



ELSEVIER

Global and Planetary Change 15 (1997) 113–121

GLOBAL AND PLANETARY
CHANGE

Latitudinal UVR-PAR measurements in Argentina: extent of the ‘ozone hole’¹

V. Luis Orce^a, E. Walter Helbling^{b,*}

^a Instituto de Genética y Biología Molecular (INGEBI-CONICET), Vuelta de Obligado 2490, 2° Piso, 1428 Buenos Aires, Argentina

^b Estación de Fotobiología Playa Unión y Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Casilla de Correos No. 153, 9100 Trelew, Chubut, Argentina

Received 31 January 1997; accepted 23 June 1997

Abstract

The UVR-PAR Argentinean Monitoring Network started its operation in September 1994 recording ultraviolet (UVR) and Photosynthetic Available Radiation (PAR) at a frequency of once per minute, at four sites, throughout the entire year. Four spectroradiometers (GUV-511, Biospherical Instruments, Inc.) were installed at research centers separated by about 8–12 degrees of latitude, extending from the Subantarctic-Fueguian region to the Tropic of Capricorn. The instruments are located in populated areas ranging from 30,000 to 11 million people and with extremely different climate regimes and conditions of tropospheric pollution. Our ground-based data indicated that the irradiance increased steadily from south to north. This increase was also observed in the calculated daily doses of UV-B (280–320 nm); however, daily integrated values for UV-A (320–400 nm) and PAR (400–700 nm) were higher at mid-latitudes (Puerto Madryn, 42°47'S). A similar south-to-north increase was evident in the ratio of the energy at 305 nm and 340 nm wavelengths (with low 305/340 ratios indicating high total ozone column concentration), with low values at Ushuaia (55°01'S) and high values at Jujuy (24°10'S). However, the 305/340 ratios increased significantly over their normal spring values at two sites, Ushuaia and Puerto Madryn, for variable time periods during October–December. Our data suggest that the ozone hole was over South America extending to about 38°S for at least a week during October and about two weeks during November–December of the years of 1994 and 1995. However, it should be noted that the erythemal irradiance, in the area influenced by the ozone hole, was at all times lower than that in Buenos Aires and well below the value at Jujuy (tropical station). This study also indicates that when assessing the impact of solar UVR upon organisms, other variables such as cloud cover, solar zenith angle, day length, latitude, and atmospheric pollution should be considered in addition to total ozone column concentration. © 1997 Elsevier Science B.V.

Keywords: ultraviolet radiation; ozone; PAR; networks

1. Introduction

Reports suggesting that the ozone hole extends its influence beyond Antarctica and reaches populated areas of the Southern Hemisphere (Seckmeyer and

* Corresponding author. Tel.: +54 (965) 96269; fax: +54 (965) 96269; e-mail: fotobiol@plancton.satlink.net

¹ Contribution EFPU # 1/97.

McKenzie, 1992; Booth et al., 1994) caused much concern in Argentina, particularly in Tierra del Fuego, which is located in the Subantarctic region about 1000 km to the north of the Antarctic continent. In addition to the statistically significant global downward trend in ozone concentration (Prather and Watson, 1990; Stolarski et al., 1992), it has been shown (Atkinson et al., 1989) that air that has been chemically altered during the hole season moves north after the breakdown of the Antarctic polar vortex and consequently large masses of ozone-depleted air mix and dilute the ozone layer over the Subantarctic and mid-latitudes areas of South America. These reports have given rise to questions such as: (1) How far north does the Antarctic 'ozone hole' extend its influence over inhabited areas of South America? (2) What are the consequences of the enhanced ultraviolet radiation (UVR) resulting from ozone depletion on plant and animal life at these mid-latitudes?

In order to get some answers to the above questions and to obtain basic UVR data, four spectroradiometers were installed as part of the UVR-PAR Argentinean Monitoring Network to measure ultraviolet radiation (UVR) and photosynthetically available radiation (PAR) reaching the surface of the Earth at four sites with latitudes ranging from 55° to 23°S. The general objectives of the network are: (a) to provide information regarding latitudinal distribution and temporal trends in UVR-PAR; (b) to obtain long-term data, in order to establish a baseline for UVR-PAR levels and trends, and to try to forecast changes in UVR irradiance as a result of alterations of atmospheric chemistry; (c) to obtain data that can be used for research in photobiology and to develop an understanding of the response of living systems to present conditions of solar radiation. The results presented in this paper are from data acquired at the four sites in Argentina since September of 1994, when the network started its operation, to December 1995.

