Impact of Antarctic polar vortex occurrences on total ozone and UVB radiation at southern Argentinean and Antarctic stations during 1997–2003 period

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[1] The evolution of total ozone and surface UV radiation over some stations in the southern region of South America and in Antarctica in relationship with polar vortex occurrences is analyzed using Total Ozone Mapping Spectrometer total ozone measurements and local surface UV data for the 1997–2003 period. The data are classified as a function of the position of the stations with respect to the polar vortex using equivalent latitude at 550 K isentropic level. The study of vortex occurrences showed that Ushuaia station (54.9°S) was located ~40% of the cases in the edge of the vortex and 5% inside the vortex core during the winter-spring period. Concerning the Marambio (62.2°S) and Dumont d'Urville (66.4°S) stations, located on the shore of the Antarctic continent, the analysis shows a zonal asymmetry with respect to the center of the vortex. Marambio is located around 60% of the time inside the vortex, while Dumont d'Urville is predominantly at the edge of or outside the vortex. The evolution of the equivalent latitude of the stations in the anomalous 2002 winter presents a different behavior with respect to other years in the 1997–2003 period. The persistence of the vortex core above the stations is in average 1.8 days over Ushuaia and 7.1 days over Marambio in October during the 1997–2003 period with corresponding mean total ozone columns of 208.2 and 181.4 Dobson units, respectively. When the stations are inside the vortex, the total ozone columns are generally larger at Ushuaia than at Marambio in October during the 1997–2003 period. Finally, the impact of ozone-depleted air mass occurrences on ultraviolet radiation is evaluated by relating total ozone and UV erythemal dose measured at the stations. Twofold or threefold UV dose increases were reached in the 55°–65° southern latitude region during vortex overpasses, reaching maximum UV dose around 5 kJ/m^2. The average increase of UV dose could be computed at the stations considered in the study when the measurement sampling and the number of vortex occurrences was sufficient. An average increase of 67.6% of the erythemal UV dose was found in October at Ushuaia over the years 1997, 1998, and 2000. This value is strongly weighted by vortex occurrences over the station in 2000. At Marambio an average UV increase of 47.4% was found over the years 1999 and 2000. Midlatitude stations like Comodoro Rivadavia (45.8°S) are generally little affected by vortex intrusions. Nevertheless, the maximum UV dose can increase by more than 50% when the vortex passes over the station.

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1. Introduction

[2] A notable stratospheric ozone chemical destruction has been discovered at Halley Bay, Antarctica, in the early 1980s by *Farman et al.* [1985]. *Solomon et al.* [1986] outlined the important role of heterogeneous chemistry in the ozone depletion over Antarctica, triggered by the accumulation of manmade chlorofluorocarbons (CFCs), a major source of chlorine in the stratosphere [*Molina and Rowland*, 1974]. Following various international protocols of CFCs emissions control, stratospheric ozone is expected to return to pre-1970s levels in the middle of the 21st century [*World Meteorological Organization* (*WMO*), 1999]. In recent years, significant polar ozone loss and general increase of the ozone hole area was observed in Antarctica [*Bodeker et al.*, 2002]. Total ozone columns drop down by more than 50% inside the vortex in the late winter period compared to 1970s levels. This loss is also seen on vertical ozone measurements in regions located close to the vortex edge like Dumont d'Urville [*Godin et al.*, 2001] and Marambio [*Karhu et al.*, 2003] in Antarctica, as well as over populated regions at lower latitudes like Lauder [*Bodeker et al.*, 1998]. Record ozone hole sizes close to 29 and 28 million km^2 in September 2000 and 2003 were observed, respectively (http://www.cpc.ncep.noaa.gov/products/stratosphere/polar/gif_files/ozone_hole_plot.png). During October, average total ozone is around 200 Dobson units (DU) within the polar vortex. In that period the vortex moves off the pole due to increasing planetary wave activity and can reach populated regions of the high-latitude Southern Hemisphere. In contrast with the previous winters, unusually large wave activity was observed in 2002 [*Allen et al.*, 2003], inducing a stratospheric warming and a split of the vortex in the middle stratosphere at the end of September [*Hoppel et al.*, 2003]. During that period the vertical distortion of the vortex between the middle and lower stratosphere masked the ozone depletion in terms of total ozone [*Kondragunta et al.*, 2004]. This major warming event (21–26 September 2002 [*Varotsos*, 2002]), never observed in the Southern Hemisphere up to those days, could suggest that changes in the stratospheric circulation might be occurring but not yet quantified. It underlines the link between ozone changes and climate changes. It is therefore important to consider the relationship between ozone changes and climate change and its impact on ultraviolet radiation (UVB) reaching the Earth surface. The inverse relationship between ozone depletion and increase of UVB radiation is well described in different works [see *WMO*, 1999, and references therein]. UV irradiance at the Earth's surface depends not only on changes in total ozone but also on atmospheric variables influenced by climate changes, such as clouds, aerosol distribution, or snow cover [*WMO*, 2003]. Significant daily UV index values were observed in southern Argentinean stations correlated with the occurrences of the vortex with ozone-depleted air masses [*Cede et al.*, 2002].

[3] The objective of this work is to study the impact of the Antarctic ozone depletion on local ozone amounts and UV radiation over populated regions during the 1997–2003 period. This paper is organized as follows. First, the main features of vortex displacements over some Argentinean stations of South America and Antarctica are analyzed using a quasi-conservative coordinate system. The temporal evolution of vortex occurrences at the South Pole Station (SPO, 89.9°S, 102°E, 2841 m above sea level (asl)) and at the midlatitude Ushuaia station (54.9°S, 68.3°W, 14 m asl) are presented. The zonal asymmetry of the vortex displacements is also studied by comparing the results between Marambio (MAR, 64.2°S, 56.7°W, 198 m asl) located in the Palmer Peninsula and Dumont d'Urville (DDU, 66.4°S, 140°E, 30 m asl). These two stations are more or less opposite with respect to the pole and located close to the vortex edge. The second part of this study is dedicated to the analysis of the total ozone evolution from August to October and to the containment of the Antarctic ozone depletion in October. It is focused on the Ushuaia and Marambio stations. Finally, we compare the evolution of total ozone and UV measurements at Ushuaia, Comodoro Rivadavia (CRI, 45.8°S, 67.5°W, 61 m asl) and Marambio stations when the vortex passes above them.

2. General Characteristics of Vortex Displacements

2.1. Methodology Used for the Classification of the Stations' Position With Respect to the Polar Vortex

[4] In order to determine the position of each station with respect to the vortex, the three-dimensional (3-D) geographical space is remapped into a 2-D quasi-conservative coordinate system (equivalent latitude/potential temperature) described by *McIntyre and Palmer* [1984]. This space can be assimilated to an approximate vortex-following coordinate. This approach allows us to classify ozone and UV measurements at the stations as a function of their position relative to the center of the vortex and thus to easily follow the occurrence of polar ozone-depleted air masses over these locations. The meteorological data used to compute the equivalent latitude (EL) and potential temperature are from the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses with a resolution of 2.5° × 2.5°. In the new coordinates system the pole corresponds to the position of maximum potential vorticity (PV). The EL is a modified PV variable defined as the latitude enclosing the same area as the corresponding PV contour. If the evolution of PV is analyzed as a function of EL, we can identify three regions: inside the vortex, characterized by high PV values; the vortex edge, corresponding to the high PV gradient area; and outside the vortex (or surf zone) with small PV values. Since the PV gradient is high within the vortex edge, it is very weakly mixed. In contrast, the PV gradient is low inside the vortex (i.e., vortex core) and outside the vortex. Therefore they are strongly mixed regions [*Lee et al.*, 2001]. The position of the vortex limit and its boundaries are calculated every day from 1 April to 31 December for each year during the 1997–2003 period, using the method of *Nash et al.* [1996]. The vortex limit corresponds to the EL where the gradient of PV, weighted by the wind module, is maximum. The inner and outer boundaries correspond to the local extrema of the PV second derivative. Finally, the limit and borders of the vortex are smoothed temporally with a moving average of 7 days.

