



**Antarctic ozone
variability inside the
polar vortex**

M. C. Parrondo et al.

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

Antarctic ozone variability inside the Polar Vortex estimated from balloon measurements

M. C. Parrondo¹, M. Gil¹, M. Yela¹, B. J. Johnson², and H. A. Ochoa³

¹Atmospheric Research and Instrumentation Branch, National Institute for Aerospace Technology, Torrejón de Ardoz, Spain

²Global Monitoring Division, NOAA Earth System Research Laboratory, Boulder, Colorado, USA

³Dirección Nacional del Antártico/Instituto Antártico Argentino (DNA/IAA), Buenos Aires, Argentina

Received: 22 February 2013 – Accepted: 26 May 2013 – Published: 13 June 2013

Correspondence to: M. C. Parrondo (parrondosc@inta.es)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

13 yr of ozonesoundings at the Antarctic Belgrano II station (78° S, 34.6° W) have been analyzed to establish a climatology of stratospheric ozone and temperature over the area. The station is inside the polar vortex during the period of development of chemical ozone depletion. Weekly periodic profiles provide a suitable database for seasonal characterization of the evolution of stratospheric ozone, especially valuable during winter time when satellites and ground-based instruments based on solar radiation are lacking. The work is focused on ozone loss rate variability (August–October) and its recovery (November–December) at different layers identified according to the severity of ozone loss. The time window selected for the calculations covers the phase of a quasi-linear ozone reduction, about day 220 (mid August) to day 273 (end of September). Decrease of the total ozone column over Belgrano during spring is highly dependent on the meteorological conditions. Largest depletions (up to 59 %) are reached in coldest years while warm winters exhibit significantly lower ozone loss (20 %). It has been found that about 11 % of the total O₃ loss in the layer where maximum depletion occurs takes place before the sun has arrived as a result of transport of lower latitude air masses, providing evidence of mixing inside the vortex. Spatial homogeneity of the vortex has been examined by comparing Belgrano results with those previously obtained for South Pole Station (SPS) for the same altitude range and for 9 yr of overlapping data. Unexpected results show more than 25 % larger ozone loss rate at SPS than at Belgrano. It has been found that the accumulated hours of sunlight are the dominant factor driving the ozone loss rate. According to the variability of the ozone-hole recovery, a clear connection between the timing of the breakup of the vortex and the monthly ozone content was found. Minimum ozone concentration of 57 DU in the 12–24 km layer remained in November for the longest vortex, while years when the final stratospheric warming took “very early”, mean integrated ozone rises up to 160–180 DU.

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

The discovery of the Antarctic ozone hole in the late 1980s (Farman et al., 1985) intensified interest in stratospheric chemistry for a better understanding of the chemical and dynamics processes involved. At present, one of the main goals for the stratospheric ozone community is to detect the expected ozone recovery thanks to the Montreal Protocol for the Protection of the Ozone Layer and its amendments (WMO, 1995, 2007, 2010) which led to the reduction in the abundance of anthropogenic ozone depleting substances (Weatherhead and Andersen, 2006) and taking into account the complex processes between ozone and climate change.

Behind the direct consequences caused by the reduction of the ozone layer as the increase levels of ultraviolet radiation at the surface (Frederick et al., 1991; McKenzie et al., 1991; Lubin et al., 1995), the impact of the ozone hole goes further. Recent studies based on coupled chemistry climate models have shown that stratospheric ozone affects the whole atmospheric circulation in an unexpected number of ways (Son et al., 2009). For instance, ozone depletion seems to have contributed to increasing the Southern Annular Mode (SAM) index (Arblaster and Meehl, 2006), poleward shifting of the westerly jet in mid-latitudes and increasing global tropopause height (Santer et al., 2003). Models predict that these changes will probably reverse due to the ozone recovery (Son et al., 2009). Thus, in recent years, great attention has been paid to the timing of ozone recovery. Chemistry climate models are an excellent tool to investigate how the decreasing in atmospheric halogen compounds loading to natural “background” levels, will lead to stratospheric ozone recovery in the near future (Austin et al., 2010). On the other hand, several indexes are commonly used to quantify and study the variability of the Antarctic ozone depletion like minimum total ozone, ozone hole area (Stolarski et al., 1990; Bodeker et al., 2005) and ozone mass deficit (Uchino et al., 1999; Huck et al., 2007). However, for individual stations, ozone loss rate is used in many studies to assess the degree of the severity of the ozone depletion. Long term series of ozone loss rate have been used to detect ozone changes as a consequence of a de-

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



cline of the equivalent effective stratospheric chlorine (EESC) levels. Assuming a linear relationship between ozone loss rate and EESC, Hassler et al. (2011), found that a reduction of the ozone loss rate at South Pole station will be detectable in 2017–2021 period. In recent years, estimations of the ozone loss rate based on different satellite instrumentation (Tilmes et al., 2006; Sonkaew et al., 2011), ground-based instrumentation (Kuttippurath et al., 2010) and balloon-borne measurements (Hassler et al., 2011; Hoffman et al., 2009) for the Antarctic region have been published.

The severe Antarctic ozone destruction is followed by its recovery in summer months. By the end of October or beginning of November, polar vortex begins to weaken, causing an exchange of air masses between vortex and extra-vortex air. When the vortex breaks up, ozone-rich air from outside replaces the ozone hole region and ozone starts its recovery. The rate and the timing of the recovery will be influenced by the meteorological conditions of the polar vortex. Several works have analyzed the interannual variability of the vortex break-up using different criteria (Waugh et al., 1999; Haigh and Roscoe, 2009; Black and McDaniel, 2007) and have exhibited a trend in the persistence of both polar vortices.

