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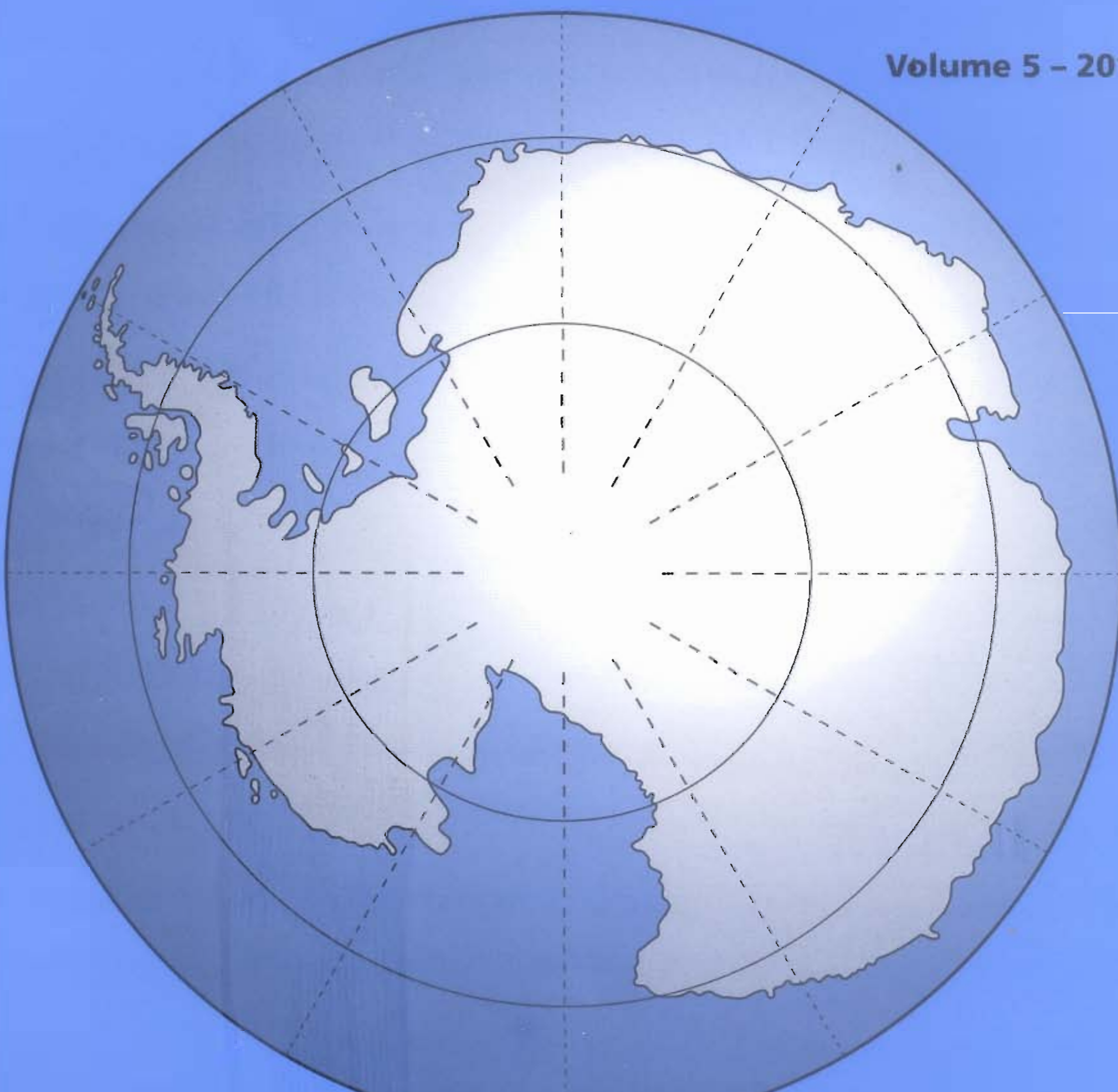

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Episodes of very low surface ozone in the South Shetland Islands (63°S, 58°W) and their stratospheric polar origin