[5] The formation of the polar vortex starts at the beginning of the winter in the upper stratosphere, result-

Table 1a. Mean Occurrence Frequency and the Corresponding 2σ Standard Error of Inside, in the Edge of, and Outside Vortex Situations at Ushuaia, Marambio, and Dumont d'Urville at 550 K Isentropic Level for Mid-August to the End of September Between 1997 and 2003[a]

	Inside	Edge	Outside
USH	4.4 ± 1.3	45.3 ± 7.7	50.3 ± 8
MAR	62.8 ± 7.7	30.4 ± 6.5	6.8 ± 2.6
DDU	11.4 ± 5.9	56 ± 13.1	32.6 ± 13.8

[a]Mean occurrence frequency is in percent.

ing in a strong temperature gradient between polar and midlatitude regions. It grows in size and develops downward. It usually persists until late November to late December, depending on the altitude. With the return of sunlight the vortex is deformed by the increasing planetary wave activity. It starts to break earlier in the upper stratosphere until the final stratospheric warming. The position and size of the vortex vary with altitude, so the choice of the isentropic level for the study of total ozone and UV evolution in relation with the vortex occurrences is important. We have calculated the correlation between ozone-mixing ratio from ozonesondes and total column ozone from the Total Ozone Mapping Spectrometer (TOMS) NASA satellite instrument measured over Antarctic stations (Marambio, Dumont d'Urville, and South Pole) at different isentropic levels in the last years. The best correlation is found for the 550 K level. For example, a correlation coefficient of 0.73 ± 0.05 as compared to 0.59 ± 0.1 at 475 K is found at Marambio between 1998 and 2002 for the August–October period. We carried out a similar analysis for the correlation between PV and total ozone. PV is calculated from ECMWF fields and interpolated at the geographical positions of the different stations. In that case, a good correlation is found at 475, 550, and 650 K levels for the Ushuaia (USH), MAR, and DDU stations, but the best correlation is found at 550 K level for SPO. This confirms the results found by *Bodeker et al.* [2002]. The 550 K isentropic level is chosen as the reference level for our analysis.

[6] The occurrence frequency of each situation (inside, at the edge of, and outside the vortex) for USH, MAR, and DDU stations over the 1997–2003 period is shown in Table 1. Table 1 is divided in two periods: the ozone destruction period from mid-August to the end of September (Table 1a), and October when relatively stable low ozone levels are contained inside the vortex core (Table 1b). The comparison of both periods for each station does not show significant differences at the 2σ level in general. As expected, USH is predominantly outside the vortex (∼52%), but the proportion of edge situations (40–45%) is very close to that of outside situations, especially during the first period studied. MAR and DDU are situated near 65°S and practically at opposite longitude (58°W and 140°E, respectively). They are usually considered typical vortex edge stations. However, the occurrences of the inside vortex situations over these stations are not similar, indicating a zonal asymmetry. MAR is predominantly inside the vortex during both periods (∼60% of the time), while DDU is predominantly at the edge of the vortex, especially in the mid-August–September period.

2.2. Analysis of the Anomalous 2002 Winter

[7] In order to analyze the impact of the unusual winter 2002 on vortex displacements over Antarctica and southern populated regions, we compare the vortex occurrences as a function of equivalent latitude over different stations. The situation before, during, and after the split of the vortex is examined and compared to daily station positions averaged over the period 1997–2001 and 2003. We first analyze the temporal evolution of the vortex on typically outside (USH) and inside (SPO) stations in order to contrast the behavior of the vortex at southern midlatitudes and polar locations. Then, we study the zonal asymmetry of the vortex by comparing the two vortex edge stations (MAR and DDU).

[8] Figure 1 illustrates the period during and after the major warming from 22 September to 2 October 2002 by maps of PV at 550 K every 2 days. The vortex movements are represented by the black area with white line contours in the PV map, and the positions of the stations are represented with squares. During the major warming of 21–26 September the vortex starts to elongate (Figures 1a and 1b), DDU is already outside the vortex, and SPO approaches the vortex edge. The populated regions of Ushuaia and Comodoro Rivadavia are outside the vortex in those days. Finally, the vortex splits in two parts (Figure 1c) on 25–26 September. Practically all the stations are within the edge of the vortex, except CRI, which is outside but close to the edge, and DDU, which is clearly outside and at the opposite side of the vortex displacement zone. The same temporal evolution is also visible in the partial column ozone reconstructed from PV/ozone relationship over the 350–600 K range in *Randall et al.*'s [2004] work and in the total ozone fields from TOMS described by *Storlaski et al.* [2004]. On 28 September the smaller lobe of the vortex moves toward the east of South America and passes over MAR and then over USH and CRI (Figures 1d and 1e). The SPO station is outside the vortex during that period. Ozone-rich air originating from midlatitudes in the middle stratosphere masked the lower stratospheric ozone depletion still present above the station [*Hoppel et al.*, 2003, Figure 2], resulting in relatively high total ozone columns. After September, MAR station is mostly outside the vortex during the dilution of the small vortex lobe toward South America (Figure 1f). DDU is always outside the vortex, and SPO approaches the vortex edge. The smaller center has already passed over USH but remains over CRI until 3 October.

[9] Figure 2 shows the temporal evolution of USH (top) and SPO (bottom) EL from June (day 152) to the end of November (day 334) 2002. The stations EL in that year are

Table 1b. Mean Occurrence Frequency and the Corresponding 2σ Standard Error of Inside, in the Edge of, and Outside Vortex Situations at Ushuaia, Marambio, and Dumont d'Urville at 550 K Isentropic Level for October Between 1997 and 2003[a]

	Inside	Edge	Outside
USH	6.9 ± 1.9	39.9 ± 4.3	53.2 ± 4.6
MAR	61.2 ± 6.1	27.3 ± 5	11.5 ± 3.1
DDU	7.1 ± 3.6	50.4 ± 12.8	42.5 ± 12.7

[a]Mean occurrence frequency is in percent.

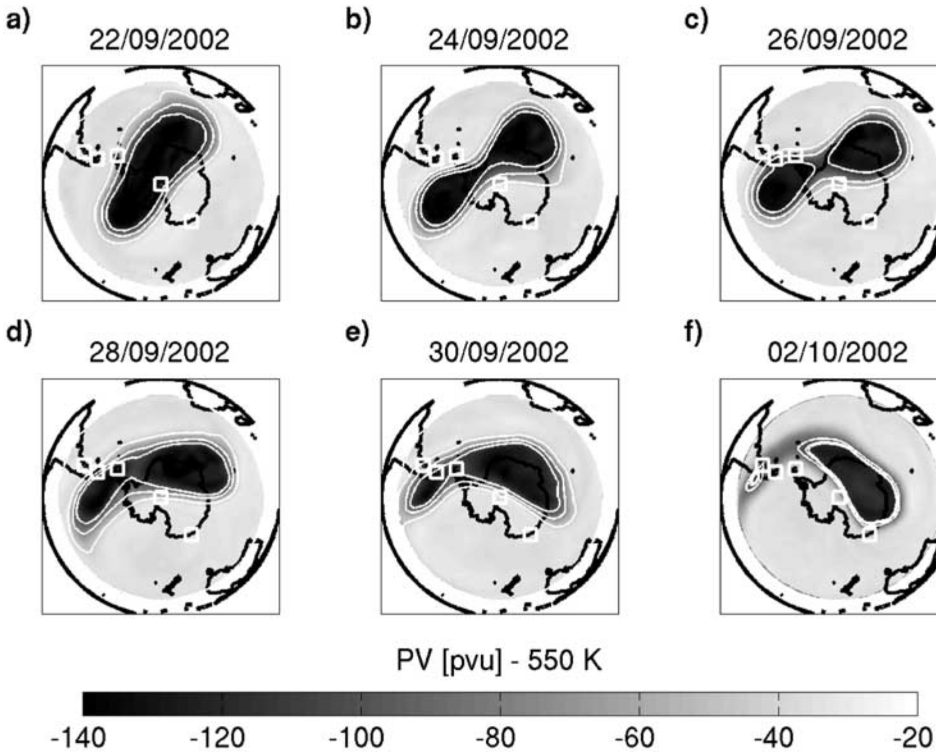

Figure 1. (a–f) PV fields at 550 K from 22 September to 2 October 2002. Vortex region is represented in black with white lines indicating the boundaries (vortex limit, inner and outer edges). White squares correspond to the location of South Pole, Dumont d'Urville, Marambio, Ushuaia, and Comodoro Rivadavia stations.