In the present paper, previous studies of the variability of the ozone loss in the Antarctic region, are extended using 13 yr of ozonesonde measurements at Belgrano II, a station located well inside the polar vortex where the ozone hole occurs each year (Parrondo et al., 2007). Results are compared to those at South Pole Station (SPS hereafter) (Hofmann et al., 2009). Interannual evolution of the ozone recovery in November and December has been analysed as well.

The paper is organized in 5 sections. After introduction, Sect. 2 describes the data used for the work. In Sect. 3, the methodology applied for ozone loss rate calculation and diagnostic of the polar vortex are presented. The main results are shown in Sect. 4 divided in five parts. Finally, a summary and the main conclusions will be exposed in Sect. 5.

2 Measurements

The ozonesounding programme at Belgrano II Antarctic station started in June 1999 as a joined effort between Argentinean Dirección Nacional del Antártico (DNA) and Instituto Nacional de Técnica Aeroespacial (INTA). Since then, ozonesondes have been regularly launched at a frequency of 2 profiles per month during summer and autumn months and up to 6–10 profiles in winter and spring months on Wednesdays at 12:00 GMT, whenever possible. Electrochemical concentration cells (ECC) from two manufacturers have been used: SPC-6A (Science Pump Corporation) and ENSCI-Z (En-SCI Corporation). Chemical sensing solutions for both types of sondes have been prepared following the recommendations of each manufacturer. The standard cathode solution used was 1 % KI buffered for SPC-6A (Komhyr et al., 1995) and 0.5 % KI buffered for ENSCI-Z type (EN-SCI Corporation, 1996). The sonde was interfaced to a meteorological radiosonde from Väisälä for pressure, temperature and humidity data. The entire system is flown on a TOTEX balloon (TX-1200) filled with helium. Balloons were dip-oil treated to reduce the occurrence of low burst height under very cold conditions, being the mean burst altitude under normal conditions around 30 km. A TSC-1 ozonizer/test unit (manufactured by Science Pump Corporation) was used for the calibration and preparation of sondes according to the recommendations given by Komhyr (1986). Laboratory studies performed to assess the quality and reliability of ozonesondes show that sondes operated according to standard operating procedures for ECC sondes can yield a precision of 3–5 % and 5–10 % accuracy up to 30 km altitude (Smit et al., 2007; Deshler et al., 2008; WMO, 2011).

For each sounding, the ratio between total ozone column obtained by an independent nearby instrument and the integrated ozone from the ozonesonde profile plus the residual ozone has been calculated as a quality control parameter (Logan et al., 1994). Based on the criterion that the ratio should be on the 0.8–1.2 range (maximum allowed discrepancy 20 %) a total of 2 % of the profiles were rejected. Residual ozone from the balloon burst altitude to the top of the atmosphere has to be estimated. Several meth-

ACPD

13, 15663–15695, 2013

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ods can be used for this purpose, giving differences about 10–20 DU (Thompson et al., 2003). In this work residual ozone was calculated assuming a constant mixing ratio above the balloon burst altitude if the balloon reaches 17 hPa (Claude et al., 1987). For reference, total ozone data from Total Ozone Mapping Spectrometer (TOMS) version 8 and from Ozone Monitoring Instrument (OMI) on board the Earth Probe satellite, and NASA's EOS-Aura respectively, as well as total ozone from the Brewer spectrometer installed at Belgrano station have been used.

3 Methodology

3.1 Selection of layers and time window

Three contiguous layers in the lower stratosphere can be identified as being affected by the ozone depletion. Selection of the boundary levels have been made according to the degree of severity in its maximum phase (October) with respect to the mean “normal” ozone profile (Kuttippurath et al., 2010). Figure 1 displays the mean profiles used for layers selection. We followed Lee et al. (2000) to select the “normal” reference as the mean profile of all available soundings from 15 June to 15 July (blue line in Fig. 1). For the most depleted period the mean ozone profile was computed from the subset of the minimum profile registered each year (black line). Minimum ozone values are generally observed by the end of September or early October. The three regions identified are the following: the first one extends from the lowest part of the stratosphere, 12 to 15 km; the central layer extends from 15 to 21 km, and the top one from 21–24 km. The ozone removal is almost complete in the central layer ($95 \pm 2.3\%$) whereas in regions below and above only about half of the ozone is destroyed. The degree of ozone loss in each region agrees with values given by Solomon et al. (2005) and Hofmann et al. (2009) for South Pole station. The low standard deviation, represented as a shadowed area, provide information on the low inter-annual variability in the shape of the maximum depleted ozone profile.

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The general evolution of ozone loss inside of the polar vortex exhibits a phase of a slow ozone decline, followed by a period of quick ozone destruction. The timing of each phase for a specific station depends on the geographic position with respect to the polar vortex (Kuttippurath et al., 2010). The time window of our study is focused on the period when the ozone decrease is nearly linear in time, and has been determined for each of the regions by the mean ozone evolution for the 1999–2011 dataset.

