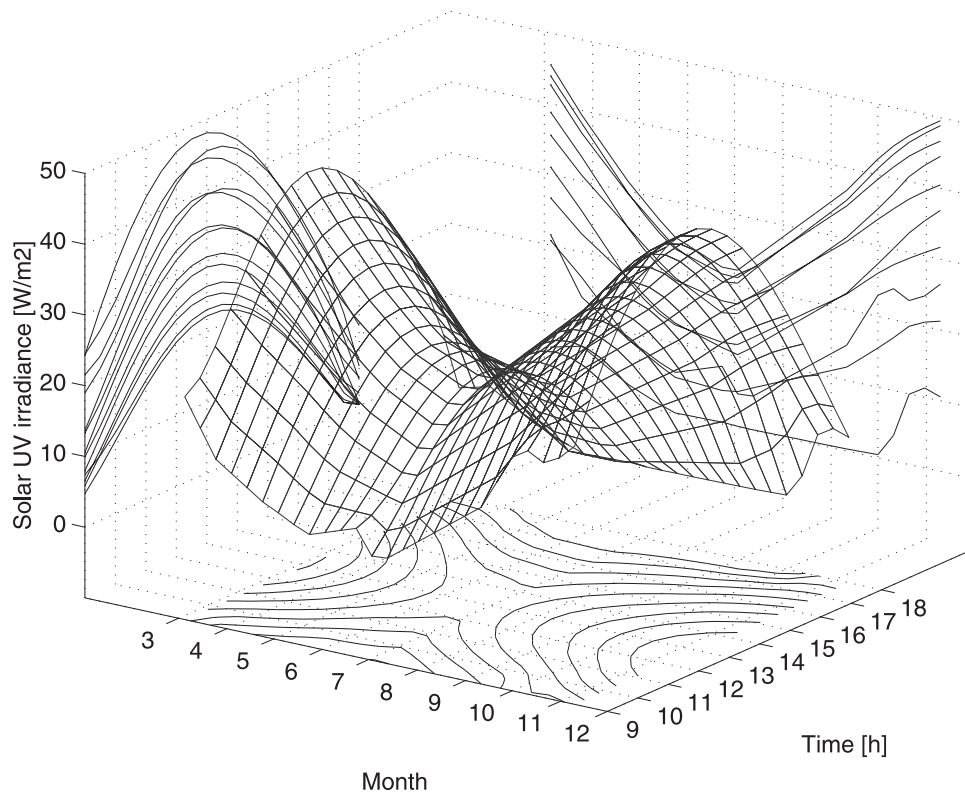


Figure 5. Three-dimensional representation of the solar UV irradiance (295–385 nm) measured during 1997 at Observatorio de Rosario, Argentina, on clear-sky days, as a function of time of day and month of year.

[10] To obtain the AOT, the UV-reduction formulas are expressed in terms of the aerosol index AI_λ (at the wavelength $\lambda = 331$ nm for TOMS/Earth Probe).

[11] The definition of AI_λ is

$$AI_\lambda = -100 \log_{10} [(I_{331})_{\text{meas}} / (I_{331})_{\text{calc}}]. \quad (1)$$

[12] Positive values of AI_λ indicate the presence of UV-absorbing aerosols (dust, smoke, and volcanic ash), while negative values are for nonabsorbing aerosols (e.g., sulfate pollution aerosols). When clouds are in the TOMS field of view, $AI_\lambda \approx 0$. This formulation permits easy distinction between the presence of absorbing aerosols and clouds and has been used for aerosol imaging and quantitative calculations of AOT [Herman *et al.*, 1997; Torres *et al.*, 1998]. The AOT_{360} is then obtained from tables of the ratio I_{331}/I_{360} versus I_{331} , constructed using radiative transfer calculations for various specific aerosol models (complex refractive index, aerosol-plume height, particle size distribution, and aerosol amount).

[13] Angström's turbidity formula was used in the model, so that the aerosol optical thickness as a function of wavelength is given by $AOT(\lambda) = AOT_{360}(0.36/\lambda)^\alpha$, with λ in micrometers, for a defined value of the wavelength exponent α . The parameters related to the aerosol characteristics, namely the wavelength exponent α , the single scattering albedo w_0 and the asymmetry factor g are taken from references (see section 4). The mean surface albedo value of 0.06 for all the period was obtained from the

TOMS reflectivity climatology (GSFC/DAAC), for clear sky conditions.

4. Results

[14] Figure 5 is a 3-D representation of the measured solar UV irradiance (295–385 nm) at horizontal plane on typical clear-sky days from morning to afternoon for different months of 1997. Two-dimensional representations of the projected data on the planes defined by the coordinates (Irradiance, time of day, and month of year) are also presented. An interesting behavior is the apparent double symmetry of the 3-D Figure 5 with respect to a fixed time near solar noon and to the winter solstice. The first symmetry effect is not strictly true since the “equation of time” introduces a change in the “local noon time” within around ± 15 min during the year. The second symmetry effect is affected by the fact that, normally, time series of ozone and aerosol atmospheric contents are out of phase with respect to the solar noon zenith angle (which is symmetric with respect to solstices).

[15] Figure 6 shows the clear sky measurements at solar noon, from August 1995 to June 1999. A rather high mean value of ~ 52 W/m² (for SZA = 10°, air mass of ~ 1.02) near the summer solstice was registered, with an absolute maximum of 56.4 W/m² on 18 December 1998. The typical minimum value, around the winter solstice, is about 22 W/m². Data are compared with theoretical calculations done with the TUV model for the period August 1996 to

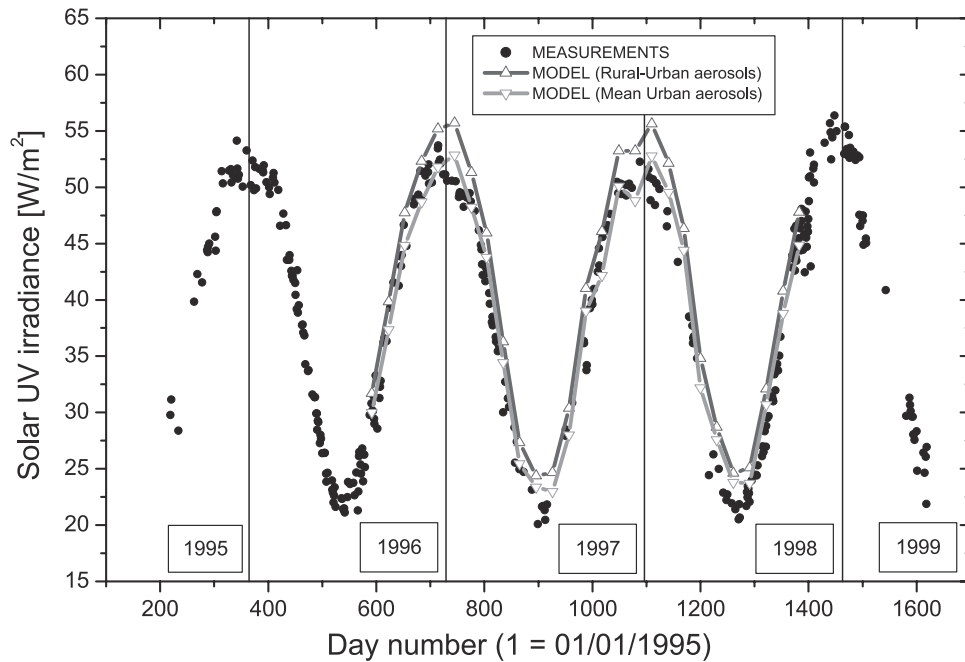


Figure 6. Solar UV irradiance (295–385 nm) measured at Observatorio de Rosario, Argentina, during the August 1995 to June 1999 period and model calculations with the TUV Madronich code for the period August 1996 to October 1998 with monthly mean values of ozone and aerosol optical thickness from TOMS/Earth Probe satellite. Higher values of the modeled irradiance correspond to rural-urban aerosol type (open up-triangles), while lower values are for mean urban aerosols (open down-triangles) (see Table 1).

October 1998. The ozone column and the aerosol optical thickness at 360 nm are available from the TOMS/Earth-Probe measurements. The values of the remaining aerosol characteristic parameters are taken from references at similar conditions to the measurement place, which is situated in the boundary region between the city and an extended coastal open field next to the Paraná River. Two test calculations are made: for “rural-urban” and for “mean urban” aerosol types; the corresponding parameters are summarized in Table 1. A smoothing of measured data show that the model results for rural-urban aerosols overestimate the measurements by about 7%, while overestimating for mean urban aerosols by only about 1%. Given the importance of the aerosols for the determination of the surface solar irradiance in this UV range (295–385 nm), it can be concluded that the last values for the parameters agree more closely with the realistic characteristics of the aerosols in the measurement place. Taking into account also the wide spatial coverage of the satellite measurements, the observed relative difference between measured and modeled UV irradiance may be considered small enough, within

the expected uncertainties [Bernhard *et al.*, 1997; Zerefos and Bais, 1997].

[16] An important UV irradiance diminution is observed in October and December 1997 (around days 1020 and 1080, respectively), with respect to the normal behavior of the 1996 corresponding months (around days 650 and 715, respectively). This can be attributed to the significantly high aerosol optical thickness of these months (22 and 24 of Figure 4), confirmed by visual observations in the form of dense haze.

[17] From the repeatability of the annual data set for all the years considered in the present work, a typical curve for a full year can be introduced for predicting the clear-sky solar noon UV irradiance in the range 295–385 nm for midlatitudes (Figure 7). Intertropical latitudes are excluded because of the double irradiance maximum produced by the sun being overhead twice during each year, and at high latitudes because of the winter night. The fit cannot be a simple sinusoid due to the rather high diffuse component contribution of the molecular and aerosol scattering in the UV range near the winter solstice minimum. Therefore a better representation is a cosine function minus a Gaussian term for improving the fitting in fall and winter,

$$I_{app}^{UV} = A + B \cdot \cos[2\pi(t + t_0)/P] - C \cdot \exp[-\gamma(t - t_1)^2], \quad (2)$$

where t is given in days, P is the annual period, and the coefficients for the region of Rosario are given in Table 2. A gives approximately the mean annual value; it is mainly determined by the latitude of the geographical point, by its elevation, and to a lesser extent by the atmospheric parameters and ground albedo. As the cosine term fit very

Table 1. Characteristic Values of the Aerosol Parameters Used in the Model

	Rural-Urban	Mean Urban
Wavelength exponent α	0.88 ^a	1.2 ^b
Single scattering albedo w_0	0.81 ^b	0.64 ^c
Asymmetry factor g	0.70 ^b	0.70 ^b

^a From [Gueymard, 1995], for relative humidity of ~60%.

^b From [Utrillas *et al.*, 1998].

^c Single scattering albedo at 400 nm.

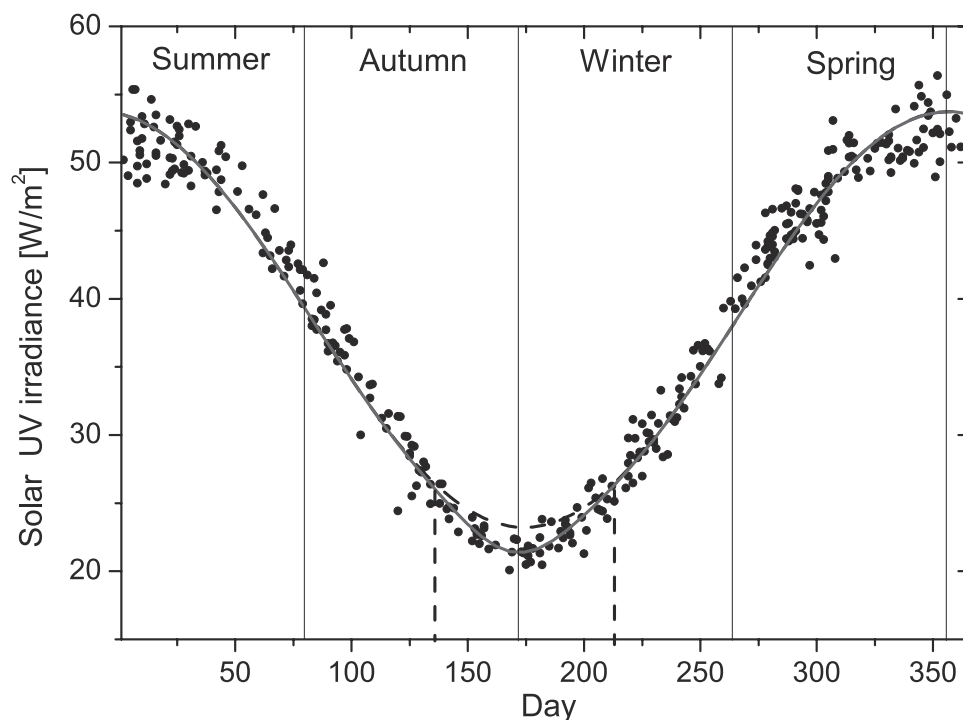


Figure 7. Solar UV irradiance (295–385 nm) as a function of day of year. All mean near noon data registered in the August 1995 to June 1999 period were included. Best simple analytical fit to the data (1) with a cosine function (dashed line) and (2) with equation (2) corresponding to the cosine function minus a Gaussian function near minimum (solid line). Vertical solid lines separate the seasons, and vertical dashed lines separate the intervals where the full best simple fit (equation (2)) must be used (interval from 15 May, day 135, to 1 August, day 213). The rest of the year can be described with a simple cosine function.

well the irradiance in the summer solstice epoch, t_0 is associated to the day of the “actual” irradiance maximum (including the geometric parameters, SZA and Earth-Sun distance, and the atmospheric parameters). Similarly, as the Gaussian term improves the fitting near the winter solstice, t_1 corresponds more directly to the day of “actual” irradiance minimum, and, due to the fact that the higher SZA make the diffuse component more relevant, C and γ are related mostly with the atmospheric parameters, principally aerosols. The formula can be applied to the Northern Hemisphere with a change in phases (see Table 2).

5. Conclusions

[18] On the basis of measurements made with a Kahl Precision Pyranometer during the August 1995 to June

1999 period, a detailed analysis has been presented of the clear-sky solar UV irradiance (295–385 nm) on a horizontal surface at Rosario, Argentina. Mean maximum values of $\sim 52 \text{ W/m}^2$ at solar noon near the summer solstice were registered, with an absolute maximum of 56.4 W/m^2 . The mean minimum value, around the winter solstice, is about 22 W/m^2 . Through measurements done during complete clear-sky days throughout the year, a 3-D representation of the annual time variation of the UV irradiance is presented.

[19] As a smooth representation of the measurements, model calculations at day 15 of each month using the pseudospherical two-stream TUV Madronich code were made. Input data include monthly mean values of ozone column and aerosol optical thickness at 360 nm measured by the TOMS/Earth Probe instrument. Two different values of aerosol parameters were analyzed: rural-urban and mean urban types, showing, in the first case, an overestimation of about 7% in comparison with a smoothing of the irradiance measurements and, in the latter case, best results with an overestimation of only about 1%. The usefulness of both the ozone and aerosol measurements from satellite, where ground-based data are not available, was demonstrated.

[20] A typical curve representing the noontime solar UV irradiance throughout the year was obtained. It can be used for extending the data to nearby geographical locations and for comparison with other regions of the world having similar atmospheric and altitude conditions. The results

Table 2. Coefficients of Formula (2)

Coefficient	Value	Units
A	38.48	W/m^2
B	15.26	W/m^2
C	1.87	W/m^2
t_0	8.2 ^a	Day
t_1	170.03 ^a	Day
γ	0.00131	$(\text{Day})^{-1}$
P	365	Day

^a Values for the Southern Hemisphere. For the Northern Hemisphere a phase change of half a year (182.5 days) must be considered.

can be used to estimate the maximum exposure throughout the year to harmful UV radiation likely to affect human health and materials.

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