compared to the mean value and the $\pm\sigma$ standard deviation of the EL of the stations in the years 1997–2001 and 2003 (gray area in Figure 2). These years correspond to typical winters that are characterized by a cold, stable, and circular vortex. The bold lines represent the temporal evolution of the EL of the vortex edge in 2002. In the other years the size of the vortex is somewhat larger: The EL of the vortex boundaries (not shown) are lower by $\sim$5° as compared to 2002. Generally, the vortex increases in size in the beginning of the winter. It reaches 60°S EL and remains close to that value until the end of September. Then, the size of the vortex starts to decrease in October until the final breakup which occurs in November–December. The reduction of the vortex size due to the early major warming in 2002 illustrated by the vortex boundaries in Figure 2 is clearly not present in the typical years.

[10] The SPO station is usually located close to the center of vortex as shown by its high EL values of $\sim$80° (Figure 2). This is the case at the beginning of the winter. Then a slow decrease of the EL of the station is generally observed toward 70°S at the end of November. From June to the end of August the average EL of the station for the years 1997–2001 and 2003 is equal to 81.1°S ± 0.3°. At the end of September the average EL of SPO is 78°S ± 0.8°. In 2002 the evolution of SPO EL shows large differences with respect to the reference years: The station EL is lower at the beginning of the winter. From 21 June up to the end of August the mean EL is 76.8°S ± 0.6°, which shows that the station is closer to the vortex edge. As expected, the largest differences are seen during and after the major warming of 2002. The station EL reaches values near 55°S on 30 September, which corresponds to a situation that generally happens when the vortex breaks up at the end of spring. The mean EL during the major warming and the split of the vortex is 61.7°S ± 1.5°, which is lower than usual at SPO. The station EL shows abrupt changes in 2002 from October until the end of November. It is closer than usual to the pole in October. In contrast, the station reaches EL of 40°S, totally outside the vortex in November.

[11] Concerning USH (Figure 2), the station is usually located outside the vortex, as illustrated by the evolution of the EL position in 1997–2001 and 2003. However, the station stays generally close to the vortex edge, and the distance between the station and the outer boundary decreases up to September as the size of the vortex increases during the winter. In November the EL decreases progressively from 60°S to near 50°S at the end of November. The number of vortex occurrences (edge and inside vortex situations) increases during the August–October period, and the station EL shows larger fluctuations compared to the earlier months.

[12] The range of EL spanned at USH during the 2002 winter is larger than during the reference years, due to the unusually strong dynamical activity during 2002 [*Allen et al.*, 2003]. As a result the time spent by the station inside or at the edge of the vortex is longer at the end of the winter as shown in Figure 2. On the other hand, the mean EL of the station is comparable, within 2σ standard error level, to that of typical years during the August–October period. However, the EL temporal evolution is very different: Lower EL

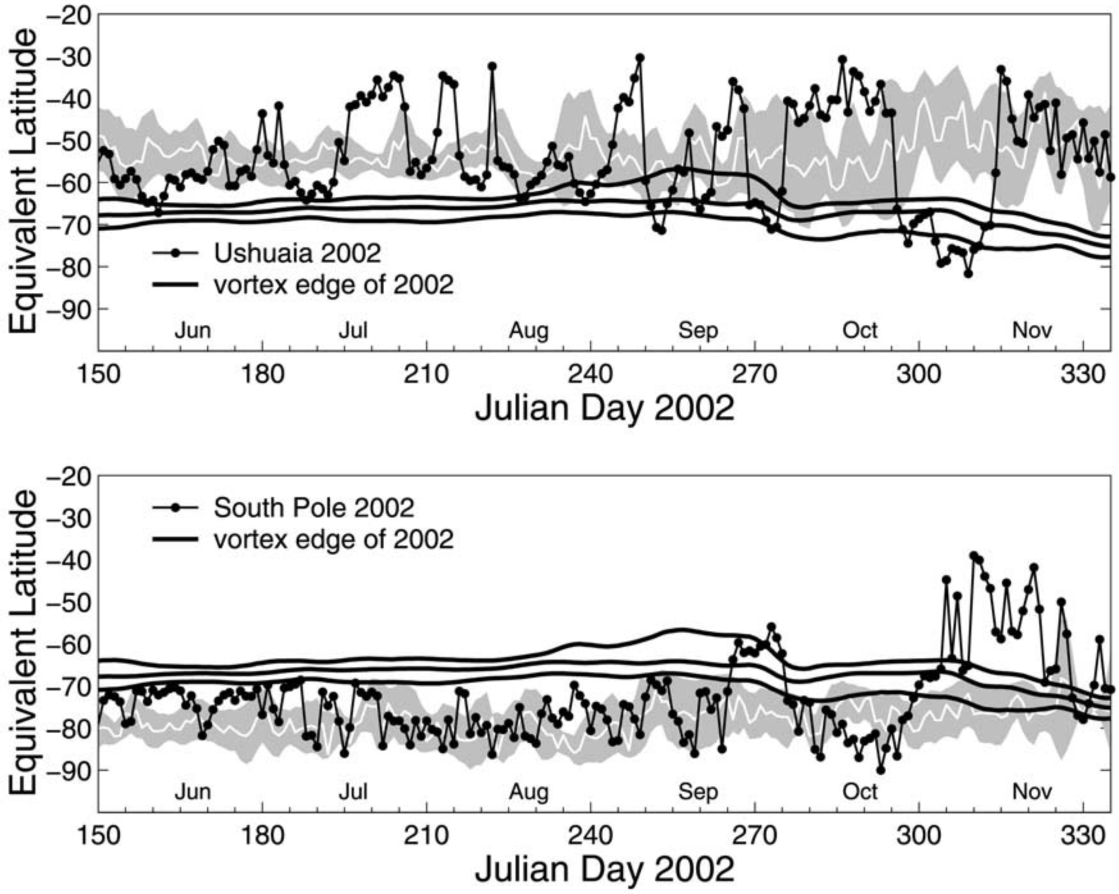

Figure 2. Temporal evolution of the positions of the vortex limit and boundaries (bold lines) and the (top) Ushuaia and (bottom) South Pole stations (lines with dots) in equivalent latitude at 550 K from June until the end of November 2002. White lines correspond to the mean value of the station EL over the 1997–2001 and 2003 period, and the gray areas correspond to $\pm\sigma$ EL standard deviation.

values close to 30°S are found at USH in September and October. In early and middle October, USH is clearly outside the vortex, with a mean EL of 40.5°S ± 0.9°. However, from the end of October until 10 November 2002 the station is at the edge of or inside the vortex with a mean EL of 73.3°S ± 1.1°. Finally, the station returns to EL values typical of the reference years in late November.

[13] Figure 3 is the same as Figure 2 but for MAR (top) and DDU (bottom). During typical years (gray area of Figure 3) both stations lie generally close to or within the vortex edge until the end of July. From August onward the MAR EL increases, with the station remaining clearly inside the vortex until the middle-end of October (Table 1). In contrast, DDU remains within the edge of the vortex, approaching the outer border. DDU is rarely inside the vortex from the end of October (Table 1). MAR moves outside the vortex later in November, with EL values reaching almost 40°S as for DDU. During those typical years, Figure 3 shows that vortex occurrences are more frequent over the Palmer Peninsula than over the DDU coast side, especially after September.