3.2 Vortex edge and position of the station with respect to the polar vortex

The position of the polar vortex and its boundaries has been calculated for each day from 1 May to 31 December using the widely accepted method of Nash et al. (1996). Potential vorticity from European Centre for Medium-Range Weather Forecasts (ECMWF) truncated to T106 horizontal resolution ($1.125^\circ \times 1.125^\circ$) at the isentropic level of 475 K has been used. The isentropic level of 475 K has been chosen for the study as it represents a mean level of the low stratosphere where the maximum ozone number density is observed. Each day was classified in three groups according to the position of the station with respect to the polar vortex: inside, outside and at the edge of the polar vortex.

3.3 Breakup of the polar vortex

The common criteria used to determinate the date of the spring breakdown of the polar vortex are based on the time when the parameters considered to diagnose the vortex reach a predetermined threshold. In this work, potential vorticity and zonal winds are used to characterize the behaviour of the polar vortex. The first criterion defines the breakup as the date when the equivalent latitude of potential vorticity at 500 K for $PV = 46$ PVU ($1 \text{ PVU} = 10^{-6} \text{ K m}^2 \text{ s}^{-1} \text{ kg}^{-1}$) is above 80° (Waugh et al., 1999). The second criterion determines the stratospheric final warming date as the day when the running 5 day average of the zonal-mean wind at 50 hPa and 70° S becomes negative

and does not change to values higher than 5 m s^{-1} until next year (Black and McDaniel, 2007).

4 Results

4.1 Ozone and temperature seasonal evolution

5 Figure 2 displays the time-height cross-section for ozone and temperature at Belgrano based on climatological monthly mean profiles. Year-to-year variations of ozone and temperature tend to cancel in the climatology. In January, ozone reaches a maximum at an altitude of 22 km and a concentration of 14 mPa. From that date onward, the maximum descends at a rate of 30 m day^{-1} in summer and 17 m day^{-1} afterwards. De-
10 scent is faster in the upper levels. The lowering in the height of the maximum is partially a consequence of an O_3 reduction in the 25–38 km layer height due to NO_x catalytic cycles (Osterman et al., 1997; Fahey and Ravishankara, 1999; Crutzen and Bhrol, 2001) poleward of 70° (Cordero and Kawa, 2001) in a season where the meridional transport is small, but also due to descent of the downward branch of the Brewer–Dobson cir-
15 culation. This climatological picture is close to the 3–7 km of descent over an 8 month period extending from 1 March to 31 October that Rosenfield et al. (1994) found for the years 1987–1992 using National Meteorological Center (NMC) temperatures and a radiation model.

From the ozonesonde record alone it is challenging to detect any evolution summer
20 in total ozone column due to large scattering in integrated data but also because the upper part of the stratosphere is truncated. OMI data (not shown), however, display a clear signature of a slow decline of no more than $0.25\text{--}0.4 \text{ DU day}^{-1}$ which is abruptly stopped when the vortex edge passes over the station. Inside the vortex, and before chemical depletion takes place, a slight increase in ozone is attributed to air subsiding
25 by diabatic cooling (Christensen et al., 2005).

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The ozone hole phase starts with the arrival of solar radiation and proceeds almost simultaneously at all levels. The recovery, on the other hand, starts from above before the maximum depletion takes place, in mid October, preventing the total ozone column from becoming even lower. The ozone enriched air resulting from poleward eddy transport arrives to the polar region when the vortex edge barrier disappears (Miyazaki et al., 2005) and propagates downwards at a rate of 74 m day^{-1} . It is worth noting that chemical ozone depletion extends until January in the 12–15 km layer.

The temperature structure is dominated by the winter radiative cooling, reaching minimum temperatures at 21 km. Height and time of Polar Stratospheric Clouds (PSC) presence defined by the threshold temperature for the existence of nitric acid trihydrate (NAT) (Hanson and Mauersberger, 1988) extends from May to late October with a large vertical extension of over 15 km, covering a 58 % of the mid and low stratospheric region (12–30 km) from May to October. Minimum temperature takes place by the end of July at 21 km. As spring proceeds, heating at upper levels propagates downwards quite in coincidence with ozone increase at a mean rate about $0.5^\circ\text{C day}^{-1}$. By the beginning of March the lower stratosphere remains essentially isothermal.

4.2 Seasonal evolution of ozone in the layer where complete ozone depletion takes place (15–21 km)

Figure 3 displays a 30 day running mean of ozone partial column over Belgrano in the layer where the maximum depletion takes place (15–21 km) for all available soundings. Four clear phases can be identified. In phase I, ozone increases from January to mid June, when annual maximum values are reached. Afterwards two periods of ozone decrease are observed. In the first one (phase II) the decay is attributed to dilution effects of poor ozone air from lower latitudes where ozone loss has already started (Roscoe et al., 1997) providing evidence that a low but not negligible mixing takes place inside the vortex (Lee et al., 2001; Roscoe et al., 2012). During this period, the partial column has decreased by almost 11 % with respect to the maximum occurring on day 160. Studies based on backward trajectories have shown how ozone depleted air from lower

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



latitude regions exposed to sunlight and in the presence of PSC could be transported poleward reducing the ozone content at higher latitudes (Sato et al., 2009). In phase III, a direct chemical depletion evolves almost linearly from day 220, just after the arrival of sunlight, and onwards. Green-blue thick curve for 78° S shows the hours of sunlight at a height of 25 km. Minimum O₃ partial column is reached by early October (day number 277), 57 days after the arrival of light at 25 km altitude. Typical ozone residual in this layer is of only 5 % of the winter values. Mean ozone depletion in this phase is 2.0 DU day⁻¹. After minimum occurrence, the ozone recovery also takes place linearly at a slower rate of 0.78 DU day⁻¹ and, as previously mentioned, is due to a downward propagating refill from the top of the layer (phase IV). Red thick line represents the daily mean distance from the vortex edge to the station in terms of equivalent latitude at the isentropic level of 475 K (approximately 18 km). Negative values indicate that the station is inside the vortex. The figure shows that Belgrano is located well inside the vortex at this level from mid-May to early December. At upper levels, however, the vortex starts to collapse earlier as can be seen by the O₃ increase in phase IV.