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ABSTRACT

Extremely low concentrations of ozone at surface level reaching 2 ppbv were measured at the Brazilian Antarctic Station Com. Ferraz (63°05′S/58°23.5′W). Unexpectedly, they occurred in the winter and spring months during the maximum ozone annual cycle, when ozone-consuming atmospheric photochemical reactions are at their minimum. The objective of this paper is to explain these uncommon levels. Local and regional weather data and analysis, and backward air trajectories provided the evidence needed. A strong anticyclone creates the down flow of ozone-depleted air to the troposphere in the central and elevated areas of the continent; katabatic winds, close to the surface transport the air to the Weddell Sea where it flows northward along the Antarctic Peninsula with the cyclonic low-pressure circulation. Next, a local wind pattern, also typical of low-pressure centers in the region, deviates the flow to the west, against the prevailing west and north winds. Over 3,000 km are covered in about eight days by the air masses under this specific coupling of weather conditions, in a way apparently not yet reported in the literature.

Key words: tropospheric ozone, Weddell Sea, Antarctic meteorology, South Shetland Islands.

INTRODUCTION

Changes in ozone surface concentrations have been related to weather since the mid 1920s (Taba 1961); Dobson et al. (1929) described a general pattern for these changes: lower values in the forward part of cyclones, and higher at their rear with the advance of anticyclones. In the Dobson-Normand principle, confirmed by field data (Normand 1953), upward flows in low pressure cyclonic systems favor lower surface ozone, while downward flow typical of high pressure anticyclonic circulation brings ozone-rich air from the upper troposphere. Barsby and Diab (1995) described synoptic relationships for surface ozone in the southern hemisphere, between 10°W to 50°W, and 0°S to 50°S, where mid-latitude cyclones bring stratospheric ozone-rich air into the troposphere. Such ozone-weather patterns were applied in numerical weather models following Allaart et al. (1994).

On a yearly basis, ozone in the lower troposphere shows seasonal patterns. Lower values in the Southern Hemisphere occur in the summer, with monthly average values in the range of 10 to 35 ppbv (Logan 1985; Oltmans and Levy 1994). Extremely low concentrations, below 5 ppbv, may be found at nighttime in remote areas not affected by air pollution (Kirchhoff 1988). Regional effects may alter the annual cycle (Logan 1985), as in Central Brazil where extensive biomass burning triggers ozone formation and levels of 80 ppbv are commonly measured (Kirchhoff and Rasmussen 1990). Subpolar latitudes, as in the present study,

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show no local or regional ozone surface sources or sinks (Elansky and Markova 1995).

Measurements of troposphere ozone at surface level were conducted since 1985 in the vicinity of the Brazilian Antarctic Station Com. Ferraz (Kirchhoff and Pereira 1986; Kirchhoff and Marinho 1992), located at 63°05′S/58°23.5′W, King George Island, South Shetland Islands, in the northwest of the Antarctic Peninsula. The data for the 1985-1992 period showed no daily cycles, but a yearly cycle is evident. Lowest monthly mean values occur in the summer months of January and February, and are close to 12 ppbv with a standard deviation of about 7 ppbv; the highest monthly average of about 30 ppbv, with a standard deviation of 9 ppbv, was found in July (Kirchhoff and Marinho 1992); similar seasonal patterns for surface ozone in Antarctica were originally presented by Wexler et al. (1960), and later on, as in Murayama et al. (1992). In the southern Atlantic Ocean and in the Weddell Sea the Ozone variations have been attributed to the passage of synoptic-scale systems and advection from middle latitudes and Antarctica (Elansky and Markova 1995). Additionally, Ozone surface concentrations in Antarctica have a characteristic annual variation which is not synchronous to the total content of ozone in the atmosphere (Schwertdfeger 1970, p. 317).

The graphs of Figures 1 and 2 show a drop in ozone levels at Ferraz Antarctic Statoin on August 22-26, 1992, when the minimum of 2 ppbv was reached; two other similar variations were also reported at Ferraz in 1990, on August 10-12, and October 1-15 (Kirchhoff and Marinho 1992). Yurganov (1990) described a similar event in the north Weddell Sea during the spring month of September/1989, stressing the need to explain the uncommon measurements. The objective of this paper is to show that these unusual reductions in surface ozone levels at Ferraz during the period of regional maxima in the annual tropospheric ozone cycle result from a unique meteorological pattern that brings stratospheric air from the Antarctic Plateau, thousands of kilometers away.

MEASUREMENTS

Ozone concentrations at surface level were measured with a calibrated ozone photometer providing mixing ratios every 15 seconds, of which only the values every round hour were used (Kirchhoff and Marinho 1992); daily ozone values used therefore correspond to the average of 24 hourly measurements. Accuracy was better than 1 ppbv, traceable to NBS. Further details of the techniques and methodology are found in Kirchhoff (1988). The sampling site was 500 m away from Ferraz (Kirchhoff and Marinho 1992) to avoid contamination from the station's 150 KVA power generator and from its garbage incinerator that operates once a week; the intake was located about 3 m above the ground and 50 m from the sea shore. The meteorological data used are those of the Ferraz weather station, World Meteorological Organization ID #89252, which at the time had automatic data logging every three hours (Setzer 2010). This station is at 20 m elevation, distant 100 m from the shoreline and also from Ferraz, and 600 m from the ozone sampling site.

DISCUSSION

Figure 1 shows the temporal variation of ozone and meteorological parameters at Ferraz in 1992, until early November. The ozone curves for maxima and minima indicate the annual cycle, showing higher values in the winter Austral months. The upper ozone curve was plotted with daily averages of 24 hourly values, while the second curve contains just the minimum hourly ozone value of each day. August contains the maxima as well as a major strong discontinuity on days 22 to 26, when the daily average minimum of 13 ppbv was reached on the 25th. Concerning the hourly values in 1992, an ozone minimum of 2 ppbv occurred in the same August period: on the 22nd at 21 UTC, on the 24th at 18 UTC, and on the 25th at 12 and 18 UTC. The drop in ozone levels observed during these days in August is a strong one in relation to the seasonal and yearly course, particularly because they occurred

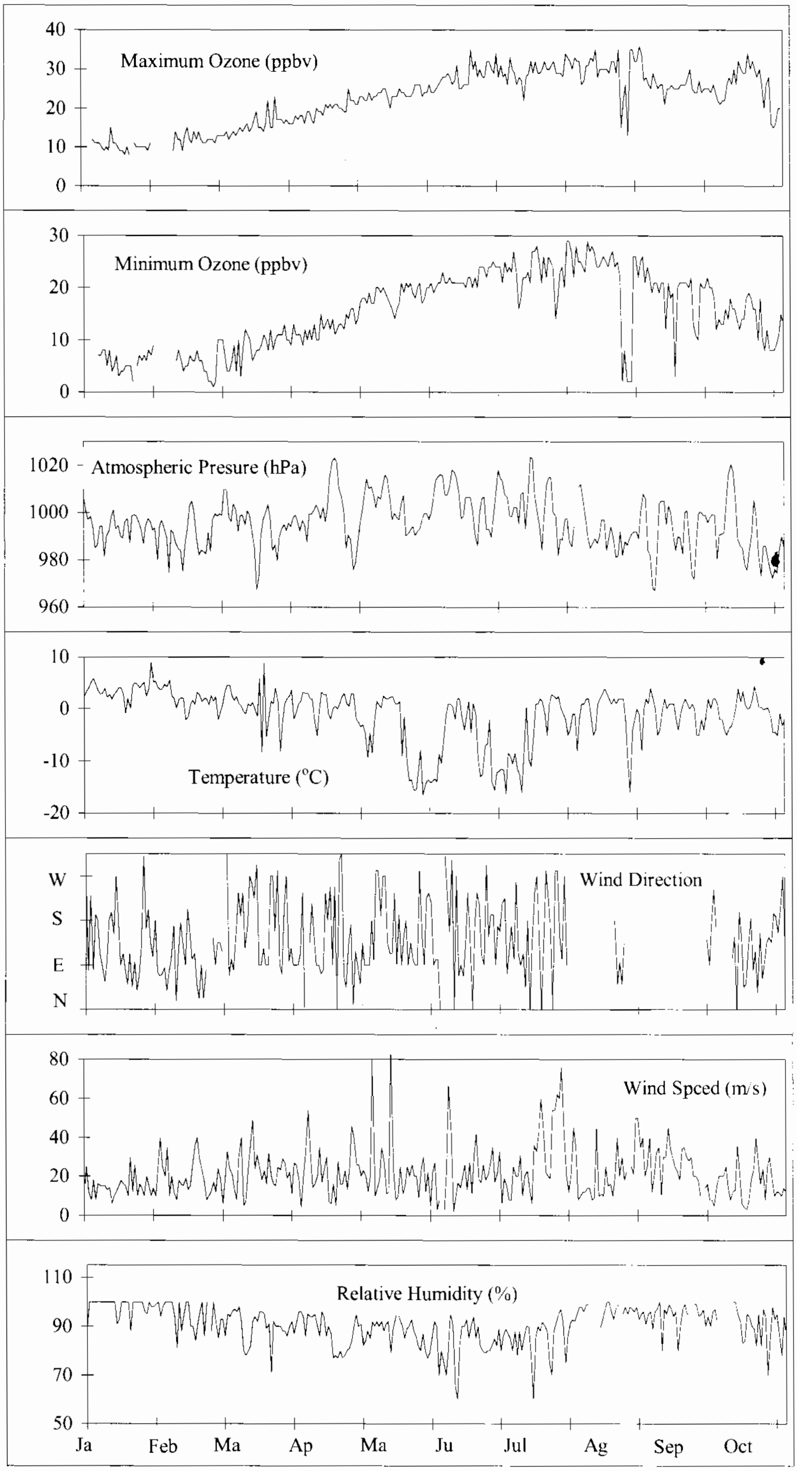

Fig. 1 – Surface ozone daily means and minima with corresponding weather data for 1992 at Ferraz Antarctic Station.

in the winter, at the annual peak of regional tropospheric ozone.

Figure 2 shows the ozone and temperature data at intervals of three hours for the period of interest. The temperature dropped from close to 0°C to below −10°C on the beginning of the 22nd, and again on the beginning of the 23rd, reaching the lower limit of −22°C on the 25th, to raise back and fast on the 26th. It is essential to note that the drop in temperature coincides with that of ozone concentrations at Ferraz, and that such low temperature episodes at Ferraz occurred in only two other cases during the year (see Fig. 1).

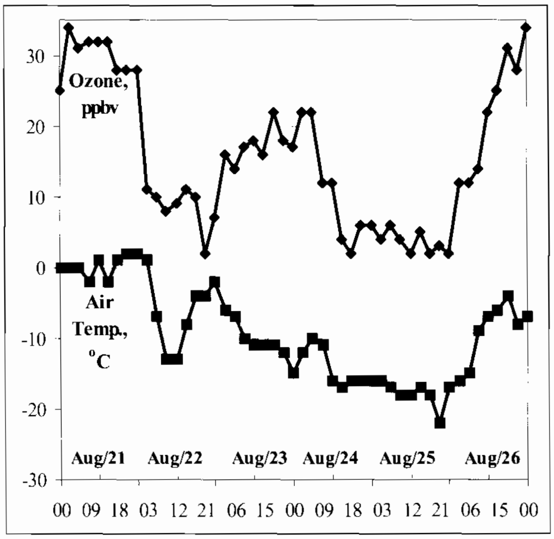

Fig. 2 – Surface ozone and temperature data for Ferraz Antarctic Station during August 21-26, 1992.

Depletion of surface ozone is also caused by photochemical reactions in the atmosphere, what explains the reduction in concentrations during spring and summer months at high latitudes and the overall yearly cycle at Ferraz presented in Figure 1. Therefore, another explanation must exist to justify very low levels of surface ozone in Antarctica during the Austral winter months of June-July-August when no solar light reaches the latitudes below the Antarctic Polar Circle.

The sea-level corrected pressure values between 970-990 hPa in this episode, indicated prevailing low pressure, and there were no organized fronts or anticyclones in the region. This is an important condition because low temperatures at the surface are expected under high-pressure systems, and not within areas of low pressure. This deviation from basic weather rules is explained below. Relative humidity in the August episode was above 95% in most of the period, indicating a wet air mass, also typical of low-pressure systems. Wind direction records were limited because of technical failures with the sensor at the time. Nevertheless, east winds were noticed on the 22nd, and on the 24th wind speed was within normal values for Ferraz, with a steady increase during the period, as seen in Figure 1. East winds usually account to 15% to 20% of the records for the month of August, when prevailing winds are from the northwest sector (Setzer 2010).

Ozone variations in the lower troposphere occur normally with the migration of systems of low and high pressure. These variations are clear in the annual graph of ozone concentrations of Figure 1 along the year. Since daily ozone cycles do not exist at the Ferraz region, the oscillations in concentrations result from air masses with different ozone loads (Elansky and Markova 1995). They are numerous because sub-Antarctic latitudes, as in the north of the Antarctic Peninsula, present the highest frequency and strength of cyclonic activity in the southern hemisphere (Schwertdfeger 1984, p. 139).

The case of August, 1992 shows a much larger and marked temperature variation in comparison to any previous one in the year, a consequence of the intrusion of cold air from the east at surface level, from the Weddell Sea. Altitude data from ozone probes launched on August/23 and 25 at Ferraz (Kirchhoff and Marinho 1992), showed no major differences in relation to 27 other ozone profile cases along the period of late March to early October, 1992; a weak tropopause was noticed at 200 hPa and 300 hPa, with west and southwest winds at these levels, respectively. As presented by Setzer and Härter (2004), significant decreases in surface temperatures at Ferraz occur with east and southeast winds in the lower troposphere under low-pressure systems, as in the period of the August/1992 low ozone episode.

The flow of cold air from the east at surface levels only happens in the Ferraz region with the penetration of air from the Weddell Sea under a peculiar circulation pattern in the region (see Fig. 3). Among its causes is a first order climatic divisor the Antarctic Peninsula (Schwerdtfeger 1970, p. 320). Narrow and 2,500 km long, with average elevation of 2 km and reaching up to 4 km, this mountain range constrains the air and water/ice circulation of the Weddell Sea's west side. With a cyclone over the Weddell Sea, northward strong cold flow develops along the Peninsula's eastern flank. In comparison to the western side, for the same latitude the eastern side of the Peninsula presents pressures 5 hPa higher and temperatures 10°C lower (Schwerdtfeger 1970, p. 320; 1975; 1984, p. 107). Once reaching the end of the Peninsula under conditions that occur with low-pressure centers surrounding the area, the colder and heavier air from the Weddell Sea spreads over the Bransfield and Drake straits (see Fig. 3). This type of flow was first described in Parish and Schwerdtfeger (1977) and in Schwerdtfeger and Amaturo (1979, p. 2 and 20-22); it was termed "low-level cold jet stream" or "low-level inertial jet stream". Further details and case studies of this so-called inertial flow are found in Schwerdtfeger (1984, p. 105-109), and Villela (1986). The data and explanations of Yurganov (1990) for his Weddell Sea low ozone values coincide with the interpretation for our data: he reported the temperature drop to low values with the low ozone values, as well as low-pressure systems on both sides of the Antarctic Peninsula.

Figure 1 also shows other episodes of marked temperature fall at Ferraz in 1992, particularly at the end of May and June, and at early July; most of them were accompanied by east winds and relatively low pressure with the cold flow from the Weddell Sea in the region. However, these other cases did not present unusually low ozone levels. Two other cases of very low ozone at Ferraz, below 5 ppbv, also were measured two years before, on August and October 1990 (Kirchhoff and Marinho 1992). They also occurred in conditions of low pressure and temperature, similar to the August 1992 case.

The origin and explanation for such low ozone levels was found a few thousand miles south, in the surface anti-cyclone dominating most of Antarctica. As seen in Figure 4, the center of the high pressure averaged during the four-day period studied indicates values over 1,080 hPa. Such unrealistic high values resulted from limitations in the reanalysis data, (Setzer and Kayano 2009), but nevertheless confirm a very strong anticyclonic effect. The high pressure was intense also at 850 hPa level and extended almost to 500 hPa; at this last level and upwards, the cyclonic circulation characteristic of the region in the period of March through October was well established.

Surface data from the Argentine station of Marambio (BAS 2010), in the northeast of the Peninsula, at 64.23°S and 56.72°W further corroborates the north flow close to the surface. On August 19th at 12 UTC, the wind direction changed from north to south, together with a drop of 13°C in air temperature, from −3.8°C to −16.8°C, and with a reduction in visibility from 15 km to 800 m; this new pattern continued until the 27th at 12 UTC, when north winds and higher temperatures returned; for this period, the minimum temperature of −29°C was recorded on the 25th at 12 UTC, and the surface pressure varied between 980 hPa and 1,000 hPa.

Figure 5 shows the backward trajectory during eight days for a parcel of air that arrived on August/24/1992, 18 UTC at 64°S and 57°W, 50 m elevation, at the northern tip of the Antarctic Peninsula, as generated from HYSPLIT (Draxler and Rolph 2010), assuming an isentropic environment; the marks in the curves of the figure define intervals of 12 hours. The upper and larger part of the figure indicates that the air originated in the central Plateau of the continent, progressed northwest, and then northwards along the Peninsula, except for a deviation to the east, followed by a return to the north. The middle part of the figure is an indication of the air temperature during the trajectory, in

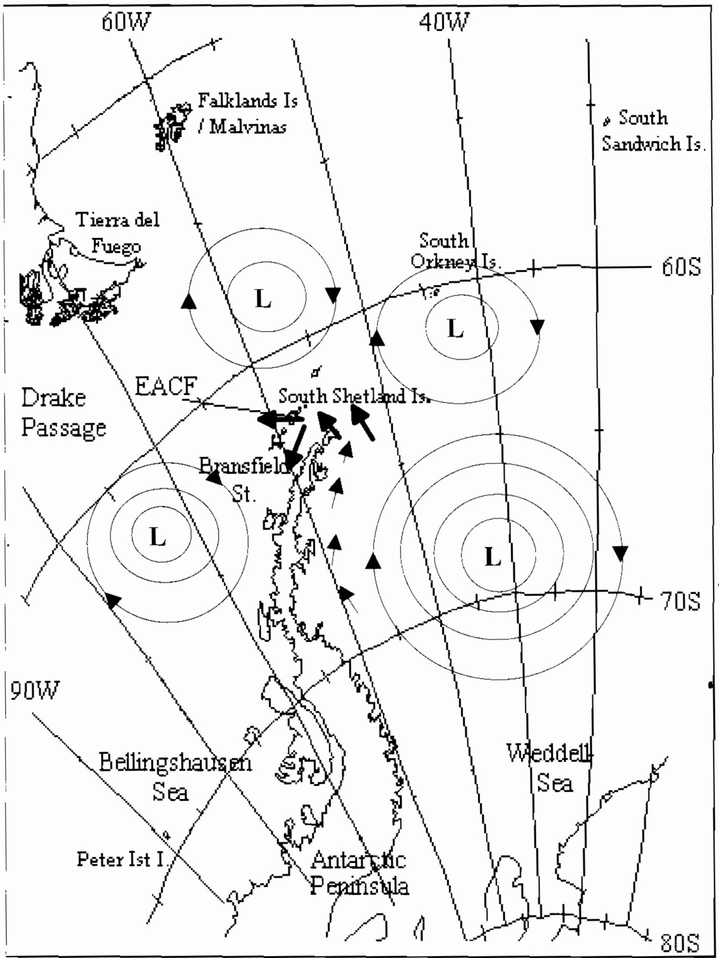

Fig. 3 – Pattern of low pressure centers related to cold surges at Ferraz Antarctic Station, originated in the Weddell Sea. Arrows along the Peninsula's east side show south winds and heavy arrows indicate winds in the South Shetland Islands (Setzer and Härter 2004).

degrees K, and the lower part shows the terrain elevation as well as the air parcel's. In approximate values, the air parcel started on the Plateu at 4,000 m and −58°C to arrive at the north of the Peninsula close to the surface with −23°C. However, this was a shallow flow, and altitude charts at 925 hPa already showed a flow to the east in the north of the Peninsula. This was possibly a case of slope katabatic winds over the continent that also transport ozone northwards from the Antarctic Plateau, as described by Gruzdev et al. (1993) and Wexler et al (1960). On the other hand, Elansky and Markova (1995) hypothesized that surface ozone values at the Weddell Sea were caused by the "outflux from the stratosphere above the central part of the hemisphere", in opposition to what is described in this paper.

As indicated above, it is relevant to notice that the lowest temperatures in the north of the Peninsula were observed under low pressure and cyclonic circulation, in opposition to the standard weather association of low temperatures to high pressure and anti-cyclonic domain. According to the literature (e.g. Taba 1961), very low levels of tropospheric ozone result only from the intrusion of low stratospheric air through anti-cyclones (high pressure) in the lower troposphere. In the episodes herein stud-

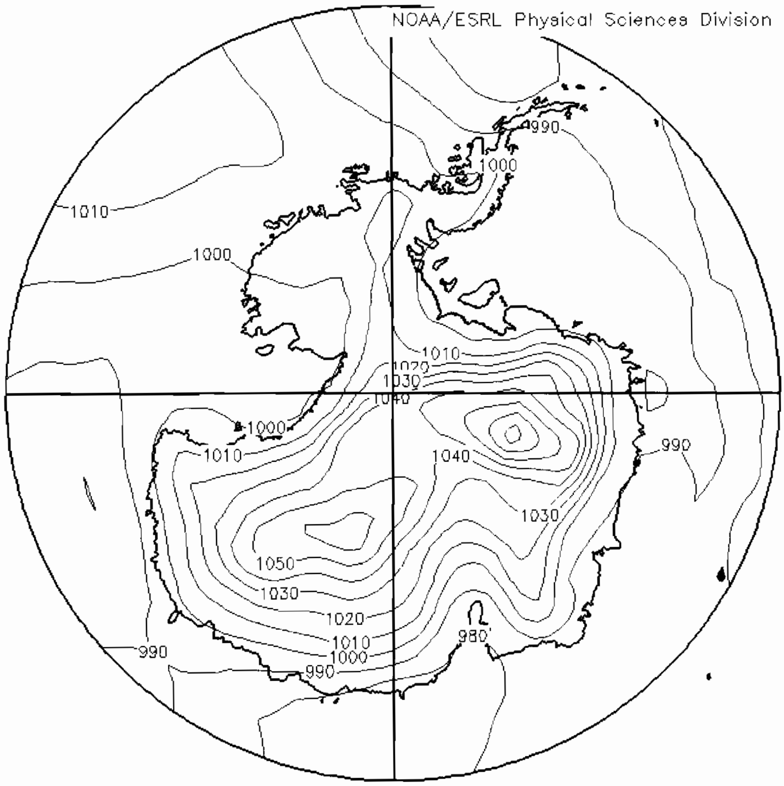

Fig. 4 – Pressure chart for Antarctica averaged for August 22-25, 1992, corrected to seal level. Note the center of the anticyclone with over 1,080 hPa (source, http://www.cdc.noaa.gov/Composites/Day/).

ied the reduction of ozone at surface level to ppbv detection limits in the peak of the annual tropospheric ozone regional cycle occurred in a context of cyclonic low pressure at surface. An anti-cyclone three thousand kilometers away and a unique regional surface flow allowed this apparent contradiction to take place.

CONCLUSION

Rare cases of extremely low ozone concentrations reaching 2 ppbv at sea level in the north of the Antarctic Peninsula (62°S) were associated to stratospheric downflow in a strong anticyclone in central Antarctica, transported northward at surface level for thousands of kilometers. These phenomena occur under a peculiar coupling of three weather conditions: very high surface pressure in the center of the continent, north flow along the east side of the Antarctic Peninsula and abnormal flow from the east in the Drake and Bransfield straits under low pressure. Such cases, apparently not yet described in the literature, indicate the complexities and wide spatial extent of tropospheric chemistry associated to individual weather events.

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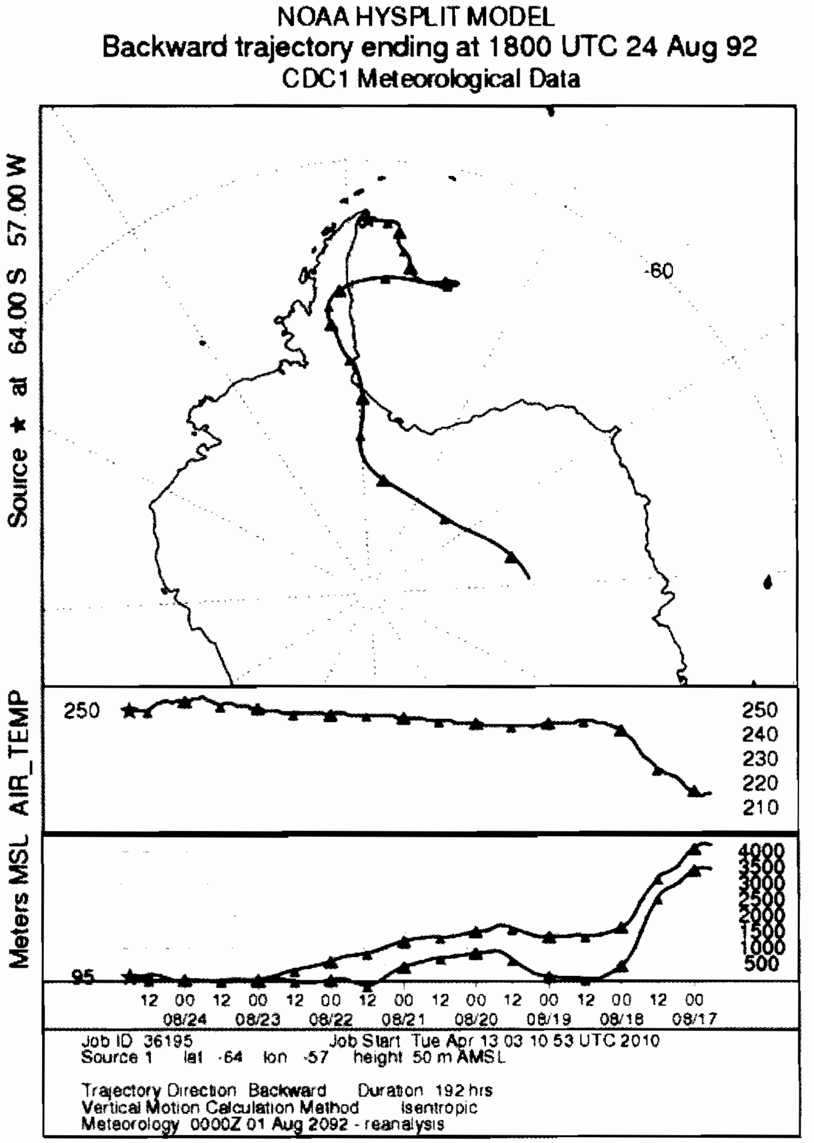

Fig. 5 – Back trajectory showing how an air parcel with very low ozone content measured in the north of the Antarctic Peninsula on August/24/1992, 18 UTC originated at the central Plateau eight days before. Generated at HYSPLIT (Draxler and Rolph 2010).

Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion mode. Partial credit for Figures 1 and 3 are due to Dr. C.S. Hungria. We also thank the INPE Ozone Lab staff, in particular Luiz S. Mangueira for running the instruments, as well as Heber R. Passos and Marilene A. Silva from the "Meteoro-H24" team. An anonymous reviewer suggested important changes in the text, which were highly acknowledged.

RESUMO

Concentrações baixas extremas de ozônio à superfície, em níveis de 2 ppbv, foram medidas na Estação Antártica Brsileira Com. Ferraz (63°05′S/58°23.5′W). Inesperadamente, elas ocorreram nos meses de inverno e primavera, no máximo anual do ciclo de ozônio, quando as reações fotos-químicas na atmosfera que consomem ozônio estão em seu mínimo. O objetivo deste trabalho é explicar estes valores incomuns. Dados e análises meteorológicas locais

e regionais, e retro-trajetórias de massas de ar, forneceram os meios necessários para tanto. Um anticiclone intenso cria o fluxo descendente de ar com baixo ozônio para a troposfera na parte central e elevada do continente; ventos catabáticos próximos à superfície transportam o ar para o Mar de Weddell, onde ele escoa para o norte ao longo da Península Antártica com a circulação ciclônica. Em seguida, um padrão local de ventos, também típico de centros de baixa pressão na região, desvia o fluxo para o oeste, contra os ventos predominantes de oeste e norte. Mais de 3.000 km são percorridos em cerca de oito dias pelas massas de ar por meio deste acoplamento de condições meteorológicas específicas, em um padrão aparentemente ainda não descrito na literatura.

Palavras-chave: ozônio troposférico, Mar de Weddell, meteorologia da Antártica, Ilhas Shetland do Sul.

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