2. Instruments and data set

The UVR-PAR Argentinean Network includes four sites which were chosen in order to cover a wide range of latitude (almost 32 degrees) and they

Table 1

Site locations of the spectroradiometers (GUV-511) of the UVR-PAR Argentinean Monitoring Network

Site	Latitude	Longitude	Population	Altitude
Ushuaia	55°01'S	68°18'W	30,000	sea level
Puerto Madryn	42°47'S	65°01'W	80,000	sea level
Buenos Aires	34°35'S	58°29'W	10,800,000	sea level
Jujuy	24°10'S	65°01'W	180,000	1200 m

include inhabited areas with different climates (Table 1, Fig. 1). At each one of these sites a spectroradiometer (GUV-511, Biospherical Instruments Inc.) is permanently installed and records data at four narrow bandwidths of UVR (305, 320, 340, 380 nm) as well as a broadband sensor for PAR (400–700 nm). These temperature-controlled radiometers are set to acquire data from each channel at a frequency of once per minute throughout the entire year, with the data being stored on a hard disk and displayed in real time. The instruments are intercalibrated once a year and also compared with the scanning spectroradiometer (SUV-100, Biospherical Instrument, Inc.) that the National Science Foundation (NSF) Network has at Ushuaia (Frederick et al., 1993; Booth et al., 1994; Díaz et al., 1994).

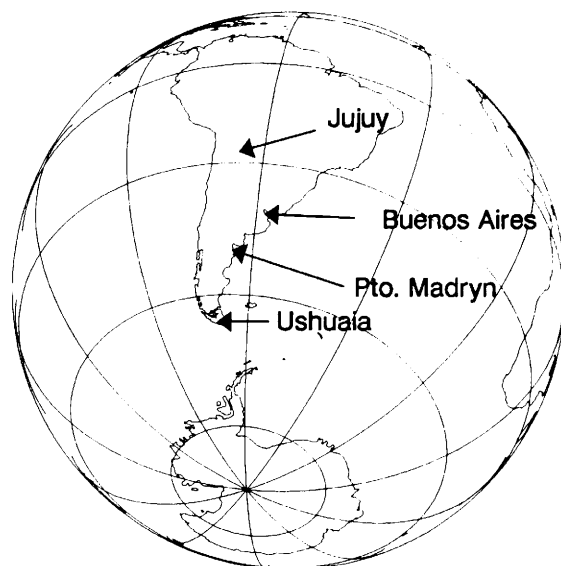


Fig. 1. Map showing South America and Antarctica. Jujuy, Buenos Aires, Puerto Madryn and Ushuaia are the four places in Argentina where a GUV-511 unit is permanently located and collecting data on spectral solar radiation.

The daily solar radiation at each site was calculated by integrating the one-minute average data from sunrise to sunset. Solar ultraviolet radiation B (UV-B, 280–320 nm) and A (UV-A, 320–400 nm) were estimated using a multiple linear regression fit comparing the data obtained from the UVR channels of the GUV-511 with the UV-B and UV-A data from the scanning spectroradiometer (SUV-100). There was a good correlation between the data sets from the different instruments so we used the data from the 305 and 320 nm channels to estimate UV-B as:

$$\text{UV - B} = 59.5 \times E_{305} + 4.1 \times E_{320} \\ \times (r^2 = 0.997, n = 320)$$

and the data from the 340 and 380 nm channels to estimate UV-A as:

$$\text{UV - A} = 87.4 \times E_{340} - 2.4 \times E_{380} \\ \times (r^2 = 0.998, n = 320)$$

with E_{305} , E_{320} , E_{340} and E_{380} the energy measured at the 305, 320, 340 and 380 nm channels, respectively.

3. Results and discussion

Daily integrated values for PAR (Fig. 2) showed a significant day-to-day variability due to cloud cover at all places, with the amplitude of this variability being generally greater at Jujuy (Fig. 2A) than at the other sites, especially during fall and winter. Previous studies carried out at Ushuaia (Frederick et al., 1993, 1994) showed that cloud cover was the major source of variability in their measurements of solar radiation. There were variations at all four sites with low irradiance values during winter and high irradiances during summer; however, the summer-to-winter difference was smallest at Jujuy (stations closest to the Tropic of Capricorn) and greatest at Ushuaia (Subantarctic region). There was a south-to-north (e.g., from Ushuaia to Jujuy) increase of daily PAR during fall and winter; however, the maximum daily integrated values during late spring–early summer were at mid-latitudes (e.g., Puerto Madryn, Fig. 2C) due to a combination of relatively high values of irradiance and longer daylight period. Daily integrated UV-A radiation (Fig. 3) showed, in general, a similar trend throughout the