4.3 Ozone loss rate and variability

Figure 4 shows ozone loss time series with respect the August value in percent (left scale) and the corresponding ozone loss rate (right scale). Decrease of the total ozone column over Belgrano during spring varies from 20 % to 59 %, depending on the year. The total amount of ozone depleted is on the top of the bars. The largest ozone loss of about 140–160 DU (55–60 %) were observed in coldest years (2000, 2003 and 2006) while lowest loss of ozone, 57 DU (20 %), occurred in 2002 due to the unprecedented major warming over the Southern Hemisphere in spring, and the vortex split into two centres (Charlton et al., 2005; Hoppel et al., 2003). Other warm winters like 2004 and 2010 exhibit lower ozone loss of 123 DU (46 %) and 77 DU (33.7 %), respectively.

When dividing the atmosphere into the three layers described above, details on ozone loss rate inter-annual variability can be better observed. Figure 5 shows how the main pattern is observed at all levels, providing evidence that ozone loss rates are

**Antarctic ozone
variability inside the
polar vortex**

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



mainly affected by the deep vortex structure rather than by effects in individual layers. Interannual variability is largest in region II, where the depletion is more severe and its contribution to the overall total ozone column reduction is maximum. Layers exhibit standard deviations ranging on 0.14–0.30 DU day⁻¹. If considering relative variability, the contribution is largest in region III (83.4 %) and might be related to the larger temperature variations resulting from stratospheric minor warmings occurring at higher altitudes. The main observed feature is a reduction of the ozone loss in 2002, reaching values below two standard deviations. The anomalous behaviour of the atmosphere in that year was a consequence of the already mentioned vortex splitting. As a result, stratospheric temperature rose fast inside the vortex. Over Belgrano, a dramatic temperature increase of 54 °C at the isentropic level of 700 hPa was observed by two consecutive soundings separated by one week. The ozone depletion process was suddenly stopped and a fast poleward transport of ozone-enriched mid-latitude air arrived the station at all levels above 550 K affecting also the levels below that height (Yela et al., 2005).

Year 2010 is also an interesting case. Ozone loss rate is the second lowest of the data series and in the top layer is even positive. Positive ozone loss rate indicates an increase in ozone during the period considered. However this case cannot be interpreted as if the ozone destruction hasn't taken place, but the ozone depletion finished earlier than the time window considered. This fact is related to a July minor Sudden Stratospheric Warming (SSW) covering the polar region, resulting in an increase of temperature of 20 °C in less than two weeks, leading to the evaporation of PSC and a deactivation of halogen species. Areas of potential PSC-I (NAT) presence have been calculated for 2010 assuming values of 5 ppmv H₂O and 9–10 ppbv HNO₃ (Müller et al., 2001) (Fig. 6). In 2010, after the mentioned Minor Warming the area of potential presence of PSC I was 20 % lower than the mean values for the period 1999–2011. The total integrated area in 2010 was 9 % lower than the mean area. Less PSCs result in less halogen activation and hence, less O₃ depletion. In addition, de Laat and van Weele (2011) found, using Microwave Limb Sounder (MLS) data, an enrichment of wa-

ter vapor in the 10–50 hPa layer which strongly modified the chemical composition of the region and inhibited the destruction process.

Year-to-year ozone loss rates are influenced by a number of factors which are not independent of each other: ozone-depleting substances (ODS) present when the sun arrives, winter temperature, sunlight available, and the amount of ozone present when depletion starts. In Fig. 7 ozone loss rates are plotted against the amount of ozone partial column by the time when direct depletion takes place to show that the amount of “initial” ozone plays a role in determining the individual year ozone loss rate. When the anomalous year is excluded from the analysis, the correlation coefficient is -0.69 indicating an ozone loss rate dependence on the initial ozone. The same result was found in a previous study for the South Pole station (Hofmann et al., 2009). Winter ozone is determined by dynamics through planetary wave forcing of the mean meridional circulation. Years with a positive anomaly in ozone are related to a larger poleward transport (Weber et al., 2011) as can be seen by the high correlation of ozone anomaly with Eliassen–Palm (EP) flux anomalies at 70 hPa at high latitudes of Southern Hemisphere (Salby et al., 2011). Therefore, inter-annual variability in dynamical forcing from planetary waves has a strong influence on the ozone loss rate as pointed out by other studies (Kravchenko et al., 2012; Weber et al., 2011).

Stratospheric temperature and the strength of the polar vortex play also major roles in the amount of ozone and the rate of depletion. A strong correlation between ozone loss and volume of PSCs ($r = 0.9$) has been found in the Arctic (Rex et al., 2004, 2006; Harris et al., 2010). In Antarctica, the interannual variability based on the correlation is meaningless since PSC occurrence reaches the saturation level inside the vortex (Yang et al., 2008). In many years the ozone loss rate is very similar (see years 1999, 2000, 2003, 2004, 2005 and 2006). Only in warm years there is a reduction in ozone loss rate which becomes apparent in 2010 and in the extreme case of 2002 mentioned above.

Recent studies based on larger time series have compared ozone loss rates in different periods finding a change in the trend for periods before and after 1996. For

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



instance, Yang et al. (2008) found a decline in rate of ozone loss since 1997, statistically significant at the 95 % confidence level, and conclude that the reduced amount of halogen over the past decade has contributed to the first stage of ozone recovery in the Antarctic region. Positive ozone trends were also reported by Austin et al. (2010) and Kieseewetter et al. (2010) during 2000–2009 using a chemistry transport model, however they attributed this fact mainly to changes in meteorology as the reduction in stratospheric halogen loading is still small in this period. From the limited ozonesonde time series at Belgrano no significant trend can be observed.

4.4 Ozone distribution within the vortex: Belgrano versus South Pole

Ozone loss rates from Belgrano have been compared with those obtained for SPS (Hofmann et al., 2009) for the same period in order to examine the vortex spatial homogeneity. In Hofmann et al. (2009) the month of September has been used for computing ozone loss rate at SPS. Results show larger ozone loss rates at SPS by as much as 25 % for the 1999–2009 overlapping period (Fig. 8). Such a large difference in ozone loss rate between two stations located clearly inside the Antarctic vortex was not an expected result. The period of stratospheric temperatures low enough for PSC formation over SPS starts few days earlier than that at Belgrano and ends at the same time. The difference in time between the two stations is too small compared to the overall period of 16–17 weeks of potential PSCs over continental Antarctica (not shown). Interestingly, the phase of almost linear ozone loss rate over SPS starts well before the arrival of the sunlight. Figure 9 displays the mean value of the ozone partial column in a layer between 15–21 km as in Fig. 3 but with the SPS data included. As already shown, sunrise at a height of 18 km over Belgrano coincides with the change in the slope of the ozone loss rate toward larger values. In SPS, almost half of the total ozone amount has been depleted before sunrise, instead. The ozone minimum is reached at same date, near days 275–280. Accumulated hours of sunlight at 18 km for both stations are also drawn. Larger rates of accumulated light seem to be the responsible of the larger ozone loss rate observed.

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ern Hemisphere polar vortex calculated using the criteria defined in Sect. 3.3. The day of the breakdown varies from early December to mid-January. It can be observed that in the last years when the polar vortex has been stronger, the final breakdown takes place later than for years with a less strong one. Some works have been done to analyze the potential factors contributing to the evolution of the Antarctic polar vortex particularly focused on the delay in its breakdown (Haigh and Roscoe., 2009; Fogt et al., 2009; Perlwitz et al., 2008; Gillett and Thompson, 2003). Their results have demonstrated that ozone depletion is a major factor influencing the delay in the polar vortex breakup, while the combined effects of solar activity, the phase of the quasi-biennial oscillation and greenhouse gases exert a small influence. Thus, all of them play an important role on the rate of the ozone recovery.

5 Summary and conclusions

An ozone and temperature climatology has been constructed based on 13 yr of ozonesonde data over the time period 1999–2011 at Belgrano station in Antarctica. The seasonal ozone maximum takes place in January at an altitude of 22 km. From that date, a slow descent is observed at a rate of 30 m day^{-1} during summer, slowing afterwards to 17 m day^{-1} . Meteorological conditions for halogen activation are present from May to late October. In this period, stratospheric temperatures below the threshold for PSC-I cover a large vertical extent above 15 km, representing the 58 % of vertical stratospheric region from 15 to 30 km. Minimum temperature takes place by the end of July at 21 km. As spring proceeds, heating at upper levels propagates downwards quite in coincidence with ozone increase at a mean rate about $0.5 \text{ }^\circ\text{C day}^{-1}$. By the beginning of March the lower stratosphere remains essentially isothermal.

Total ozone depletion during spring varies from 20 % to 59 % of August values, depending on the year. The largest ozone losses were of about 140–160 DU in coldest years while the lowest value of 57 DU (20 %) occurred in 2002 due to the unprecedented major warming over the Southern Hemisphere.

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



An in-depth analysis of ozone variability was performed in three stratospheric layers in which ozone suffers chemical depletion. It has been observed that 11 % reduction of the ozone partial column in the most severely affected layer (15–21 km) takes place when Belgrano is still in darkness, and is attributed to dilution effects with air from a lower-latitude belt, where ozone depletion has already started. When sunlight reaches the station, an almost linear mean ozone loss rate of -2.0 DU day^{-1} is found. By comparison with South Pole Station it was found that the ozone loss rate at the latter station was over 25 % larger than at Belgrano and the ozone minimum was reached simultaneously around day 275 (2 October) when the lower stratosphere above both stations have received the same amount of light, around 600 h, suggesting that the amount of sunlight is the determinant factor controlling the ozone loss rate.

Finally, the analysis of the rate of the ozone-hole build-up in November and December shows a clear relationship between the persistence of low ozone content during this period, the strength of the polar vortex and the timing of its final breakdown.

Acknowledgements. We thank the different ozonesounding operational teams at Belgrano station. We also would like to thank to ECMWF for provided potential vorticity and temperature data. This work has been partially funded by Spanish Polar Program (CICYT-ANT97-0433, REN2000-0245-C02-01, CGL2004-05419-C02-01/ANT, POL2006-0382 and CGL2010-20353) and EU 5th framework Programme (QUOBI project, EVK2-2001-00129).

References

- Arblaster, J. M. and Meehl, G. A.: Contributions of external forcings to southern annual mode trends, *J. Climate*, 19, 2896–2905, 2006.
- Austin, J., Struthers, H., Scinocca, J., Plummer, D. A., Akiyoshi, H., Baumgaertner, A. J. G., Bekki, S., Bodeker, G. E., Braesicke, P., Brühl, C., Butchart, N., Chipperfield, M. P., Cugnet, D., Dameris, M., Dhomse, S., Frith, S., Garny, H., Gettelman, A., Hardiman, S. C., Jöckel, P., Kinnison, D., Kubin, A., Lamarque, J. F., Langematz, U., Mancini, E., Marchand, M., Michou, M., Morgenstern, O., Nakamura, T., Nielsen, J. E., Pitari, G., Pyle, J., Rozanov, E., Shepherd, T. G., Shibata, K., Smale, D., Teyssède, H., and Yamashita, Y.:

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Chemistry-climate model simulations of spring Antarctic ozone, *J. Geophys. Res.*, 115, D00M11, doi:10.1029/2009JD013577, 2010.

Black, R. X. and McDaniel, B. A.: Interannual variability in the Southern Hemisphere circulation organized by stratospheric final warming event, *J. Atmos. Sci.*, 64, 2968–2974, 2007.

5 Bodeker, G. E., Shiona, H., and Eskes, H.: Indicators of Antarctic ozone depletion, *Atmos. Chem. Phys.*, 5, 2603–2615, doi:10.5194/acp-5-2603-2005, 2005.

Charlton, A. J., O'Neill, A., Lahoz, W. A., and Berrisford, P.: The splitting of the stratospheric polar vortex in the Southern Hemisphere, September 2002: dynamical evolution, *J. Atmos. Sci.*, 62, 590–602, ISSN 1520-0469, 2005.

10 Christensen, T., Knudsen, B. M., Streibel, M., Andersen, S. B., Benesova, A., Braathen, G., Claude, H., Davies, J., De Backer, H., Dier, H., Dorokhov, V., Gerding, M., Gil, M., Henchoz, B., Kelder, H., Kivi, R., Kyrö, E., Litynska, Z., Moore, D., Peters, G., Skrivankova, P., Stübi, R., Turunen, T., Vaughan, G., Viatte, P., Vik, A. F., von der Gathen, P., and Zaitcev, I.: Vortex-averaged Arctic ozone depletion in the winter 2002/2003, *Atmos. Chem. Phys.*, 5, 131–138, doi:10.5194/acp-5-131-2005, 2005.

15 Claude, H., Hartmannsgruber, R., and Köhler, U.: Measurement of atmospheric ozone profiles using the Brewer/Mast sonde, WMO Global Ozone Research and Monitoring Project, Report No. 17, WMO/TD, No. 179, 1987.

20 Cordero, E. C. and Kawa, S. R.: Ozone and tracer transport variations in the summer Northern Hemisphere stratosphere, *J. Geophys. Res.*, 106, 12227–12239, doi:10.1029/2001JD900004, 2001.

Crutzen, P. J. and Brühl, Ch.: Catalysis by NO_x as the main cause of the spring to fall stratospheric ozone decline in the Northern Hemisphere, *J. Phys. Chem.*, 105, 1579–1582, 2001.

25 Deshler, T., Mercer, J. L., Smit, H. G. J., Stubi, R., Levrat, G., Johnson, B. J., Oltmans, S., Kivi, R., Thompson, A. M., Witte, J., Davies, J., Schmidlin, F. J., Brothers, G., and Sasaki, T.: Atmospheric comparison of electrochemical cell ozonesondes from different manufacturers, and with different cathode solution strengths: the balloon experiment on standards for ozonesondes, *J. Geophys. Res.*, 113, D04307, doi:10.1029/2007JD008975, 2008.

EN-SCI Corporation: Instruction Manual, Model 1Z ECC-O3-Sondes, Boulder, Colo., 1996.

30 Fahey, D. W. and Ravishankara, A. R.: Summer in the stratosphere, *Science*, 285, 208–210, 1999.

Farman, J. C., Gardiner, B. G., and Shanklin, J. D.: Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interactions, *Nature*, 315, 207–210, 1985.

**Antarctic ozone
variability inside the
polar vortex**

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Fogt, R. L., Perlwitz, J., Pawson, S., and Olsen, M. A.: Intra-annual relationships between polar ozone and the SAM, *Geophys. Res. Lett.*, 35, L04707, doi:10.1029/2008GL036627, 2009.
- Frederick, J. E. and Alberts, A. D.: Prolonged enhancement in surface ultraviolet radiation during the Antarctic spring of 1990, *Geophys. Res. Lett.*, 8, 1869–1871, 1991.
- 5 Gillett, N. and Thompson, D. W. J.: Simulation of recent Southern Hemisphere climate change, *Science*, 302, 273–275, 2003.
- Haigh, J. D. and Roscoe, H. K.: The final warming date of the Antarctic polar vortex and influences on its interannual variability, *J. Climate*, 22, 5809–5819, 2009.
- Hanson, D. and Mauersberger, K.: Solubility and equilibrium vapor-pressures of HCl dissolved
10 in polar stratospheric cloud materials – ice and the trihydrate of nitric-acid, *Geophys. Res. Lett.*, 15, 1507–1510, 1988.
- Harris, N. R. P., Lehmann, R., Rex, M., and von der Gathen, P.: A closer look at Arctic ozone loss and polar stratospheric clouds, *Atmos. Chem. Phys.*, 10, 8499–8510, doi:10.5194/acp-10-8499-2010, 2010.
- 15 Hassler, B., Daniel, J. S., Johnson, B. J., Solomon, S., and Oltmans, S. J.: An assessment of changing ozone loss rates at South Pole: twenty-five years of ozonesonde measurements, *J. Geophys. Res.*, 116, D22301, doi:10.1029/2011JD016353, 2011.
- Hofmann, D. J., Johnson, B. J., and Oltmans, S. J.: Twenty two years of ozonesonde measurements at the South Pole, *Int. J. Remote Sens.*, 30, 3995–4008, doi:10.1080/01431160902821932, 2009.
- 20 Hoppel, K., Bevilacqua, R., Allen, D., Nedoluha, G., and Randall, C.: POAM III observations of the anomalous 2002 Antarctic ozone hole, *Geophys. Res. Lett.*, 30, 1394, doi:10.1029/2003GL016899, 2003.
- Huck, P. E., Tilmes, S., Bodeker, G. E., Randel, W. J., McDonald, A. J., and Nakajima, H.: An improved measure of ozone depletion in the Antarctic stratosphere, *J. Geophys. Res.*, 112, D11104, doi:10.1029/2006JD007860, 2007.
- 25 Kiesewetter, G., Sinnhuber, B.-M., Weber, M., and Burrows, J. P.: Attribution of stratospheric ozone trends to chemistry and transport: a modelling study, *Atmos. Chem. Phys.*, 10, 12073–12089, doi:10.5194/acp-10-12073-2010, 2010.
- 30 Komhyr, W. D.: Operations handbook Ozone measurements to 40-km altitude with model 4A electrochemical concentration cell (ECC) ozonesondes (used with 1680 MHz radiosondes), NOAA Tech. Memo. ERL ARL-149, Air Resour. Lab., Boulder, Colorado, 49 pp., 1986,

**Antarctic ozone
variability inside the
polar vortex**

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Komhyr, W. D., Barnes, R. A., Brothers, G. B., Lathrop, J. A., and Opperman, D. P.: Electrochemical concentration cell ozonesonde performance evaluation during STOIC 1989, *J. Geophys. Res.*, 100, 9231–9244, 1995.

Kravchenko, V. O., Evtushevsky, O. M., Grytsai, A. V., Klekociuk, A. R., Milinevsky, G. P., and Grytsai, Z. I.: Quasi-stationary planetary waves in late winter Antarctic stratosphere temperature as a possible indicator of spring total ozone, *Atmos. Chem. Phys.*, 12, 2865–2879, doi:10.5194/acp-12-2865-2012, 2012.

Kuttippurath, J., Goutail, F., Pommereau, J.-P., Lefèvre, F., Roscoe, H. K., Pazmiño, A., Feng, W., Chipperfield, M. P., and Godin-Beekmann, S.: Estimation of Antarctic ozone loss from ground-based total column measurements, *Atmos. Chem. Phys.*, 10, 6569–6581, doi:10.5194/acp-10-6569-2010, 2010.

de Laat, A. T. J. and van Weele, M.: The 2010 Antarctic ozone hole: Observed reduction in ozone destruction by minor sudden stratospheric warmings, *Scientific Reports*, 1, 38, doi:10.1038/srep00038, 2011.

Lee, A. M., Roscoe, H. K., and Oltmans, S.: Model and measurements show Antarctic ozone loss follows edge of polar night, *Geophys. Res. Lett.*, 27, 3845–3848, doi:10.1029/2000GL011441, 2000.

Lee, A. M., Roscoe, H. K., Jones, A. E., Haynes, P. H., Shuckburgh, E. F., Morrey, M. W., and Pumphrey, H. C.: The impact of the mixing properties within the Antarctic stratospheric vortex on the ozone loss in spring, *J. Geophys. Res.*, 106, 3203–3211, 2001.

Logan, J.: Trends in the vertical distribution of ozone: an analysis of ozonesonde data, *J. Geophys. Res.*, 99, 25553–25585, 1994.

Lubin, D. and Jensen, E. H.: Effects of clouds and stratospheric ozone depletion on ultraviolet radiation trends, *Nature*, 377, 710–713, 1995

McKenzie, R. L., Matthews, W. A., and Johnston, P. V.: The relationship between erythemal UV and ozone, derived from spectral irradiance measurements, *Geophys. Res. Lett.*, 18, 2269–2272, 1991.

Miyazaki, K., Iwasaki, T., Shibata, K., and Deush, M.: Role of transport in the seasonal variation of the total ozone content, *J. Geophys. Res.*, 110, D18309, doi:10.1029/2005JD005900, 2005.

Monier, E. and Weare, B. C.: Climatology and trends in the forcing of the stratospheric zonal-mean flow, *Atmos. Chem. Phys.*, 11, 12751–12771, doi:10.5194/acp-11-12751-2011, 2011.

**Antarctic ozone
variability inside the
polar vortex**

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Müller, M., Neuber, R., Beyerle, G., Kyrö, E., Kivi, R., and Wöste, L.: Non-uniform PSC occurrence within the Arctic polar vortex, *Geophys. Res. Lett.*, 28, 4175–7178, 2001.
- Nash, E. R., Newman, P. A., Rosenfield, J. E., and Schoeberl, M. R.: An objective determination of the polar vortex using Ertel's potential vorticity, *J. Geophys. Res.*, 101, 9471–9478, 1996.
- 5 Osterman, G. B., Salawitch, R. J., Sen, B., Toon, G. C., Stachnik, R. A., Pickett, H. M., Margitan, J. J., Blavier, J., and Peterson, D. B.: Balloon-borne measurements of stratospheric radicals and their precursors: implications for the production and loss of ozone, *Geophys. Res. Lett.*, 24, 1107–1110, 1997.
- Parrondo, M. C., Yela, M., Gil, M., von der Gathen, P., and Ochoa, H.: Mid-winter lower strato-
10 sphere temperatures in the Antarctic vortex: comparison between observations and ECMWF and NCEP operational models, *Atmos. Chem. Phys.*, 7, 435–441, doi:10.5194/acp-7-435-2007, 2007.
- Perlwitz, J., Pawson, S., Fogt, R. L., Nielsen, J. E., and Neff, W. D.: Impact of strato-
15 spheric ozone hole recovery on Antarctic climate, *Geophys. Res. Lett.*, 35, L08714, doi:10.1029/2008GL033317, 2008.
- Rex, M., Salawitch, R., von der Gathen, P., Harris, N., Chipperfield, M., and Nau-
jokat, B.: Arctic ozone loss and climate change, *Geophys. Res. Lett.*, 31, L04116, doi:10.1029/2003GL018844, 2004.
- Rex, M., Salawitch, R. J., Deckelmann, H., von der Gathen, P., Harris, N. R. P., Chipper-
20 field, M. P., Naujokat, B., Reimer, E., Allaart, M., Andersen, S. B., Bevilacqua, R., Braa-
then, G. O., Claude, H., Davies, J., De Backer, H., Dier, H., Dorokov, V., Fast, H., Gerding, M.,
Godin-Beekmann, S., Hoppel, K., Johnson, B., Kyrö, E., Litynska, Z., Moore, D., Nakane, H.,
Parrondo, M. C., Risley, A. D., Skrivanova, P., Stübi, R., Viatte, P., Yushkov, V., and Zere-
25 fos, C.: Arctic winter 2005: implications for stratospheric ozone loss and climate change,
Geophys. Res. Lett., 33, L23808, doi:10.1029/2006GL026731, 2006.
- Roscoe, H. K., Jones, A. E., and Lee, A. M.: Midwinter start to Antarctic ozone depletion:
evidence from observations and models, *Science*, 278, 93–96, 1997.
- Roscoe, H. K., Feng, W., Chipperfield, M. P., Trainic, M., and Shuckburgh, E. F.: The existence
of the edge region of the Antarctic stratospheric vortex, *J. Geophys. Res.*, 117, D04301,
30 doi:10.1029/2011JD015940, 2012.
- Rosenfield, J. E., Newman, P. A., and Schoeberl, M. R.: Computations of diabatic descent in
the stratospheric polar vortex, *J. Geophys. Res.*, 99, 16677–16689, 1994.

- Salby, M., Titova, E., and Deschamps, L.: Rebound of Antarctic ozone, *Geophys. Res. Lett.*, 38, L09702, doi:10.1029/2011GL047266, 2011.
- Salby, M. L., Titova, E. A., and Deschamps, L.: Changes of the Antarctic ozone hole: controlling mechanisms, seasonal predictability, and evolution, *J. Geophys. Res.*, 117, D10111, doi:10.1029/2011JD016285, 2012.
- Sato, K., Tomikawa, Y., Hashida, G., Yamanouchi, T., Nakajima, H., and Sugita, T.: Longitudinally dependent ozone increase in the Antarctic polar vortex revealed by balloon and satellite observations, *J. Atmos. Sci.*, 66, 1807–1820, doi:10.1175/2008JAS2904.1, 2009.
- Santee, M. L., Lambert, A., Read, W. G., Livesey, N. J., Manney, G. L., Cofield, R. E., Cuddy, D. T., Daffer, W. H., Drouin, B. J., Froidevaux, L., Fuller, R. A., Jarnot, R. F., Knosp, B. W., Perun, V. S., Snyder, W. V., Stek, P. C., Thurstans, R. P., Wagner, P. A., Waters, J. W., Connor, B., Urban, J., Murtagh, D., Ricaud, P., Barrett, B., Kleinböhl, A., Kuttippurath, J., Küllmann, H., von Hobe, M., Toon, G. C., and Stachnik, R. A.: Validation of the Aura Microwave Limb Sounder ClO measurements, *J. Geophys. Res.*, 113, D15S22, doi:10.1029/2007JD008762, 2008.
- Santer, B. D., Wehner, M. F., Wigley, T. M. L., Sausen, R., Meehl, G. A., Taylor, K. E., Ammann, C., Arblaster, J., Washington, W. M., Boyle, J. S., and Brüggemann, W.: Contributions of anthropogenic and natural forcing to recent tropopause height changes, *Science*, 301, 479–483, 2003.
- Smit, H. G. J., Straeter, W., Johnson, B. J., Oltmans, S. J., Davies, J., Tarasick, D. W., Hoegger, B., Stubi, R., Schmidlin, F. J., Northam, T., Thompson, A. M., Witte, J. C., Boyd, I., and Posny, F.: Assessment of the performance of ECC ozone sondes under quasiflight conditions in the environmental simulation chamber: insights from the Juelich Ozone Sonde Intercomparison Experiment (JOSIE), *J. Geophys. Res.*, 112, D19306, doi:10.1029/2006JD007308, 2007.
- Solomon, S., Portmann, R. W., Sasaki, T., Hofmann, D. J., and Thompson, D. W. J.: Four decades of ozonesonde measurements over Antarctica, *J. Geophys. