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The ozone hole over Punta Arenas, Chile

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Abstract. Three fundamental questions are addressed for the location of Punta Arenas (53.0°S, 70.9°W), Chile: Does the Antarctic ozone hole extend over the city? If so, at what height is most of the ozone depleted? And by how much does the UVB radiation increase under ozone hole conditions? It is shown that Punta Arenas is affected by the Antarctic ozone hole, even though it is a considerable distance away from the pole. In comparison with the average global trend of -0.25% per year, the downward ozone trend at Punta Arenas is -0.5% per year (twice as large as the global average) and -1.2% per year (almost 5 times larger than the global average) using the monthly October averages. To obtain these figures, an ozone climatology of TOMS (Total Ozone Mapping Spectrometer) data from 1979 to 1992 has been used. Observations of the ozone hole over Punta Arenas are described during the austral spring periods of 1992, 1993, and 1994. Systematic observations with a Brewer spectrophotometer have been made in order to measure the vertical column of ozone and the simultaneous variations in UVB radiation. In addition, the vertical distribution of ozone has been investigated during ozone hole conditions, by using ozone ECC (Electrochemical Concentration Cell) sondes launched on balloons, in order to determine at which height the ozone is reduced most. Using the 220 DU (Dobson Units) threshold as reference, we identified the ozone hole over Punta Arenas on five occasions during the 3 year period of these observations, September 1993, October 1992, 1994; and November 1993 and 1994. The vertical distribution of ozone during ozone hole conditions shows maximum ozone destruction efficiency near 15-17 km, where ozone nearly vanishes completely, on several occasions. The largest amount of ozone depletion, however, occurs above this height, just under and at the main ozone peak, where it may reach about 50%. The UVB radiation in small spectral bands may increase dramatically during ozone hole events; at 295-297 nm the observed factors of increase for Punta Arenas were between 10 and 38. The maximum integrated/weighted intensities in October, during hole events increased over background values between 2 and 3 times, which represent values near the local summer maximum but not yet beyond levels normally observed at low-latitude stations.

Introduction

Ozone is an important chemical constituent of the atmosphere. One of its major roles in the atmosphere is to screen out biological damaging solar radiation in the wavelength region between 280 and 320 nm, the UVB radiation [*Brasseur and Solomon, 1984*]. In addition to the global decreasing ozone trend, regions near the south pole are affected by the Antarctic ozone hole phenomenon [*Solomon, 1988, 1990*]. This is a seasonal strong ozone loss mechanism caused by heterogeneous chemical reactions [*Stolarski et al.*, 1986; *Stolarski*, 1988; *Solomon and Garcia*, 1986; *Anderson et al.*, 1991] and normally seen in southern spring. The NASA Total Ozone Mapping Spectrometer (TOMS) instrument has been very important to describe ozone depletions near the poles [*Herman et al.*, 1993].

Punta Arenas (53.0°S, 70.9°W, Chile) and Ushuaia (54.5°S, 68.0°W, Argentina) are the southernmost cities of the South American continent, the first with about 100,000 inhabitants and the second with about 30,000. These populations are the first group of people that have been exposed to the ozone hole effects, including larger intensities of UVB radiation. To study these effects on a long-term basis, and to produce local competence in this scientific area, a Brewer spectrophotometer was installed in Punta Arenas's University of Magallanes in June 1992, in collaboration with the Instituto Nacional de Pesquisas Espaciais (INPE) of Brazil [*Kirchhoff et al.*, 1993].

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Instrumentation

Total ozone as well as UVB radiation are measured systematically with a Brewer spectrophotometer [*Brewer*, 1973; *Brewer and Kerr*, 1973]. This instrument was developed by the Canadian Atmospheric Environment Service and has been commercially available since the early 1980s. Presently, there are more than 100 of these instruments in operation. It was specifically designed to meet the very demanding performance criteria to measure accurately the ultraviolet radiation necessary for the calculation of ozone column amounts using direct solar beam absorption. The Brewer instrument makes spectral observations at wavelengths between 290 and 325 nm. The resolution for ozone observations is about 0.6 nm, and the wavelengths are placed at 306.3, 310.0, 313.4, 316.7, and 319.9 nm. The instrument includes automatic wavelength calibration using an internal mercury discharge lamp, as well as a relative spectral intensity source from a quartz-halogen lamp. A computer-controlled azimuth mount ensures automatic solar pointing.

The vertical distribution of ozone over Punta Arenas has been determined by using ozone Electrochemical Concentration Cell (ECC) sondes launched on balloons. The balloonsonde is a small 20x30x30 cm instrument developed in the early 1970s [*Komhyr*, 1969; *Komhyr and Harris*, 1971], which flies together with a standard radiosonde, providing, in addition to ozone concentrations, temperature, humidity, and pressure. The ozone sensor is based on two platinum electrodes immersed in a liquid in which a chemical reaction occurs when ozone is introduced into the chemical solution. The result of the reaction is the production of free electrons, which are amplified to an electric current proportional to the ozone concentration bubbled into the electrodes from the outside air. The digital ozonesondes used can make as many as 60 ozone observations per kilometer, including pressure, temperature, humidity, temperature of the sensor, battery voltage, and ozone. This technique has been used extensively over the last 10 years for ozone observations [*Kirchhoff et al.*, 1991].

Objective

The objective of this work is to describe the appearance of the ozone hole over Punta Arenas, Chile, during the years 1992, 1993, and 1994, using observations of a Brewer spectrophotometer installed specifically for this purpose. In addition, the vertical distribution of ozone during ozone hole conditions was measured using ozone ECC sondes. The intensities of the UVB radiation during ozone hole conditions at Punta Arenas are compared with normal low-latitude UVB radiation at Natal, Brazil (6°S).

Results and Discussion

Ozone Averages Over Punta Arenas

The Antarctic ozone hole is clearly a polar phenomenon, in which the polar vortex and its dynamics and the extremely low stratospheric temperatures play important roles [*Schoeberl and Hartmann*, 1991]. However, when the polar vortex breaks up and the ozone hole starts to disappear, large volumes of low-ozone air, which are pieces of the disrupted polar air, may be transported to lower latitudes, where they act as local perturbations. Such perturbations have been reported from observations at lower latitudes [*Atkinson et al.*, 1989; *Kane*, 1991; *Thompson*, 1991; *Kirchhoff et al.*, 1996b]. Model calculations have also predicted that Antarctic ozone lows may be transported to lower latitudes, as shown by *Prather and Jaffe* [1990] and *Prather et al.* [1990].

Punta Arenas is not within the Antarctic circle. Clearly, Punta Arenas is not always inside of the Antarctic ozone hole region. Does that mean that it is not affected by the Antarctic ozone hole? In order to answer this question a NASA database, that includes 14 years of TOMS (version 6.0 [*Krueger et al.*,1992]) data, was used. An ozone climatology for Punta Arenas was obtained from this 1979 to 1992 data set, a sequence that is used in this work for basic comparisons. In what follows it will be designated as the reference historical climatology (RHC). On the basis of these background data we show that there is an obvious and systematic effect of the Antarctic ozone hole over Punta Arenas.

Figure 1 shows ozone column amounts in Dobson Units (DU) as a function of time in years. The yearly average column ozone amounts from the above mentioned climatology are shown in Figure 1 by squares. These show a clear downward trend of the ozone column amounts. A simple linear fit to the data gives a trend of -0.5% per year, twice as large as the global average trend [World Meteorological Organization, 1988, 1989] of -0.25% per year. Because of the ozone depletions in spring the total ozone column amounts decrease significantly with respect to the yearly averages; this decrease is shown in Figure 1 by the

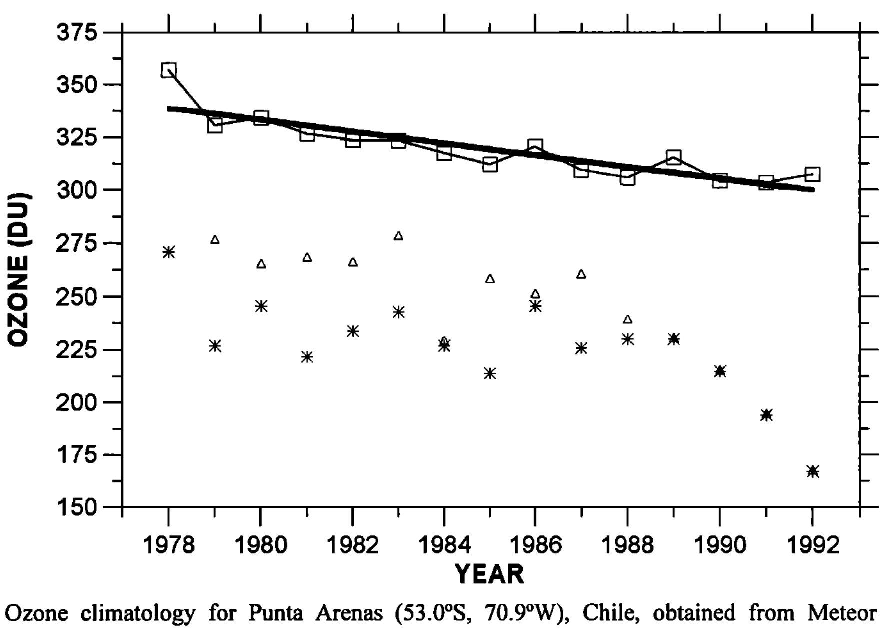

Figure 1. Ozone climatology for Punta Arenas (53.0°S, 70.9°W), Chile, obtained from Meteor 3/TOMS (version 6) data. Shown are the yearly averages, (squares) and a linear fit of -0.5% per year. Also shown are yearly minima (asterisks) and October minima (triangles).

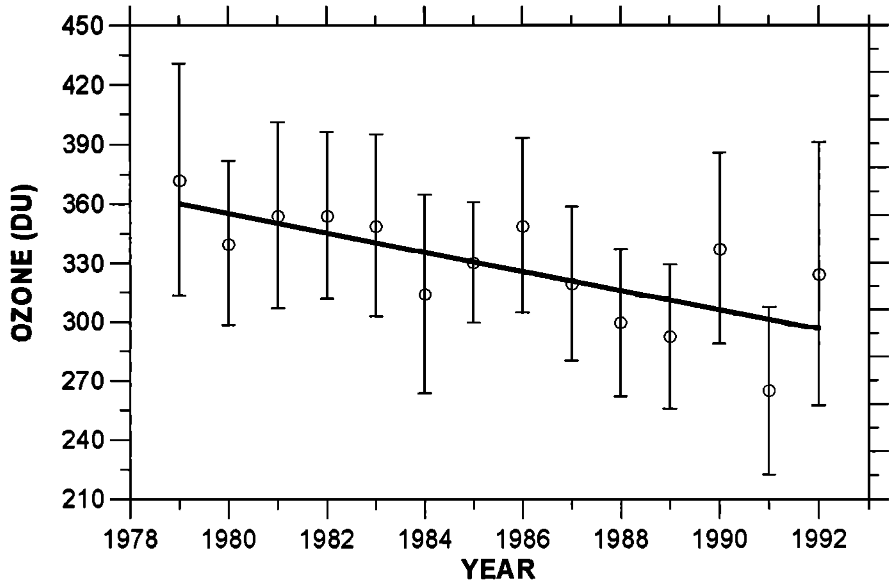

Figure 2. Ozone climatology for Punta Arenas, Chile obtained from Meteor 3/TOMS (version 6) data. The October averages are shown. A simple linear fit for trend analysis gives -1.2% per year.

yearly minima (asterisks); at Punta Arenas these yearly minima may occur in September, October, or November. Figure 1 also shows the October minima (triangles). Roughly, the yearly minimum from 1978 to 1988 was near 250 DU, but from 1988 onward, the minimum is decreasing at a considerably faster rate; the 1992 minimum was 164 DU, and it was 196 DU the year before. The Brewer data show a minimum ozone column for 1994 of 145 DU in October (for which the climatological average is 334 DU). This appears to have been the lowest ozone column observation ever for Punta Arenas. During the last 4 years the yearly minima all occurred in October.

Figure 2 shows average ozone column amounts for the month of October, as a function of time in years, using the monthly October means of the above mentioned ozone climatology for Punta Arenas. The rate of ozone decrease gives a linear fit trend of -1.2% per year, 5 times the global average trend. It is clear therefore that Punta Arenas is considerably affected by the Antarctic ozone hole phenomenon.

From observations of satellite images of total ozone in the area of interest it is clear that the transport time constant for change is of the order of only a few days, whereas the chemical time constant for ozone is much larger [*Anderson et al.*, 1991; *Molina et al.*, 1987]. The ozone hole itself is defined in this study by the geographic area inside of which the ozone column has less than 220 DU. This is normally a rounded large area over the south pole. The exact shape is not always circular; it may stretch out in an elliptical shape, for example [*Herman et al.*, 1995a, b]. When this feature takes an oval shape, it may sweep over the Punta Arenas area. Examination of many of these occasions shows that the ozone hole occurs over the city when the Antarctic ozone hole reaches out in an elongated shape; during these occasions the tip of the ozone hole may stay over Punta Arenas for a few days, after which the elongated shape of the hole stretches back, becoming circular again, or the oval shape continues but rotates beyond Punta Arenas, either to the west or to the east.

Brewer Spectrophotometer Observations

In addition to UVB radiation, we obtained systematic ozone column amounts using a Brewer spectrophotometer in Punta Arenas. For the 3 years of observations, ozone column values were extremely low on several occasions. For this study, low-ozone events were defined as those below 2 standard deviations of the climatological mean; these values are listed in Table 1. We observed ozone hole conditions on five occasions, using the criteria that the observer is inside the ozone hole when the ozone column decreases below 220 DU. These events are shown in Table 1 with an asterisk. The ozone decreases in terms of percentage, shown in Table 1, are calculated by using as reference the RHC defined earlier (monthly averages are shown in parentheses in column 3 of Table 1).

The five ozone hole events (shown in Table 1 with an asterisk*) observed at Punta Arenas during 1992, 1993, and 1994 are further described in Table 2; all days with column ozone values less than 220 DU are shown. The event number of the second column is the same number used in Table 1. Again, the percent reduction is determined by using the RHC as reference. Three of the ozone hole events lasted only 1 day; that is, although the ozone may have been low on the days before and after the event, it was higher than 220 DU. These were all ozone hole events that occurred in either September or November. During October the ozone hole events at Punta Arenas were longer: 3 days in October 1992 and 7 days in October 1994. The largest ozone reduction was observed on October 17, 1994, when a 60% reduction (more than half the layer) occurred.

Daily average ozone column observations made with the Brewer spectrophotometer are shown in Figures 3-5. The shaded rectangle in each panel, introduced as a background in the figures, is the average plus or minus 1 standard deviation from the ozone climatology described earlier (the RHC). Figure 3 is for September, Figure 4 is for October and Figure 5 is for November.

Table 1. Low-Ozone Events Observed at Punta Arenas During 1992,1993, and 1994

Event	Date of Minimum Ozone	Ozone Low, DU	Ozone Decrease, (%)	Duration, Days
1	Sept. 05, 1992	241.2 (330)	26.9	3
2	Sept. 24, 1992	245.0 (330)	25.7	2
3	Sept. 10, 1993	264.1 (330)	20.0	1
4	Sept. 27, 1993	205.9 (330)*	37.6	4
5	Sept. 08, 1994	263.0 (330)	20.3	1
6	Sept. 15, 1994	237.8 (330)	27.9	2
7	Oct. 05, 1992	190.3 (334)*	43.0	4
8	Oct. 04, 1993	235.1 (334)	29.6	2
9	Oct. 15, 1993	238.6 (334)	28.6	2
10	Oct. 22, 1993	236.1 (334)	29.3	3
11	Oct. 26, 1993	230.9 (334)	30.8	3
12	Oct. 02, 1994	261.9 (334)	21.6	1
13	Oct. 10, 1994	235.3 (334)	29.5	4
14	Oct. 17, 1994	145.8 (334)*	56.3	7
15	Nov. 01, 1993	251.0 (334)	24.8	4
16	Nov. 12, 1993	219.3 (334)*	34.3	7
17	Nov. 28, 1993	266.0 (334)	20.3	2
18	Nov. 04, 1994	244.1 (334)	26.9	3
19	Nov. 10, 1994	204.6 (334)*	38.7	8
20	Nov. 18, 1994	238.4 (334)	28.6	6
21	Dec. 08, 1992	266.4 (334)	20.2	3

*Events further described in Table 2.

In addition, the figures show a line at 220 DU, for reference; this is the threshold value we have chosen to define the ozone hole condition, as mentioned before. Figures 3 to 5 show that there is considerable ozone variability in a monthly time interval. This is mainly caused by transport of ozone irregularities over the Punta Arenas instrument, as mentioned already. The vertical error bars in Figures 3 and 4 show the typical size of the standard deviation of the daily mean, as observed by the Brewer spectrophotometer.

Figure 3 shows that low ozone values are seen in September of all years, but there is only one occasion, in September 1993, on which the threshold of 220 DU is reached. There are occasions on which the ozone becomes larger than the climatological means used for comparison, but clearly, for most of the time the ozone values are below average. Similar results are seen for October, in Figure 4. Two large hole events are seen for 1992 and 1994, when the ozone went below 220 DU. A large hole event was seen on October 5, 1992, when the daily average was 190.3 DU. The lower limit was reached at a downward rate of 31.25 DU per day, starting around October 1. Punta Arenas was clearly inside the ozone hole area on October 4, 5 and 6, as shown in Table 2. After this date the elongated ozone hole pattern shifted eastward, beyond the city limits of Punta Arenas, and the ozone levels started to increase.

During October 1993 the lower limit of 220 DU was never reached, but in 1994 again the ozone hole was present from October 14 to 19. The lowest value seen during this period was 145.8 DU, on October 17. This lower limit ozone column value represents only 43% of the climatological mean (RHC), and was

Table 2. Days With Ozone Hole Conditions (O_3 Less than 220 DU) at Punta Arenas; During 1992, 1993, and 1994

Sequence	Event #	Dates Of Event	Ozone, DU	Ozone Decrease, %
1	04	Sept. 27, 1993	205.9	37.6
2	07	Oct. 04, 1992	202.8	39.3
	07	Oct. 05, 1992	190.3	43.0
	07	Oct. 06, 1992	203.5	39.1
3	14	Oct. 13, 1994	250.7	24.9
	14	Oct. 14, 1994	216.1	35.3
	14	Oct. 15, 1994	195.6	41.4
	14	Oct. 16, 1994	192.2	42.4
	14	Oct. 17, 1994	145.8	56.3
	14	Oct. 18, 1994	193.9	41.9
	14	Oct. 19, 1994	197.2	40.9
4	16	Nov. 12, 1993	219.3	34.3
5	19	Nov. 10, 1994	204.6	38.7

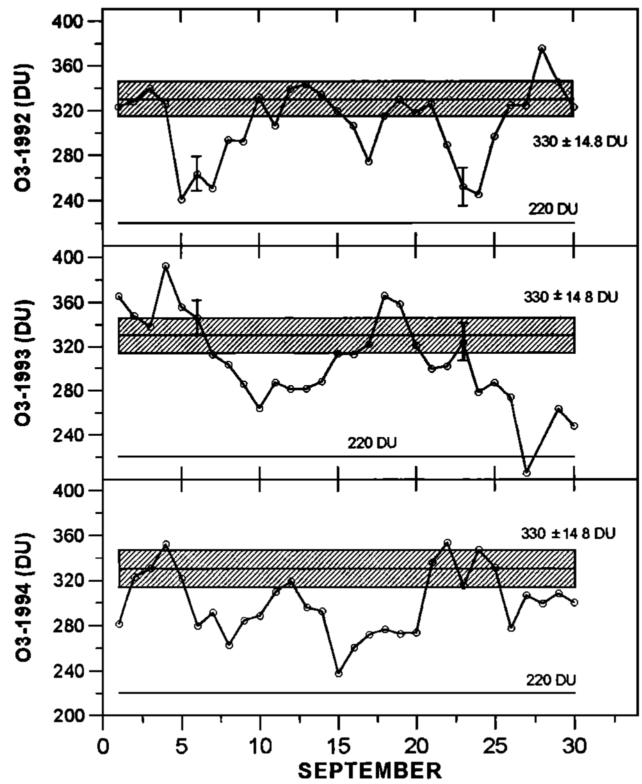

Figure 3. Brewer spectrophotometer September daily averages for 1992, 1993, and 1994 for Punta Arenas. The hatched rectangle represents the climatological average plus and minus the standard deviation, shown for reference. Vertical bars are typical standard deviations for the daily means. The 220 DU threshold line is shown for reference. A hole condition was observed on September 27, 1993 (daily average was lower than 220 DU).

reached at a rate of 21.1 DU per day, starting October 8, as shown in Figure 4.

The ozone hole condition over Punta Arenas can be seen as far into summer as November, as shown in Figure 5. In contrast to 1992, which had ozone values very close to the climatological mean, both 1993 and 1994 had at least one occasion of very low ozone: 219.3 DU for November 12, 1993, and 204.6 DU for November 10, 1994. In addition, during the whole month, values in 1993 and 1994 stayed considerably below the climatological mean.

The ozone hole condition was not observed in the data for December. However, there is a clear decrease in ozone values in December in comparison with the climatological averages.

Ozonesonde Measurements: Vertical Distribution of Ozone

Measurements of the ozone column do not show the vertical distribution of ozone concentrations. Ozonesonde measurements were made to obtain the vertical distribution of ozone concentration during normal and perturbed conditions. The soundings were made across the Magallanes channel at King George Island, the Brazilian Antarctic Station Comandante Ferraz (62.1°S, 58.4°W). Several sondes were launched during summer 1991, and the whole winter/spring 1992 period. The data have been described by *Kirchhoff and Marinho* [1992] with emphasis on the troposphere and by *Kirchhoff et al.*, [1996a] with emphasis on the stratosphere. Another special ozone sounding campaign was held during October 1995 in Punta Arenas. This special campaign will be described elsewhere.

Figure 6 shows ozone concentrations (in partial pressure of ozone, nanobars) as a function of height. Two ozone profiles are shown, one for an ozone hole condition and the other for comparison. The comparison profile is a "typical" ozone profile at the latitudes of interest. Obtained in a seasonal period when the ozone hole had completely dissipated (January 21, 1991), it shows peak ozone concentration near 40-50 hPa, which corresponds to 19-21 km. The tropopause transition is near 8-10 km. In contrast, the second profile shown in Figure 6 was obtained in the middle of the ozone hole period of 1992, on September 25. As can be seen, this profile represents a severe ozone hole condition for the Ferraz station. The hatched area between both profiles is equal to the ozone loss between the normal and the perturbed condition. Ozone losses occurred in the lower stratosphere at all heights, but the largest percentage of loss occurs at 15-17 km, where ozone destruction is almost complete. Higher up, near the peak of the ozone layer, the depletion is close to 50%, and most of the ozone loss in terms of the layer content comes from this height region, that is, 18-25 km. It is interesting to note that the ozone hole did not reach as far as Punta Arenas this day. However, more recent sounding events at Ferraz, at Punta Arenas, and at Siowa station confirm the general description of the vertical distribution of ozone during hole condition, as described in Figure 6.

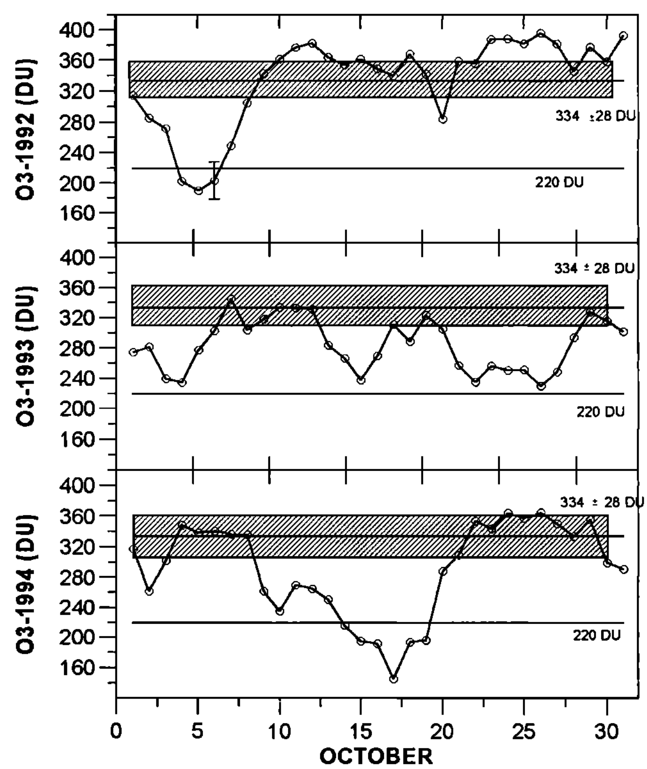

Figure 4. Brewer spectrophotometer October daily averages for 1992, 1993, and 1994, for Punta Arenas. The hatched rectangle represents the climatological average plus and minus 1 standard deviation, shown for reference. Vertical bars are typical standard deviations for the daily means. The 220 DU threshold line is shown for reference. A hole condition was observed around October 5, 1992; and October 17, 1994 (daily average was lower than 220 DU).

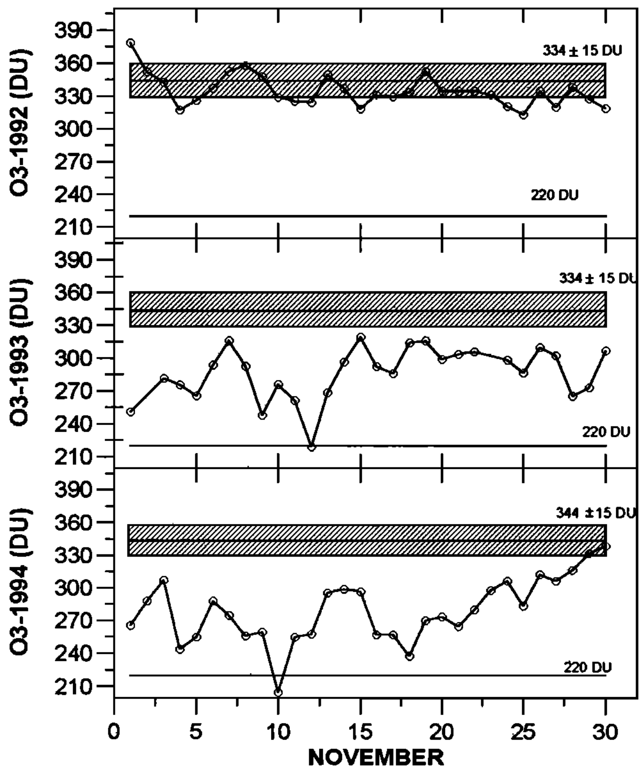

Figure 5. Brewer spectrophotometer November daily averages for 1992, 1993, and 1994, for Punta Arenas. The hatched rectangle represents the climatological average plus and minus the standard deviation, shown for reference.The 220 DU threshold line is shown for reference. A hole condition was observed on November 12, 1993, and November 10, 1994 (daily average was lower than 220 DU).

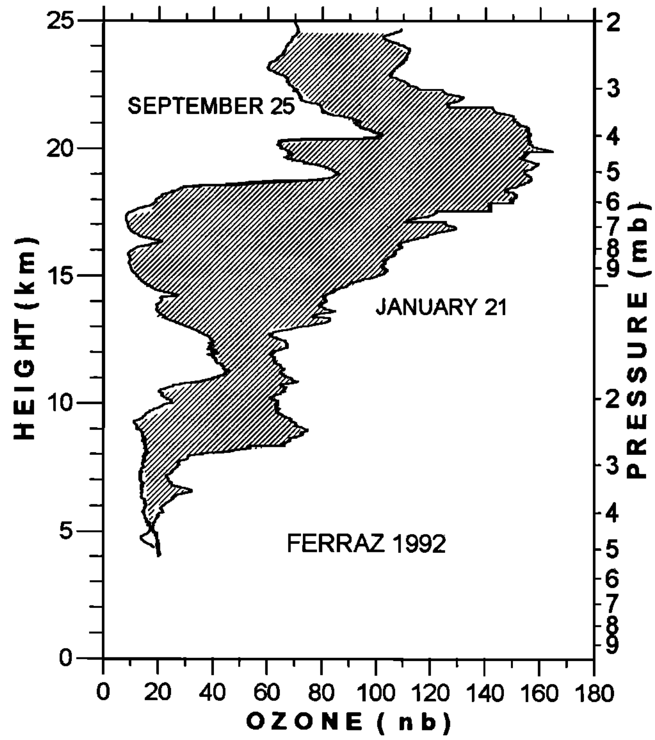

Figure 6. Vertical distribution of ozone near Punta Arenas for normal and perturbed (ozone hole) conditions, obtained from ozonesoundings. The normal layer, shown for reference, was obtained on January 21, 1991. The perturbed ozone profile was obtained on September 25, 1992.

The ozone profile with the strongest ozone loss, closest (in timing) to the ozone hole events observed in Punta Arenas during 1992, is shown in Figure 7. This is for October 3, 1992, 1 day before the ozone hole condition observed at Punta Arenas, October 4, 5, and 6, 1992. The strong surface winds common on the islands of the Antarctic Peninsula, result in very long ranges between the balloon and the ground antenna. In some cases they cause the loss of signal before balloon burst. This makes some of the profiles incomplete, as in this case for October 3, 1992. Ranges of 100-150 km distance have been obtained when the balloon is at heights of 18-20 km. On October 3 the Brewer spectrophotometer at Punta Arenas measured an average of 267 DU, well below the climatological average but still above the 220 DU hole threshold. Again, in Figure 7 the control layer used for comparison is that for January 21, 1991. The October 3 sounding, although incomplete, clearly shows that again the percentage of ozone destruction was most severe near 15-16 km, where the ozone concentration virtually vanished (from a normal concentration of about 80 nbar). Up to about 19 km, just below the ozone peak, the ozone concentration is reduced by more than 60%, which is probably maintained upward. As mentioned, ozone soundings made in Punta Arenas during October 1995 have also shown this behavior of severe ozone destruction near 15 km, as observed, for example, in the soundings of October 11,12, and 13, 1995 (not shown). In summary, during ozone hole conditions, vertical soundings show that there is severe ozone reduction in the lower stratosphere. On many occasions the ozone concentration

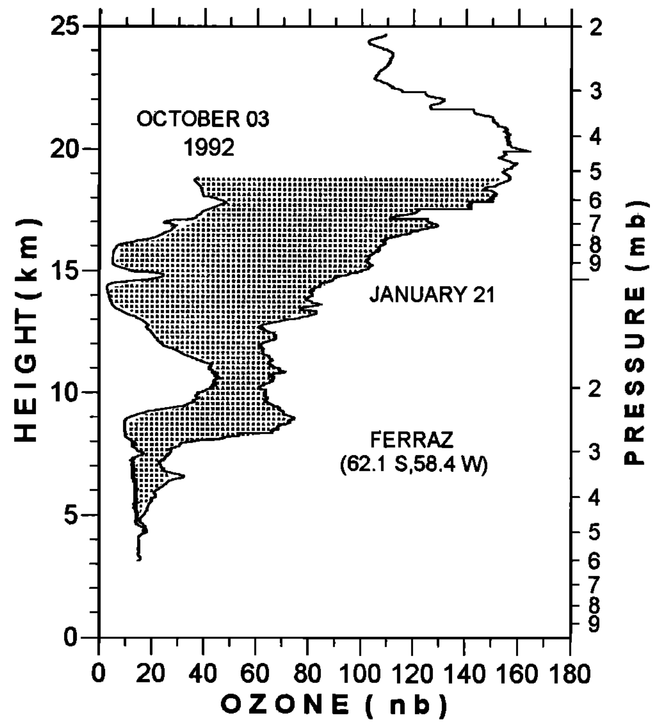

Figure 7. Vertical distribution of ozone near Punta Arenas for normal and perturbed (ozone hole) conditions, obtained from ozonesoundings. The normal layer, shown for reference, was obtained on January 21, 1991. The perturbed ozone profile was obtained on October 3, 1992.

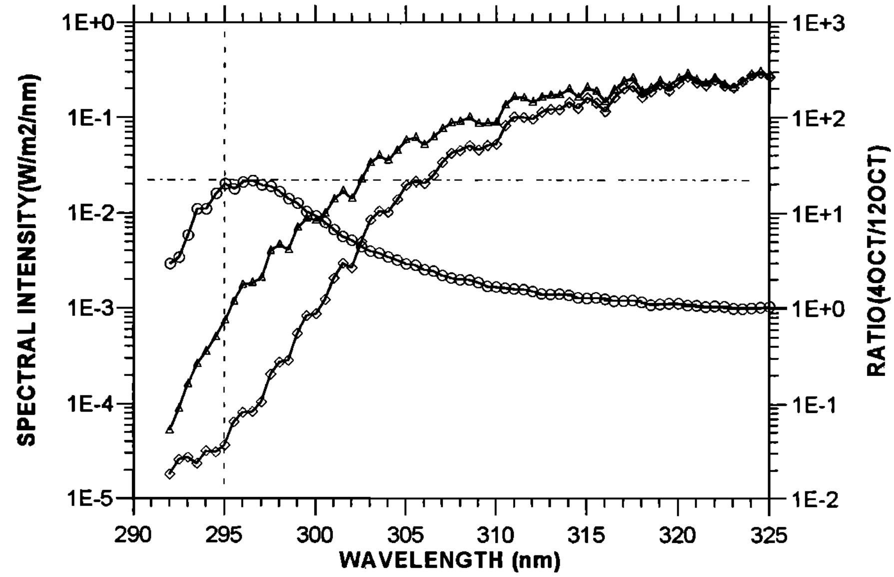

Figure 8. Spectral UVB intensity measurements as a function of wavelength. Two spectra are shown, one on October 4, 1992, for low (triangles) and one on October 12, 1992, for normal (diamonds) ozone column amounts. Also shown (circles) is the ratio between the two spectra, showing maximum enhancements at 295-297 nm.

nearly vanishes at heights of 15-17 km. Near the peak of the ozone layer the ozone loss may decrease to 40-60%.

UVB Measurements

As we mentioned before, the Brewer spectrophotometer makes UVB measurements between 290 and 325 nm. Figure 8 shows UVB spectra obtained at Punta Arenas, that is, the UVB spectral intensity in $W/m^2/nm$ as a function of wavelength, from 290 to 325 nm. These are true intensity measurements; that is, they have not yet been weighted by spectral biological sensitivity functions. The spectral UVB intensities shown in Figure 8 are for 2 days in 1992: October 4, when ozone was reduced (triangles), and October 12, when the ozone at Punta Arenas was normal (diamonds). Figure 8 also shows a curve for the ratio of both spectra, proving that the spectral intensity variation, from low to high column ozone, is a strong function of wavelength, with a peak between 295 nm and 297 nm (the vertical dot-dashed line at 295 nm is shown for reference only). This peak may be an unexpected result, an artifact resulting from stray light phenomena at the very low wavelength, where the instrumental corrections become marginal. The instrumental behavior in this short-wavelength region is presently under further investigation. In any case the maximum value of the ratio, near 296 nm, is quite large, nearly 22 (the horizontal dot-dashed line is shown at 22 for reference only). The ratio decreases for longer wavelengths, becoming nearly unity at 325 nm, where ozone is no longer an important absorber of UV radiation.

The UV spectra obtained from the Brewer were weighted by the *International Illumination Commission* (CIE) [1987] action spectra for erythema, which give a general indication of the

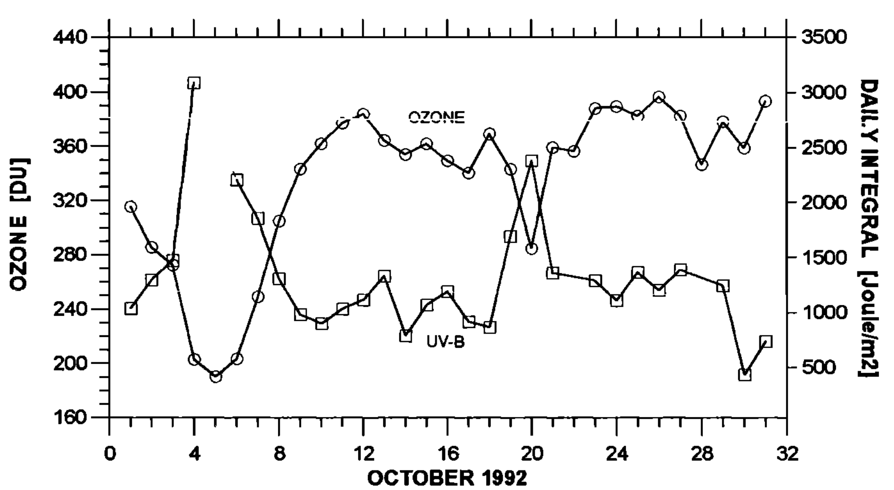

Figure 9. Brewer spectrophotometer ozone column amounts for October 1992 at Punta Arenas and simultaneous UVB radiation integrated/weighted daily integrals, showing expected strong anticorrelation, for days of low ozone.

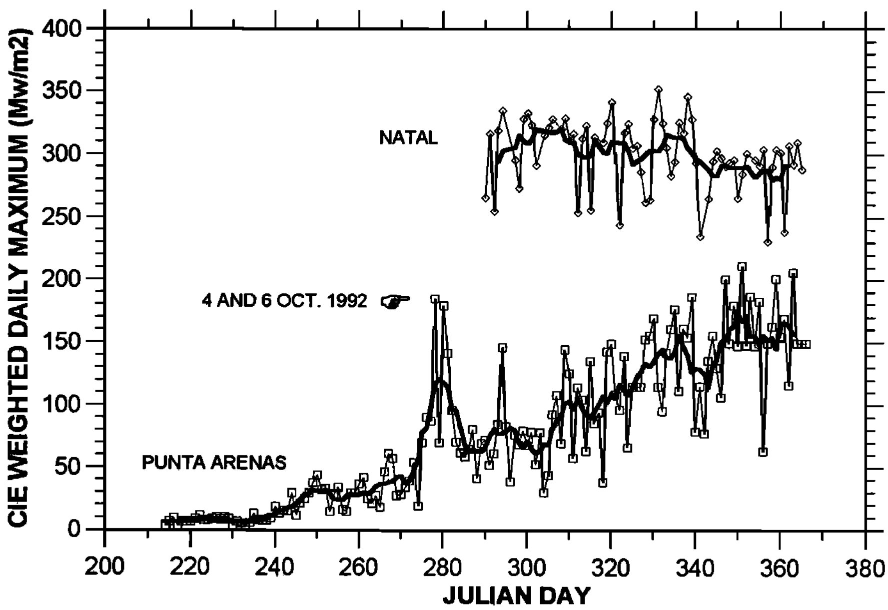

Figure 10. Comparison of daily maxima UVB integrated/weighted intensities for Punta Arenas (53.0°S, 70.9°W), Chile, and for Natal (6.0°S, 35.0°W), Brazil.

biological importance of the UV radiation. The weighted irradiances were then integrated over wavelength, and over each day, giving the integrated UVB intensities.

Increases of UVB radiation during low-ozone events (that is, the expected anticorrelations) are shown for October 1992 in Figure 9. Here the UVB radiation is weighted by the erythema action spectrum [CIE, 1987]. Shown are the ozone column values, already described, and the UVB radiation (CIE-weighted) integrated for each day (J/m^2). As expected, there is a clear negative correlation, with high UVB doses on occasions of low ozone. The case for October 4 is evident, when the UVB radiation doses increased over their background values from about 1000 to 3000 J/m^2, an increase of a factor of 3; this is still a large factor but much less than the spectral maximum of 22, shown in the previous figure. For October 4 and 6 the UVB intensities almost equal the summer maxima at Punta Arenas. For October 20 the integrated UVB increase is also large, about a factor of 2.

To determine how the Punta Arenas radiation compares with normal low-latitude observations, where the largest UVB radiations are expected, the Punta Arenas daily UVB maxima are compared with UVB values measured at the low-latitude station Natal (6°S, 35°W), Brazil; only data between the middle and end of October are available for Natal, as shown in Figure 10. The observations of Natal were also obtained with a Brewer spectrophotometer, the same type of instrument as was used at Punta Arenas. The comparison clearly shows that the radiation spectra observed under special ozone hole circumstances at Punta Arenas, Chile, are still lower (by roughly a factor of 3; around 0.18 at Punta Arenas and around 0.35 W/m^2, CIE weighted, at Natal) than normal UVB radiation levels observed for the Natal station.

It is interesting to speculate about the UVB increases that were observed: what do they actually mean biologically? Clearly, for "normal" conditions it would appear that absolute values have not yet reached alarming levels, for example, those much higher than normal equatorial readings. On the other hand, local living beings may have adapted to normally low Antarctic UVB levels, and these increases may represent much more than we can evaluate on the basis of our comparison with only low-latitude values. This is an interesting question that must be investigated further.

Conclusions

We investigated ozone hole conditions for the city of Punta Arenas, Chile. From a NASA ozone database, from 1978 to 1992, we determined that the downward ozone trend at Punta Arenas is twice as large as the global average when the yearly averages are used and 5 times as large when the October averages are used. This finding clearly shows a strong influence of the Antarctic ozone hole condition on the city of Punta Arenas. Local measurements were obtained with a Brewer spectrophotometer from 1992 to 1994; we examined the ozone hole condition and found that the threshold of 220 DU was passed on five occasions. The longest-duration hole condition over Punta Arenas occurred in October 1994 (7 days), when the ozone column decreased to 145 DU, a dramatic reduction to less than half the ozone column thickness. The UVB radiation during ozone hole conditions increased by a factor of 22 at the wavelength of 295-297 nm. When integrated between 290 and 325 nm, and weighted by the CIE erythema action spectrum, the UVB radiation for the 1992 hole event, for example, increased on October 4 and 6 to values observed normally in the summer. However, these exceptional ozone hole, large UVB increases observed at Punta Arenas are still below the normal limits of low-latitude measurements, as shown in comparison with observations at Natal.

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References

Anderson, J. G., D. W. Toohey, and W. H. Brune, Free radicals within the Antarctic vortex: The role of CFCs in Antarctic ozone loss, *Science, 251*, 39-52, 1991.

Atkinson, J. R., W. A. Matthews, P. A. Newman, and R.A. Plumb, Evidence of the mid-latitude impact of Antarctic ozone depletion. *Nature, 340*: 290-294, 1989.

Brasseur, G., and S. Solomon, *Aeronomy of the middle atmosphere,* 441 pp. 1984, Norwell, Mass., D. Reidel.

Brewer, A.W., A replacement for the Dobson spectrophotometer?, *Pure Appl. Geophys., 106-108*: 919-927, 1973.

Brewer, A.W., and J.B Kerr, Total ozone measurements in cloudy weather, *Pure Appl. Geophys., 106-108*: 928-937, 1973.

International Illumination Commission (CIE), A reference action spectrum for ultraviolet induced erythema in human skin, *Com. Int. Eclairage*, *6*,17-22, 1987.

Herman, J.R., R. McPeters, and D. Larko, Ozone depletion at northern and southern latitudes derived from January 1979 to December 1991 Total Ozone Mapping Spectrometer data, *J. Geophys. Res.*, *98*, 12,783-12,793, 1993.

Herman, J.R. et al., The 1993 ozone hole using Meteor-3/TOMS data, *J. Geophys. Res.*, *100*, 2973-2984, 1995a.

Herman, J.R., P.A. Newman, and D. Larko, Meteor-3/TOMS observations of the 1994 ozone hole, *Geophys Res Lett.*, *22*, 3227-3229, 1995b.

Kane, R.P., Extension of the Antarctic ozone hole to lower latitudes in the South-American region, *Pure Appl. Geophys.*, *135*, 611-624, 1991.

Kirchhoff, V.W.J.H., R.A. Barnes, and A.L. Torres, Ozone climatology at Natal, Brazil, from in situ ozonesonde data, *J. Geophys. Res.*, *96*, 10,899-10,909, 1991.

Kirchhoff, V.W.J.H., and E.V.A. Marinho, Tropospheric ozone measurements at the Brazilian Antarctic station, *Rev. Bras.Geofis.*, *10*, 61-71, 1992.

Kirchhoff, V.W.J.H., J.R. Alves, F.R. da Silva, A.G. Motta, J.R. Chagas, F. Zamorano, and C. Casiccia, The brazilian network of stratospheric ozone monitors: observations of the 1992 ozone hole. *Rev. Bras. Geofis.*, *11*, 205-213, 1993.

Kirchhoff, V.W.J.H., F.R. da Silva, and R. A. Barreira, The Antarctic ozone hole as observed at the Brazilian Antarctic station in 1992, Latin-American Conference on Space Science in Antarctica, *Transtec Editorial*, in press, 1996a.

Kirchhoff, V.W.J.H., N.J. Schuch, D.K. Pinheiro, and J. Harris, Evidence for an ozone hole perturbation at 30^{o} south, *Atmos. Environ.*, *30*, 1481-1488,1996b.

Komhyr, W.D., Electrochemical concentration cell for gas analysis, *Ann. Geophys.*, *25*, 203-210, 1969.

Komhyr, W.D., and T.B. Harris, Development of an ECC ozonesonde, Tech. Rep., *ERL 200 APCL 18*, 54 pp., Nat. Oceanic and Atmos. Admin., Boulder, Co., 1971.

Krueger, A.J., L.M. Penn, C.J. Scott, and D.E. Larko, Nimbus 7 total ozone mapping spectrometer (TOMS) Antarctic ozone atlas, NASA Ref. Publi.1283, 169 pp., 1992.

Molina, M.J., T. Tso, L.T Molina, and F.C. Wang, Antarctic stratospheric chemistry of chlorine nitrate, hydrogen chloride, and ice: Release of active chlorine, *Science, 238*: 1253-1257, 1987.

Prather, M., and H. Jaffe, Global impact of the Antarctic ozone hole: Chemical propagation, *J.Geophys. Res.*, *95*, 3473-3492, 1990.

Prather, M., M.M. Garcia, R. Suozzo, and D. Rind, Global impact of the Antarctic ozone hole: Dynamical dilution with a three-dimensional chemical transport model, *J. Geophys. Res.*, *95*, 3449-3471, 1990.

Schoeberl, M.R., and D.L. Hartmann, The dynamics of the stratospheric polar vortex and its relation to springtime ozone depletions, *Science, 251*: 46-52,1991.

Solomon, S., The mystery of the Antarctic ozone "hole", *Rev. Geophys., 26*: 131-148, 1988.

Solomon, S. Progress towards a quantitative understanding of Antarctic ozone depletion, *Nature, 347*: 347-354, 1990.

Solomon, S., and R. Garcia, On the depletion of Antarctic ozone, *Nature, 321*: 755-758, 1986.

Stolarski, R. S., The Antarctic ozone hole, *Sci. Am.*, *258*, 20-26, 1988.

Stolarski, R.S.; A.J. Krueger, M.R. Schoeberl, R.D. McPeters, P.A. Newman, and J.C. Alpert, Nimbus 7 satellite measurements of the springtime Antarctic ozone decrease, *Nature, 322*: 808-811, 1986.

Thompson, A.M., New ozone hole phenomenon, *letters to Nature*, *352*, 282-283, 1991.

World Meteorological Organization, Report of the International Ozone Trends Panel 1988, *Rep.18*, Geneva. Switzerland, 1988.

World Meteorological Organization, Scientific Assessment of Stratospheric Ozone: 1989, *Rep. 20*, Geneva, Switzerland, 1989.

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