[14] The strong wave activity present in 2002 from May onward [*Allen et al.*, 2003] is highlighted by the larger variations of the stations' EL as compared to the reference years. This is particularly noticeable at MAR, with a large range of EL spanned by the station in the beginning of June and in July. During the first stage of the major warming (end of September), DDU is outside the vortex, whereas MAR is inside for several days when the smaller lobe of the vortex passes over South America. During the dilution of this lobe, MAR is again outside the vortex (Figure 1f). This is shown by the exceptional range of EL spanned by MAR (from 30° to 80°S and again back to 30°S). After the main lobe of the vortex returns over the center of the Antarctic continent in October, the number of vortex occurrences is comparable to typical years for DDU as shown on Figure 3. MAR, which is mostly inside or within the vortex edge in September and October during typical years, is mainly outside the vortex in 2002, except for a short period inside the vortex at the beginning of October. Then, the vortex remains for a long period of 21 days over MAR from 20 October to 9 November 2002. The mean EL of the station during that period is 79°S ± 0.7°.

3. Impact of Vortex Occurrences on Ozone Columns at Ushuaia and Marambio

[15] In section 2 the vortex was found to pass more frequently over regions located close to the Palmer Peninsula. Therefore the analysis of the impact of vortex occur-

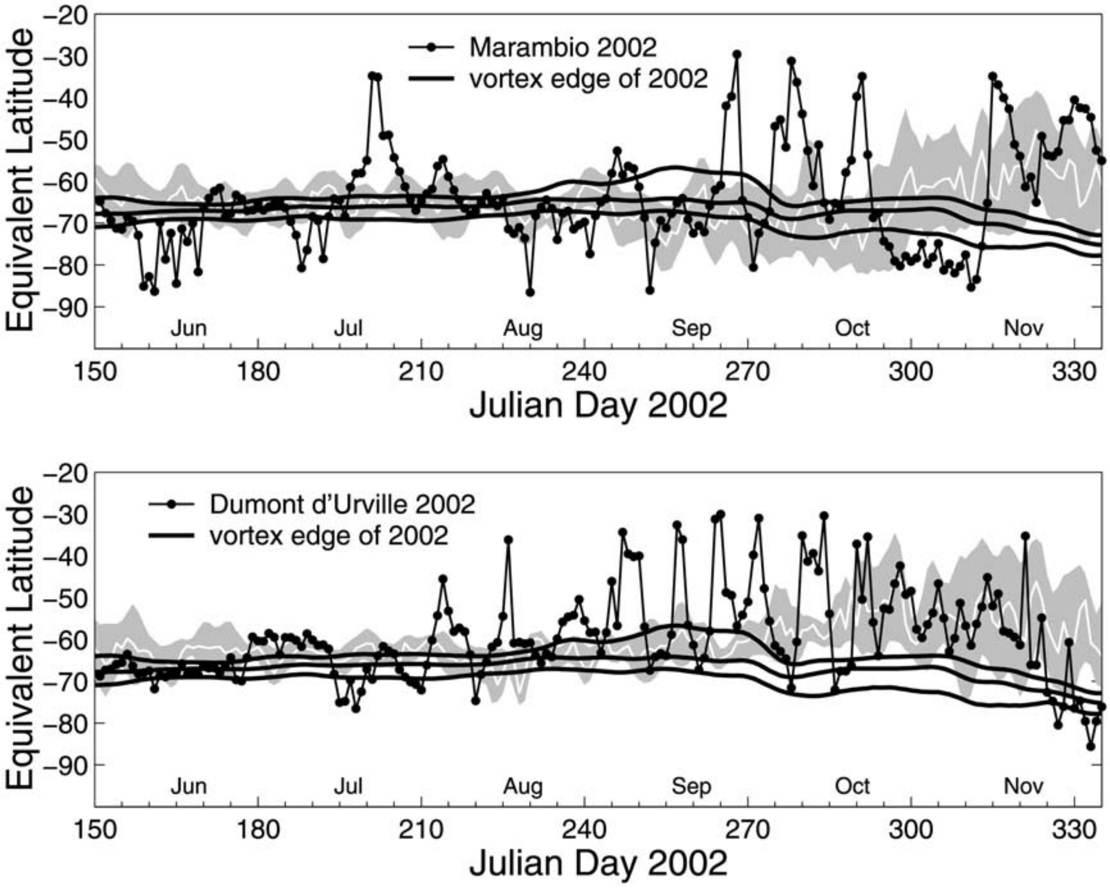

Figure 3. Same as Figure 2 for (top) Marambio and (bottom) Dumont d'Urville stations.

rences on total ozone is focused on this region. Marambio and Ushuaia are chosen to contrast the influence of the Antarctic ozone depletion on two different equivalent latitude domains. The total ozone data at MAR and USH are obtained from version 7 of the best matched TOMS field of view at these stations on board the Earth Probe satellite [*McPeters et al.*, 1998].

[16] Figure 4 displays the temporal evolution of total ozone over Ushuaia and Marambio classified according to the EL position of the vortex for the years 2002 (top) and 2003 (bottom). A clear difference in total ozone can usually be observed between inside and outside situations at both stations for each year. The variability of the vortex displacements determines the evolution of total ozone at these stations.

[17] The high sampling frequency of inside vortex situations during winter and spring at MAR allows us to estimate the ozone decrease rate. The ozone decline was computed from a linear regression of the total ozone data inside the vortex as a function of time between 1 August, when the ozone destruction begins, until 20 September, for each year in the 1997–2003 period. The analysis period stops on 20 September in order to avoid the influence of the major warming in 2002. It must be kept in mind that chemical ozone destruction is the process that dominates the ozone evolution inside the vortex from the beginning of August. The subsidence within the Antarctic polar vortex virtually stops in late July, in the lower and middle stratosphere, and is strongly reduced in the upper stratosphere [*Rosenfield et al.*, 1994]. Its influence is thus not very important for the evolution of ozone inside the vortex during the 1 August to 20 September period. Another process is the horizontal mixing of air masses from outside the vortex. This process can be neglected at first order [*Schoeberl et al.*, 1992; *Godin et al.*, 2001]. On the other hand, the evaluation of the total ozone decrease rate does not take into account the EL range sampled by the station when it is inside the vortex during the period in consideration. This range is 3°–22° from the vortex limit over the whole 1997–2003 period. Thus the decrease rate can not be considered strictly as a chemical loss rate. The average value of the ozone decline between 1 August and 20 September is 1.7 ± 0.1 DU/day. A maximum decrease rate of 2.3 DU/day is obtained in 2000. Minimum total ozone amounts were measured in 2000 and 2003 with 123.6 and 120.7 DU, respectively. In 2002 and 2003 the ozone decrease rates are close to the average with 1.6 and 1.4 DU/day, respectively. In 2002 the minimum total ozone value observed at MAR is 146.4 DU on 18 September.

[18] In the case of USH the differences in total ozone between inside and outside situations can also be easily identified. However, the poor sampling of inside vortex situations, of the order of 5% (Table 1), prevents the quantification of the polar ozone decrease for vortex

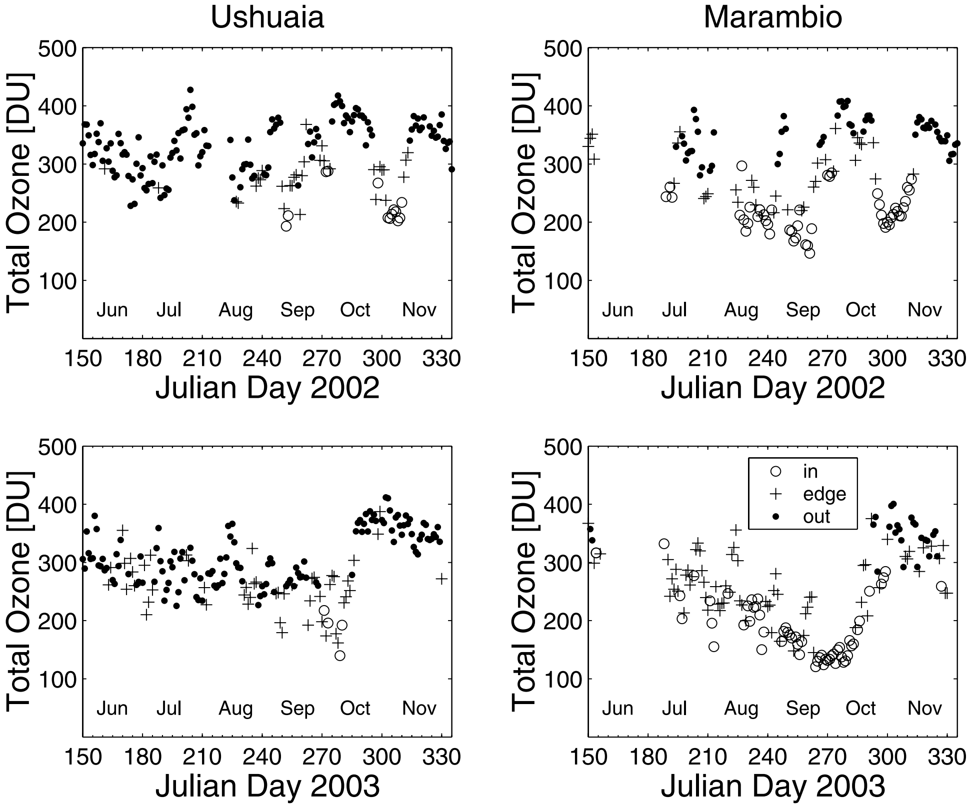

Figure 4. Temporal evolution of total ozone over Ushuaia and Marambio, classified with respect to the position of the polar vortex at 550 K for (top) 2002 and (bottom) 2003. Inside, in the edge of, and outside vortex situations are represented by open circles, pluses, and dots, respectively.

occurrences over the station. From August to October for the 1997–2003 period the average value of total ozone is 213.7 ± 5.8 DU when the station is inside the vortex. Minimum total ozone values are observed in 2000 and 2003 with 147 and 139.7 DU, respectively. In 2002 the minimum total ozone for this period is 193 DU, close to the average value during vortex occurrences over the whole period.

[19] Ozone values outside the vortex are close to 350 DU in November at both stations with similar ozone evolution. Minimum ozone values as low as those noticed at MAR are observed at USH in 2003 during the August–October period. In contrast, the major warming in 2002 prevents both stations to reach the very low ozone values observed in 2003. The lowest ozone columns are seen at MAR before the major warming, but after this event, comparable values are observed at both stations (~200 DU).

[20] Another way to analyze the impact of vortex occurrences over the stations is to study their persistence. For the whole 1997–2003 period the mean number of days in October during which the vortex core remains continuously over MAR is 7.1 ± 1.5 days with a corresponding average total ozone of 181.4 ± 3.1 DU. When the ozone destruction period is added (16 August to 30 September), the persistence of the vortex occurrences does not change significantly. In contrast, if we include the vortex edge in the study of vortex occurrences, the vortex remains continuously over MAR for 13.6 ± 3 days on average, with a corresponding mean total ozone value of 205.3 ± 4.2 DU. Mean total ozone at MAR is larger if we add edge situations, but it is significantly lower than total ozone in outside situations (see Table 2). The maximum number of days of vortex persistence over MAR was 20 days (late September to early October) in 2003 if we consider only inside situations and practically the whole June–October period if we include the edge situations.

[21] In the case of USH the mean vortex persistence is about 1.8 ± 0.3 days with a corresponding mean total ozone of 208.2 ± 7.4 DU for inside situations in October. No significant change in vortex persistence is obtained when the August–September period is included. If edge situations are taken into account, the mean value increases to 3.6 days, with an average total ozone value of 255.4 ± 5.2 DU. The maximum number of days of vortex core persistence over USH was 4 days at the end of October in 1998 with a corresponding mean total ozone of 191.4 DU. If edge situations are considered, the maximum vortex persistence

Table 2. Total Ozone Average Value and 2σ Standard Error at Ushuaia and Marambio Stations Obtained Inside, at the Edge of, and Outside the Vortex at 550 K in October in the 1997–2003 Period[a]

	Total Ozone Mean (October)		
	Inside	Edge	Outside
USH	208.2 ± 7.4	271.1 ± 5.3	345.2 ± 3.6
MAR	181.4 ± 3.1	268.7 ± 6.2	351.2 ± 3.6

[a]Total ozone average value is in DU.

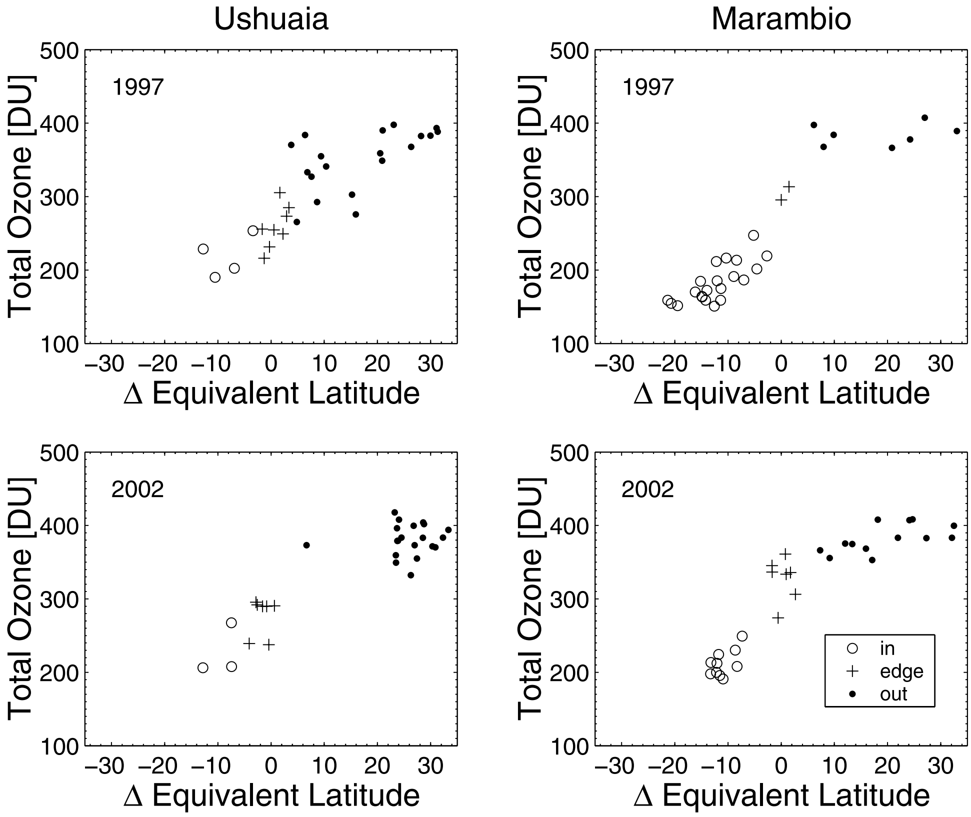

Figure 5. Total ozone at Ushuaia and Marambio as a function of the equivalent latitude difference with the vortex limit at 550 K in October (top) 1997 and (bottom) 2002. Symbols are the same as in Figure 4.

is observed in late September to early October 2003 with 16 days and a mean total ozone of 219 DU.

4. Containment of the Antarctic Ozone Depletion

[22] In order to estimate the containment of the vortex with respect to the Antarctic ozone depletion we consider the stations close to the vortex edge, where vortex occurrences are the most frequent: USH and MAR. Then, we analyze total ozone data over these stations as a function of the distance of the station to the polar vortex border, in October for the whole 1997–2003 period. October was selected for the analysis because most, if not all, ozone destruction has taken place by the end of September and total ozone is low and relatively stable inside the vortex core.

[23] Figure 5 shows total ozone over Ushuaia and Marambio in 1997 and 2002 as a function of the difference in equivalent latitude between the station and the vortex limit. The containment is well shown in Figure 5 by the sharp change in total ozone between inside and outside situations over the vortex edge, which correspond to $\sim 8°$ at both stations. The difference between inside and outside ozone mean values is 132 DU at USH and 198 DU at MAR for 1997. These differences correspond to 60% of the inside mean value at USH and are larger than the values observed inside the vortex at MAR. In 2002 a difference of 153.8 DU is observed at USH, and 171 DU is observed at MAR. These values correspond to 68 and 80% of inside mean ozone value at USH and MAR, respectively.

[24] To give a more general view over the whole 1997–2003 period, the average total ozone was calculated at both stations for each situation with respect to the polar vortex, and the results are presented in Table 2. A mean difference of $\sim$30 DU is observed between the two stations when they are inside the vortex and <10 DU for the other situations. The differences in total ozone for inside situations between MAR and USH are due to the fact that the latter station samples more frequently the outer edge of the vortex core.

[25] Table 2 shows that the difference between inside and outside mean ozone values is 137 DU at USH and 169.8 DU at MAR, which corresponds to 65.8% and 100% of the mean total ozone inside the vortex at both stations, respectively. During the cold winter of 2003 a difference of 204 DU was observed at USH, corresponding to 123% of the inside average value, the largest over the whole 1997–2003 period, and even larger than the differences observed at MAR during that year.

5. Effect of Vortex Overpasses on UV Amounts

[26] The role of stratospheric ozone as a filter of harmful ultraviolet radiation (UVB) is well known. The reduction of ozone levels in the stratosphere induces an increase of UV radiation that can affect human health, animals, and plants [*Kerr and McElroy*, 1993; *WMO*, 1999; *United Nations Environment Programme*, 2003]. Thus it is important to evaluate the impact of vortex intrusions with ozone-poor air masses on UVB radiation over high-latitude and midlatitude populated regions.

Table 3. Number of Days With UVB Measurements From 1 June to 30 November (Period 1) and October (Period 2) in the 1997–2003 Period at Comodoro Rivadavia, Ushuaia, and Marambio Stations

	Comodoro Rivadavia		Ushuaia		Marambio	
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2
1997	182	31	163	23	48	8
1998	167	31	160	30	57	27
1999	109	31	0	0	87	29
2000	179	30	177	31	14	7
2001	147	31	63	0	91	31
2002	176	30	51	0	150	31
2003	133	13	0	0	98	0

[27] In order to study the effect of vortex occurrences on UVB over Southern America we analyze the temporal evolution of total ozone in relation with the UVB surface radiation at Ushuaia and Comodoro Rivadavia, a station located further north at 45° latitude. For reference, MAR is also considered in the study as a station generally within the vortex or the vortex edge. A 501 UV biometer of Solar Light Co. is used to measure the UV radiation. These instruments belong to the Argentine UV network [*Cede et al.*, 2002]. It is a broadband UV instrument working in the 280–320 nm spectral range, which integrates the incoming spectral radiation with the Commission Internationale de l'Eclairage (CIE) action spectrum for erythema [*McKinlay and Diffey*, 1987]. The daily UV data are delivered in a unit of the erythemal dose expressed as the minimum erythemal dose (MED) which causes a noticeable erythema for a typical Caucasian skin type. The data are expressed in our work in effective daily erythemal exposure considering the relationship of 1 MED is equal to the CIE-weighted irradiation of 0.21 kJ/m^2. The UV data were not systematically screened for clouds. In some cases the presence of clouds can mask the inverse relationship between UVB and total ozone that can be seen in clear sky days. The number of days with UV measurements for the three stations is presented in Table 3 for two periods: from June to November and, more specifically, for October.

[28] The evolution of the daily UV dose and total ozone in 2000 is shown in Figures 6a and 6b at CRI and USH stations. The evolution of the difference in equivalent latitude between the stations and the vortex limit is shown in Figures 6c and 6d. The bold lines represent the vortex boundaries. In order to evaluate the increase of UV levels when the vortex passes over the stations, we fitted a third-order polynomial to the UV data obtained outside the vortex. The solid gray line in Figures 6a and 6b represents this polynomial fit. This is an approximate reference for the seasonal UV increase outside the vortex since it does not take into account the cloud cover above the stations. In the case of MAR the low sampling frequency outside the vortex also hinders the fitting of the data. The CRI station is far away from the vortex, and the polar vortex does not usually pass very often over the station (Figures 6a and 6c). However, in 2000 the vortex edge passed over CRI during 10 days in mid-October (286–295 period). The maximum

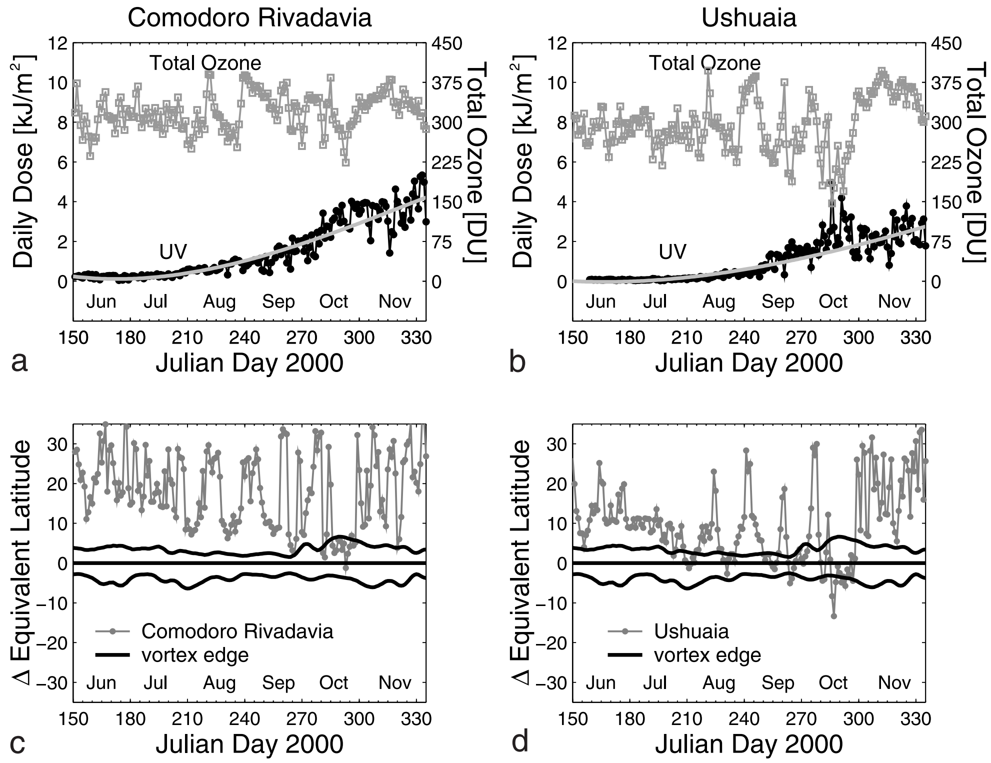

Figure 6. (a and b) Evolution of the daily UV erythemal dose and total ozone at Comodoro Rivadavia and Ushuaia stations from 1 June to 30 November 2000. Gray line shows a polynomial fit to the UV doses measured during outside situations. (c and d) Equivalent latitude difference between the stations and the vortex limit at 550 K. Bold lines represent the vortex boundaries.

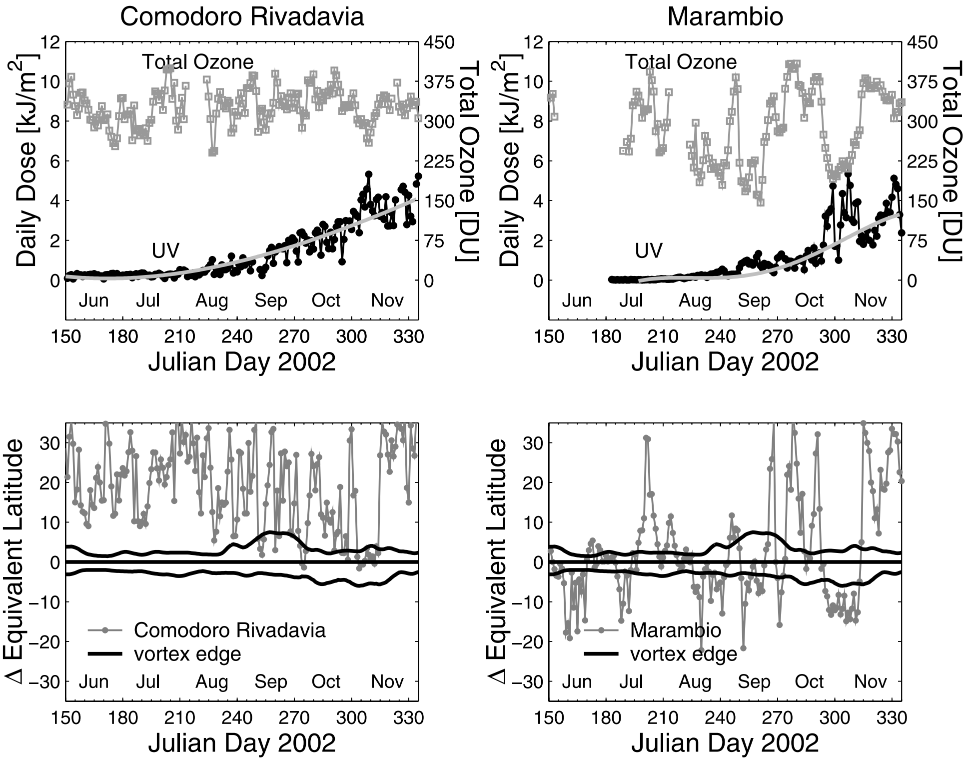

Figure 7. Same as Figure 6 for Comodoro Rivadavia and Marambio stations in 2002.

UV dose measured during that period was 3.8 kJ/m^2 on 17 October, which corresponds to an increase of 42.7% compared to the value of the polynomial fit on the same day (gray line in Figure 6a). On that day the total ozone value was 274 DU, and the cloud cover was 7/8. The minimum total ozone measured during that period was 223 DU. It was obtained on 19 October when the CRI station was located in the inner edge of the vortex. There is no UV measurement on that day. A UV dose can be estimated if we consider the UV erythemal dose sensibility to total ozone, expressed by the "Radiation Amplification Factor" (RAF). The RAF value considered is 1.1 [*Madronich et al.*, 1998] for the action spectrum of *McKinlay and Diffey* [1987] which corresponds to the 501 biometer measurements. A UV dose of 3.7 kJ/m^2 can be computed for 19 October (ozone column of 223 DU) if we consider for the ozone and UV dose references the median values of the measurements obtained during the 17–20 October period (275.2 DU and 2.9 kJ/m^2, respectively). These median values are used in order to reduce the influence of ozone and UV variability during the period considered. The cloud cover condition on 19 October was 8/8, the worst of the 17–20 October period. Note that 19 October was the cloudiest of the period. Therefore the estimated UV dose appears to be an upper limit. Thus the UV dose of 3.8 kJ/m^2 measured on 17 October can be considered the largest during that period. As expected in the case of USH, the influence of vortex overpasses is larger (Figures 6b and 6d). The impact on UV is more important at USH, especially during a large vortex excursion period of 14 days in mid-October (285–298 period). The minimum ozone value measured during that period was 147 DU, leading to a maximum UV dose of 5 kJ/m^2 on 12 October, which corresponds to an increase of more than twice the value of the polynomial fit. The cloud cover condition on that day was 5.5/8. The UV values are, in general, lower than the CRI ones, which is consistent with the higher latitude of USH. However, some values of erythemal UV dose are higher at USH when the station is inside the vortex, as on 12 October. The UV dose exceeds that measured at the CRI station during the same period which shows a maximum value of 3.8 kJ/m^2.

[29] Figure 7 is the same as Figure 6 but for CRI and MAR stations and for the year 2002. As seen in Table 3, no data were obtained at USH in that year for comparison. The UV and total ozone evolution is largely influenced by vortex occurrences at both stations, in particular at MAR. During the major warming the vortex remained over MAR from 26 September to 1 October (269–274 period). The maximum UV dose was 1.3 kJ/m^2, corresponding to an increase of 69% in a cloud cover condition of 2/8. The total ozone measured on that day was 284.9 DU. The minimum total ozone of 278.6 DU was measured 1 day before with a UV dose of 1.2 kJ/m^2 (showing an increase of 62.6%) and a cloud cover condition of 6/8. The cloud cover condition changed on these 2 days from 6 to 2/8, which explains the increase of the UV dose together with an increase of total ozone. The ozone column at MAR during the period of the major warming is higher than the ozone 1997–2003 average inside the vortex for October (Table 2). This is due to the vertical misalignment of the vortex as discussed in the introduction. After the vortex split in the upper levels, the small lobe moves toward South America, passing 4 days over CRI (273–276 period) with a minimum total ozone of 287.3 DU leading to a maximum UV dose of 2.4 kJ/m^2. It corresponds to an increase of 30% compared to typical values during outside situations. The cloud cover condi-

Table 4. Mean Relative Difference and 2σ Standard Error Between UV Daily Erythemal Dose Measured at Marambio, Ushuaia, and Comodoro Rivadavia Stations During Vortex Overpasses in October and the Polynomial Fit Corresponding to Outside Situations[a]

	$\Delta UV/UV_{fit}$		Number of Situations		Years Considered in the Analysis
	Inside	Edge	Inside	Edge	
MAR	47.4 ± 10.1	10.2 ± 16	34	7	1999, 2002
USH	67.6 ± 19.8	29.5 ± 8.6	18	26	1997, 1998, 2000
CRI	-	7.7 ± 6.5	-	23	2000, 2001, 2002, 2003

[a]Total number of inside and edge situations for the years are also shown. Number of inside and edge situations is also limited by the absence of UV measurement. Mean relative difference is in percent.

tion on that day was 5/8. The most important vortex overpass in that year occurred between 30 October and 8 November (303–312 period) at CRI and between 20 October and 11 November (293–313 period) at MAR. In the CRI station a minimum ozone value of 259 DU was found, leading to a maximum UV dose of 5.3 kJ/m^2 corresponding to a 65.3% increase of UV levels, with a cloud cover of 1/8. In the case of MAR the minimum total ozone of 191 DU was measured on 26 October with a UV dose of 4.7 kJ/m^2. The cloud cover condition on that day was 4.5/8. However, the maximum UV dose of 5.3 kJ/m^2 is detected several days after (3 November), during a vortex intrusion with a total ozone value of 210.5 DU and a cloud cover of 6/8. The increase of UV in that case is explained by the sharp UV evolution in November. It must be mentioned that a UV dose of 5 kJ/m^2 corresponds to more than 20 MED of harmful UV radiation. This is close to what is obtained at Buenos Aires at the same period of the year [*Micheletti et al.*, 2003]. The cloud cover at MAR during the vortex overpass varies between 3/8 and 8/8 during the day. High values of cloud cover explain small daily UV dose during the 293–313 period, such as the value of 1 kJ/m^2 measured on 29 October (day 302) when it snowed the whole day.

[30] For a more general view of the relation between ozone decrease due to polar vortex occurrences and UV increase at the stations analyzed in this paper, Table 4 shows for MAR, USH, and CRI the average relative difference between daily erythemal UV doses measured during inside or edge situations in October and the polynomial fit representing outside situations. For each station we considered only those years in the 1997–2003 period when a good daily sampling of UV measurement was achieved, allowing a realistic polynomial fit for outside situations. These years are 1999 and 2002 for MAR, 1997–1998 and 2000 for USH, and 2000–2003 for CRI. The relative increase due to the vortex occurrences is close to 50% for MAR and 70% for USH. The relative UV increase of 70% at USH is highly weighted by measurements obtained in 2000 when the station was totally inside the vortex for 9 days. If we remove that year, the UV increase is limited to 33.1% ± 21.5. The rather poor sampling of UV measurements at both stations prevents us from comparing in a systematic way the impact of vortex occurrences on UV radiation for the same period. Furthermore, the cloud cover is another variable that determines the differences in UV radiation at both stations. The only period when both stations are within the vortex at the same time in October is in 1998. The EL of USH is ~70°S, whereas MAR is at ~85°S EL. The maximum UV dose is found on 20 October for both stations with UV doses of 3.5 and 5.7 kJ/m^2 at USH and MAR, respectively, and corresponding total ozone values of 196 and 140 DU. In vortex edge situations the UV increase is limited to 30% at USH and 10% at MAR. Only edge situations were observed at CRI. They correspond to an average UV increase of 7.7%. This relatively low value is explained by the fact that during most edge cases this station is located close to the outer border of the vortex edge. For USH and MAR the impact on UV is more important when the stations are inside the vortex, but the difference is not significant at 2σ level. This is due to the fact that the data are not systematically screened for cloud cover, and therefore a large range of UV values is measured at both stations.

6. Conclusion

[31] In order to study the impact of vortex occurrences on ozone and UV levels in southern populated regions the vortex displacements have been characterized over these areas during the 1997–2003 period. The unusual 2002 winter was compared to more typical years. We used the 2-D (equivalent latitude, potential temperature) coordinate system in order to classify the data as a function of the station position relative to the polar vortex. The study focused on the Ushuaia station located in southern Argentina. Nonetheless, stations located typically inside the vortex (South Pole), or at the edge of the vortex (Marambio and Dumont d'Urville) were also considered. The data classification used the PV field at 550 K because the best correlation between total ozone and local ozone mixing ratio and between total ozone and PV was found at this level at most of the stations. The general characteristics of vortex displacements were determined from August to the end of October. In typical years the following pattern is observed: MAR and DDU remain at the edge of the vortex during most of the time, and USH is outside but close to the edge during winter. The study of vortex occurrences showed that USH was located ~40% of the cases at the edge of the vortex during that period. Concerning the stations located on the shore of the Antarctic continent (MAR and DDU), the vortex occurrences present a zonal asymmetry at similar latitudes. MAR is located around 60% of the time inside the vortex, while DDU is predominantly at the edge of or outside the vortex. The equivalent latitude of SPO, generally close to 80°, shows that the southern polar vortex is well centered over the pole but it becomes more variable in spring, in relation to the increasing planetary wave activity. The effect of the major warming in 2002 was highlighted in different ways at the various stations. To begin with, the strong wave activity from May onward induced a larger variability in the vortex position during the winter. The EL

of SPO was lower (in absolute value) and the station was closer to the vortex edge. At MAR, DDU, and USH the larger variability was shown by the larger range of EL spanned by these stations during 2002 as compared to typical years. Immediately after the major warming, SPO station reached EL close to 55°S, a value that is usually reached only when the vortex breaks up. Then, the remaining part of the vortex returned to the geographic pole and broke up at the end of October, earlier than during typical years. During the dilution of a smaller lobe over South America after the major warming event, USH was inside the vortex, but MAR remains mostly outside. The evolution of USH and MAR EL is opposite from October to mid-November as compared to typical years. DDU is mostly outside the vortex.

[32] The impact of vortex intrusions was analyzed in regions close to the Palmer Peninsula where the number of vortex occurrences is larger during the ozone destruction period. It was studied in October when ozone columns are low and rather stable inside the vortex core. The study focused on Ushuaia, the southern most populated region of the Southern Hemisphere with more than 60,000 habitants, and on Marambio station. Minimum total ozone values in the whole 1997–2003 period were found in 2003 at both stations. Evidence of ozone layer recovery after the unusual major warming at the end of September 2002 is thus not yet visible as already shown in many works reviewed by *Varotsos* [2004]. The persistence of the vortex core above the stations is, in average, 1.8 days over USH and 7.1 days over MAR in October during the 1997–2003 period, and these values increase by a factor of 2 when the region of the vortex edge is considered. The containment of Antarctic ozone depletion in October was well noticeable during all years, including 2002, with a difference of total ozone between inside and outside situations of 68% of the mean value inside the vortex for USH and 80% for MAR.

[33] The influence of vortex intrusions with depleted ozone on UVB radiation over populated regions such as USH and CRI has been analyzed. The MAR station was also considered in the study. The impact of vortex occurrences on UV levels is noticeable at all three stations but in a different way. UV levels at midlatitude stations like CRI (45.8°S) are generally not often perturbed by vortex intrusions. Nevertheless, the UV dose can increase by more than 50% as compared to typical levels when the vortex passes over the station like at the beginning of November 2002. In that period a maximum UV daily dose of 5.3 kJ/m^2 was observed, larger than the mean value in December of that year (4.8 kJ/m^2). In the case of USH the UV levels can be more than triple compared to the seasonal mean outside the vortex, as in October 2000, with a minimum ozone amount of 147 DU and a UV maximum dose of 5 kJ/m^2. This value is much larger than the mean UV levels of 3.1 kJ/m^2 in December, and it is also larger than the UV dose at CRI during this period. For MAR the UV maximum increase during a vortex occurrence over the station is generally close to 100% of the corresponding reference when the station is outside the vortex. The maximum UV increase for the whole 1997–2003 period was found at MAR at the end of October of 2002, with a percentage increase of 148%, corresponding to a UV dose of 4.7 kJ/m^2. UV levels in that period were larger than the mean UV dose in December during the same year (3.3 kJ/m^2). During vortex overpasses the total ozone column in October is generally larger at USH than at MAR for the 1997–2003 period. The analysis of the average impact of vortex occurrences in the years characterized by a good sampling of UV measurements shows an average percentage UV increase of 67.6% at USH over the years 1997, 1998, and 2000 and of 47.4% at MAR over 1999 and 2002. The larger increase at USH was shown to be strongly weighted by the 9 days of vortex occurrences in 2000. Taking into account the differences in UV measurements sampling, vortex occurrences, and cloud cover at the various stations considered in this study, it is difficult to compare in a systematic way the impact of vortex overpasses on UV levels at these stations over the whole 1997–2003 period. In this sense the comparisons can only be described as semiquantitative. Only in few circumstances a comparison for exactly the same period was possible. For example, larger maximum UV values were found at USH than at CRI for close time interval when the vortex passed over both stations in similar cloud cover conditions in 2000.

[34] The present work has resulted in the quantification of the UV erythemal dose increase due to vortex overpasses in ozone hole conditions over several southern Argentinean stations. The southern region of South America will be under the influence of the Antarctic ozone hole for some decades as forecasted by several chemistry climate models [*Austin et al.*, 2003]. In the mean time the evolution of wave activity in relation to climate change might increase the occurrences of vortex overpasses over this region. It is thus of prime importance to continue the monitoring of ozone and UV in the Southern Hemisphere. In order to study the evolution of the UV/ozone relationship, other parameters have to be kept in mind, such as the evolution of cloud cover and surface albedo.

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