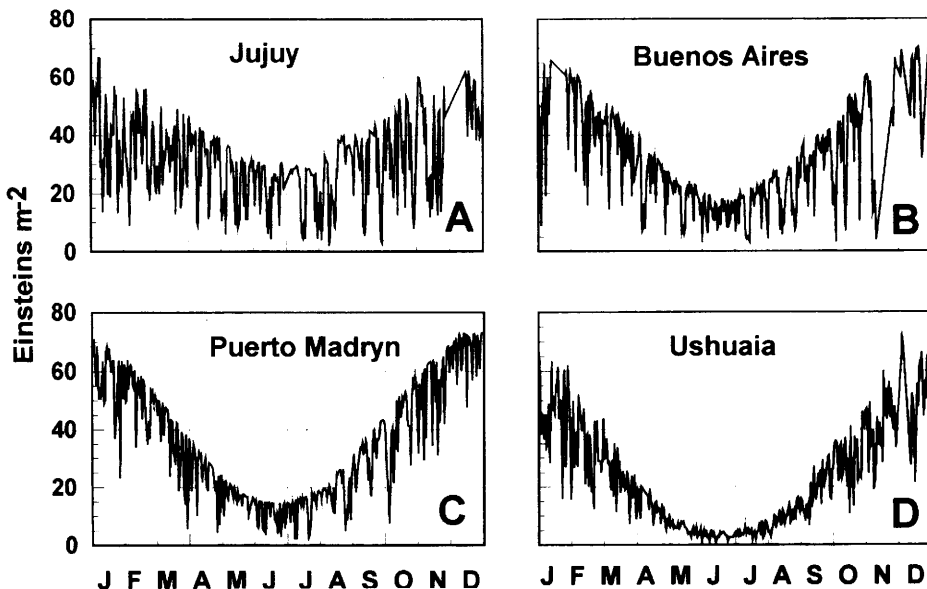


Fig. 2. Integrated daily PAR (400–700 nm) in Einsteins m^{-2} from January 1 to December 31, 1995 (1 Einstein = 1 mol of photons). Data are for the four sites where the GUVs are installed: (A) Jujuy, (B) Buenos Aires, (C) Puerto Madryn, and (D) Ushuaia.

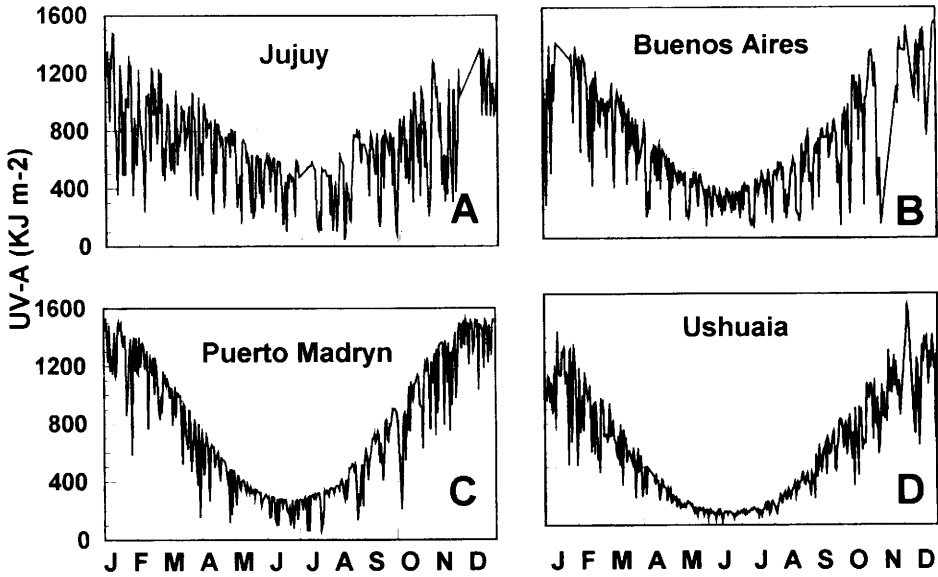


Fig. 3. Integrated daily UV-A (320–400 nm) in kJ m^{-2} from January 1 to December 31, 1995 as estimated from the 340 nm and 380 nm measurements (explanation in text). Data are for the four sites where the GUVs are installed: (A) Jujuy, (B) Buenos Aires, (C) Puerto Madryn, and (D) Ushuaia.

year as the one observed for PAR (Fig. 2), with great variability at all sites and maximum values during summer. The highest values of daily integrated UV-B

(Fig. 4) were also observed close to or at the summer solstice (December 21); however, relatively high values were also observed at some days during October

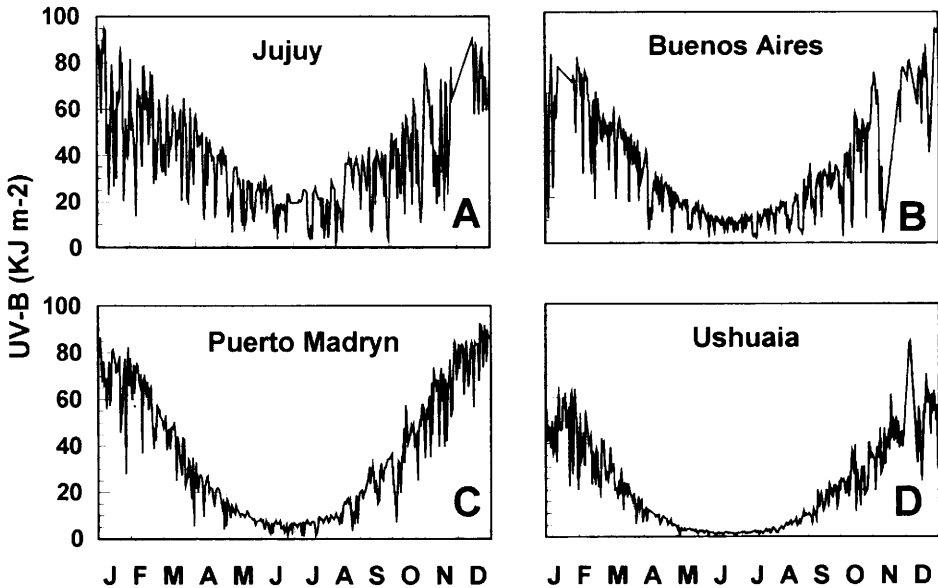


Fig. 4. Integrated daily UV-B (280–320 nm) in kJ m^{-2} from January 1 to December 31, 1995 as estimated from the 305 nm and 320 nm measurements (explanation in text). Data are for the four sites where the GUV's are installed: (A) Jujuy, (B) Buenos Aires, (C) Puerto Madryn, and (D) Ushuaia.

Table 2

Local noontime UVR irradiances (W m^{-2}) for the clearest day at each site: Ushuaia, December 21, 1995; Puerto Madryn, December 22, 1995; Buenos Aires, December 29, 1995; Jujuy, December 31, 1994

Site	305 nm	320 nm	340 nm	380 nm	UV-B	UV-A
Ushuaia	0.024	0.29	0.51	0.72	2.61	42.85
Puerto Madryn	0.038	0.36	0.61	0.85	3.74	51.27
Buenos Aires	0.041	0.38	0.63	0.86	3.99	52.99
Jujuy	0.048	0.40	0.66	0.92	4.46	55.47

Data at 305, 320, 340 and 380 nm from GUV's instruments; data for UV-B and UV-A were estimated as mentioned in the text.

and November. Jujuy was the site that showed the minimum seasonal (summer–winter) variability in the daily solar UV-B irradiance while Ushuaia (Fig. 4D) and Puerto Madryn (Fig. 4C) showed the maximum. With normal total ozone column concentration and no cloud conditions, the noontime solar UV-B irradiances were higher at Jujuy and the values tended to decrease southward, with Ushuaia having the lowest UV-B irradiance (Table 2). These data agree with model outputs (Holm-Hansen and Lubin, 1993) that show maximum daily integrated values at latitudes of about 40° but noontime irradiance values de-

creasing from the tropics to the poles. It is expected that atmospheric pollution in Buenos Aires, together with relatively high tropospheric ozone concentrations (Fishman et al., 1990) could result in a reduction of UVR at ground levels (Brühl and Crutzen, 1989; Hough and Derwent, 1990; Oltmans and Levy, 1992), with values smaller than predicted if based on latitude alone.

The ratio of the irradiance at 305 nm versus 340 nm reflects the relative proportions of UV-B and UV-A radiation, and was used to estimate column ozone concentration (Stamnes et al., 1991), with low values of this ratio indicating high ozone column concentration. These 305/340 ratios (Fig. 5) were higher at the tropical station in Jujuy (Fig. 5A), and decreased towards the south. In tropical areas total ozone column concentration (under normal conditions) is smaller than in polar areas (Madronich, 1993) and due to lower solar zenith angles there is less absorption of shorter UV-B radiation resulting in the observed trend. At all sites there was considerable daily variation in the 305/340 values; however, a significant increase in this ratio was observed at Ushuaia (Fig. 5D) during mid-October and mid-November, with the peak during mid-October sur-

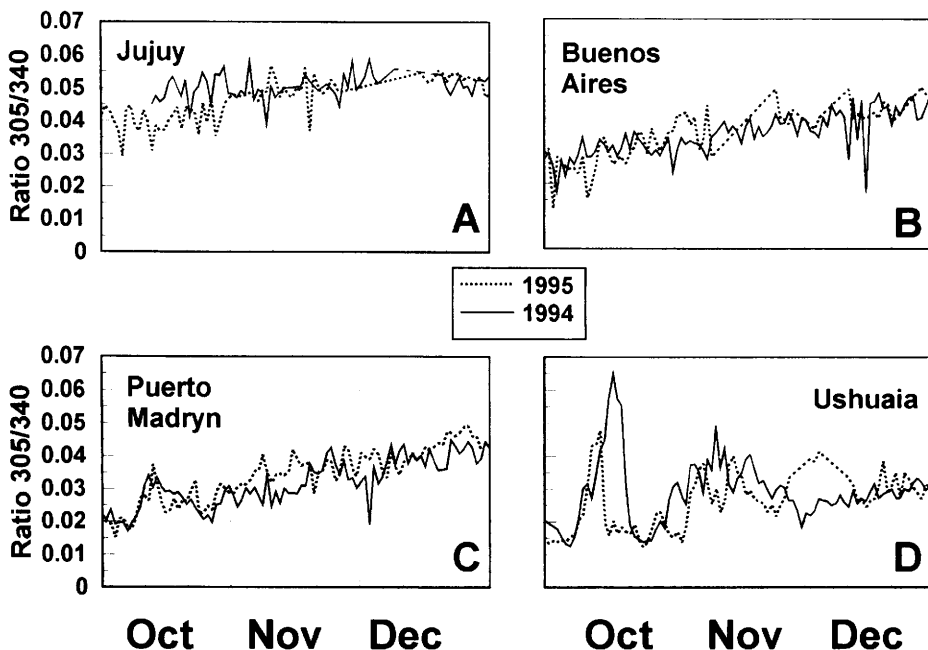


Fig. 5. Mean daily ratio of energy at 305 nm divided by the energy at 340 nm from October 1 to December 31, of 1994 and 1995. Data are for the four sites where the GUVs are installed: (A) Jujuy, (B) Buenos Aires, (C) Puerto Madryn, and (D) Ushuaia.

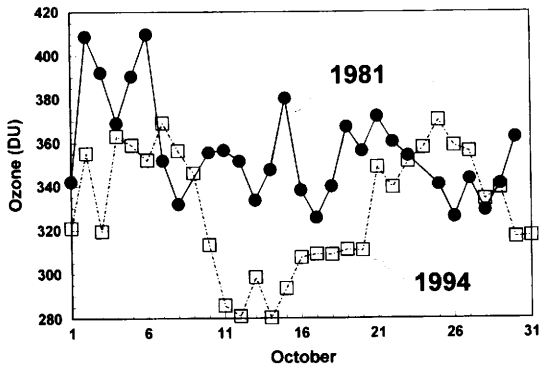


Fig. 6. Daily satellite ozone concentration data for October of 1981 (●) and 1994 (□), for Puerto Madryn. Data are from the Total Ozone Mapping Spectrometer, made available by the Ozone Processing Team, NASA Goddard Space Flight Center (see <http://jwocgy.gsfc.nasa.gov/> on the World-Wide-Web).

passing the values observed at Jujuy (Fig. 5A) at that time. Puerto Madryn and Buenos Aires showed an increase in the 305/340 values as the spring progressed towards the summer solstice. An increase in this ratio was also observed at Puerto Madryn (Fig. 5C) during mid-October.

Since an increase in the ratio 305/340 indicates low ozone concentrations it is expected that the variations observed at Ushuaia during October and November are related to the geographical extent of the ‘ozone hole’. The extent of low-ozone air masses over Ushuaia and the tip of South America has been well documented in other studies (Frederick et al., 1993, 1994; Booth et al., 1994). The variations noted at Puerto Madryn, although much smaller than the ones at Ushuaia, are thought to be related to the ‘ozone hole’ as they occurred at the same time as the ones observed at Ushuaia (Fig. 5D), and at Palmer Station, Antarctica (64.7°S, 64.1°W) during the same time period in 1994 (data from NSF-UVR Monitoring Network). We used ozone satellite data to compare with our ground measurements of UVR at Puerto Madryn. The satellite ozone concentrations for the months of October of 1981 and 1994 are presented in Fig. 6. During the first and last weeks of October, the ozone data of both years were quite similar and comparable with the historical mean, for this month, of 343 Dobson units (S.D. of 29.6 DU). However, during the second and third weeks, significantly low ozone concentrations were observed dur-

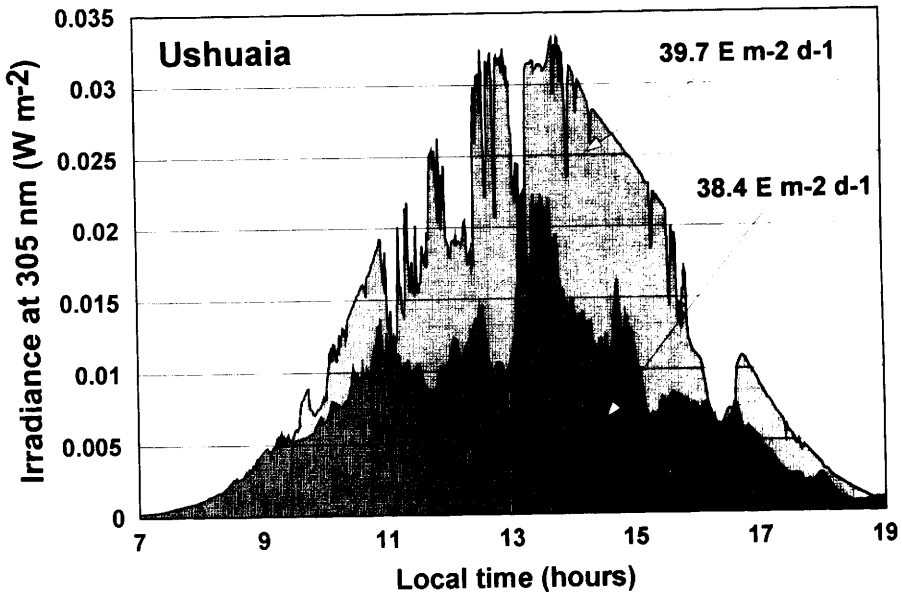


Fig. 7. Irradiance at 305 nm (in $W m^{-2}$) as a function of time of the day at Ushuaia for the day with the maximum value for the ratio of irradiance at 305 nm to 340 nm (October 16, 1994; clear shading) and for the day at the summer solstice (December 21, 1994; dark shading). Note that both days have approximately similar values of PAR.

ing 1994 but not during 1981; these low ozone values for 1994 agree with our measurements and with the ratio 305/340 at Puerto Madryn (Fig. 5C). Low-ozone air masses for the month of October were also determined as far as Southern Brazil (about 30°S) as a strip that leaked out the ozone hole (Kirchhoff et al., 1996). We believe that the high values of the 305/340 ratio (Fig. 5) are related to the extension of the ozone hole rather than to the breakdown of the polar vortex (Atkinson et al., 1989) as this phenomenon occurs later in the season (e.g., December). Our data set showed no significant differences in the 305/340 ratio in the late spring and summer values that might indicate the appearance of low-ozone air masses over the continent.

Data for irradiance at 305 nm at Ushuaia, in two days with similar PAR values but with different ratios 305/340, are presented in Fig. 7. During October 16, 1994, the day with the maximum value for the 305/340 ratio, the irradiance at 305 nm reached a maximum of approximately 0.033 W m^{-2} , a value that was higher than during the summer solstice (0.022 W m^{-2}). However, this maximum

value at 305 nm at Ushuaia did not exceed the maximum value at the other three sites (Puerto Madryn, Buenos Aires, and Jujuy). The relative increase of irradiance at 305 nm as compared to 340 nm at Ushuaia was about 3–5 times higher during low-ozone-episodes than during normal ozone conditions in the month of October, but with the absolute irradiance and daily dose at 305 nm been equal or slightly higher than its value at Puerto Madryn (Fig. 8). Similar values of relative increase of erythemal irradiances at Ushuaia were found in the study of Bojkov et al. (1995) for the years of 1989–1993. Our data show that even though there was a significant increase of shorter wavelengths of UV-B radiation (e.g., 305 nm) at Ushuaia, the absolute value of irradiance was not significantly different from the values recorded during the summer at the same site and was lower than the maximum value measured at the site located at about 12° of latitude to the north. As mentioned before, cloud cover was the major source of variance for irradiances at Ushuaia (our data; Frederick et al., 1993). Similar results have been found in other places where the influence of

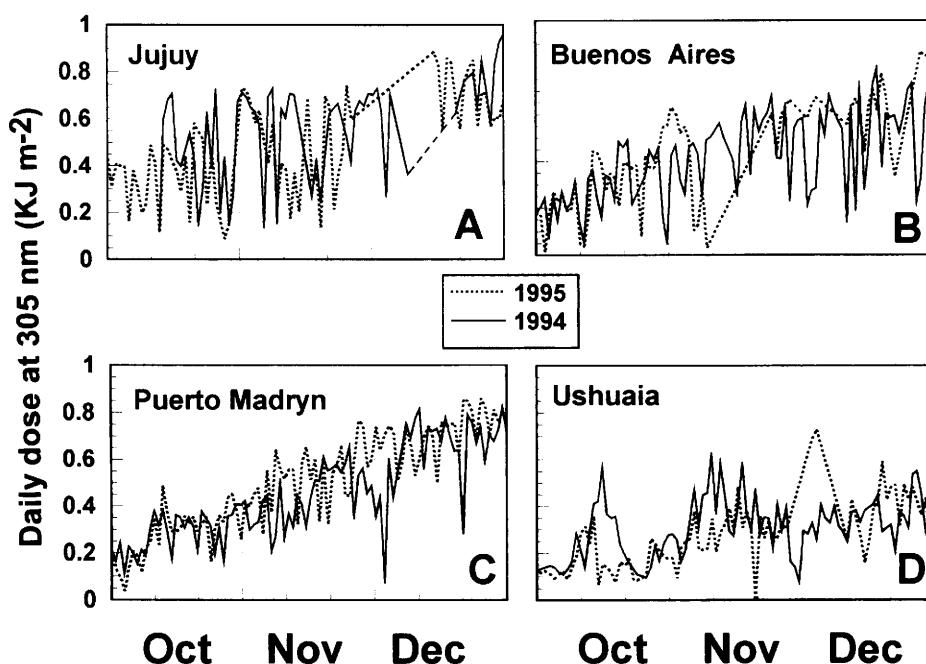


Fig. 8. Daily doses at 305 nm (in kJ m^{-2}) from October 1 to December 31, in 1994 and 1995. Data are for the four sites where the GUVs are installed: (A) Jujuy, (B) Buenos Aires, (C) Puerto Madryn, and (D) Ushuaia.

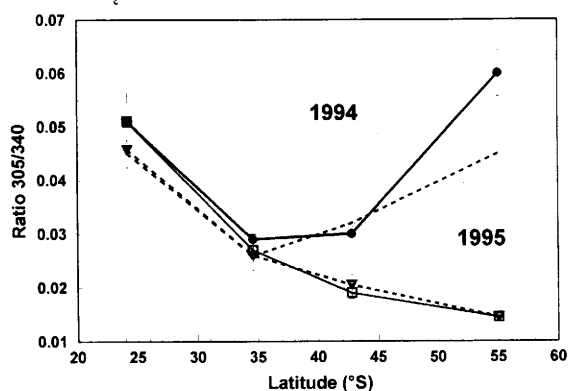


Fig. 9. Mean daily ratio of energy at 305 nm divided by the energy at 340 nm as a function of latitude. Data are the average values for the three days showing the maximum 305/340 ratio during 1994 (October 15–17, • and solid line) and during 1995 (October 12–14, ○ and broken line). The average values for the three-day period ten days before and after the time of maximum 305/340 ratio, are given for 1994 (∇ and broken line) and for 1995 (□ and solid line). The standard deviation of each data point is indicated by the + symbols.

varying cloudiness on global erythemal irradiances was greater than the varying ozone (Blumthaler et al., 1996).

In order to establish how far north low-ozone air masses extend over South America, as inferred from the ratio 305/340, a plot of this ratio versus latitude was used as shown in Fig. 9. With normal ozone column concentration, the ratio 305/340 decreased with latitude and was higher at Jujuy (about 0.045–0.05) and smaller at Ushuaia (0.015), with intermediate values at Buenos Aires and Puerto Madryn. However, during the time of the ozone hole in 1994 and 1995, the ratio 305/340 increased significantly ($p < 0.001$) at the Ushuaia and Puerto Madryn sites, but remained the same for Buenos Aires and Jujuy as compared with the normal ozone conditions. The relative increase in the shorter UV-B radiation at Ushuaia during 1994 was significantly higher ($p < 0.05$) than at Jujuy, but during 1995, the ratio values at the two sites were comparable (Fig. 9). The ratio energy values were similar during 1994 and 1995 at Puerto Madryn. Our data thus indicate that air masses with low ozone concentrations were over South America to at least 42°S but probably further north (i.e., about 38°S). At this latitude (38°S) there were

significant differences between the 305/340 ratio of days when the ozone hole was over Ushuaia, and days before and after that period when the ozone concentration was normal (Fig. 9).

Our data indicate that although low-ozone air masses are periodically found over the southern portion of South America with resulting enhancement of UVR, great care should be taken regarding the evaluation of the impact that this increase of UVR could have on organisms, as other variables such as cloud cover, daylength, and latitude, must be taken into account in addition to column ozone concentration.

Acknowledgements

We thank all the people at our home institutions that helped with data collection and equipment control and maintenance. We thank Drs. N. San Román, G. Rae, V. Villafañe, O. Holm-Hansen and J. Frederick for support and valuable discussions. We specially thank Dr. Walter Cravero for providing satellite ozone data. We also thank two anonymous reviewers for their valuable help.

References

- Atkinson, R.J., Matthews, W.A., Newman, P.A., Plumb, R.A., 1989. Evidence of the mid-latitude impact of Antarctic ozone depletion. *Nature* 340, 290–294.
- Blumthaler, M., Ambach, W., Cede, A., Staehelin, J., 1996. Attenuation of erythemal effective irradiance by cloudiness at low and high altitude in the Alpine Region. *Photochem. Photobiol.* 63 (2), 193–196.
- Bojkov, R.D., Fioletov, V.E., Díaz, S.B., 1995. The relationship between solar UV irradiance and total ozone from observations over southern Argentina. *Geophys. Res. Lett.* 22 (10), 1249–1252.
- Booth, C.R., Lucas, T.B., Morrow, J.H., Weiler, C.S., Penhale, P.A., 1994. The United States National Science Foundation's Polar Network for monitoring ultraviolet radiation. In: Weiler, C.S., Penhale, P.A. (Eds.), *Ultraviolet Radiation in Antarctica: Measurements and Biological Effects*. Am. Geophys. Union, 62, Washington, D.C., pp. 17–37.
- Brühl, C., Crutzen, P.J., 1989. On the disproportionate role of tropospheric ozone as a filter against solar UV-B radiation. *Geophys. Res. Lett.* 16 (7), 703–706.
- Díaz, S.B., Booth, C.R., Lucas, T., Smolskaia, I., 1994. Effects of ozone depletion on irradiances and biological doses over Ushuaia. *Arch. Hydrobiol. Beih.* 43, 115–122.

- Fishman, J., Watson, C.E., Larsen, J.C., Logan, J.A., 1990. Distribution of tropospheric ozone determined from satellite data. *J. Geophys. Res.* 95 (D4), 3599–3617.
- Frederick, J.E., Soulen, P.F., Díaz, S.B., Smolskaia, I., Booth, C.R., Lucas, T., Neuschuler, D., 1993. Solar ultraviolet irradiance observed from Southern Argentina: September 1990 to March 1991. *J. Geophys. Res.* 98 (D5), 8891–8897.
- Frederick, J.E., Díaz, S.B., Smolskaia, I., Espósito, W., Lucas, T., Booth, C.R., 1994. Ultraviolet solar radiation in the high latitudes of South America. *Photochem. Photobiol.* 60 (4), 356–362.
- Holm-Hansen, O., Lubin, D., 1993. Solar ultraviolet radiation: effects on rates of CO₂ fixation in marine phytoplankton. In: Tolbert, N.E., Preiss, J. (Eds.), *Regulation of Atmospheric CO₂ and O₂ by Photosynthetic Carbon Metabolism*. Oxford Univ. Press, New York, pp. 55–74.
- Hough, A.M., Derwent, R.G., 1990. Changes in the global concentration of tropospheric ozone due to human activities. *Nature* 344, 645–648.
- Kirchhoff, V.W.J.H., Schuch, N.J., Pinheiro, D.K., Harris, J.M., 1996. Evidence for an ozone hole perturbation at 30°South. *Atmos. Environ.* 30 (9), 1481–1488.
- Madronich, S., 1993. The atmosphere and UV-B radiation at ground level. In: Young, A.R., Björn, L.O., Moan, J., Nultsch, W. (Eds.), *Environmental UV Photobiology*. Plenum, New York, pp. 1–39.
- Oltmans, S.J., Levy, H., 1992. Seasonal cycle of surface ozone over the western North Atlantic. *Nature* 358, 392–394.
- Prather, M.J., Watson, R.T., 1990. Stratospheric ozone depletion and future levels of atmospheric chlorine and bromine. *Nature* 344, 729–734.
- Seckmeyer, G., McKenzie, R.L., 1992. Increased ultraviolet radiation in New Zealand (45°S) relative to Germany (48°N). *Nature* 359, 135–137.
- Stamnes, K., Slusser, J., Bowen, M., 1991. Derivation of total ozone abundance and cloud effects from spectral irradiance measurements. *Appl. Opt.* 30 (30), 4418–4426.
- Stolarski, R., Bojkov, R., Bishop, L., Zerefos, C., Staehelin, J., Zawodny, J., 1992. Measured trends in stratospheric ozone. *Science* 256, 342–349.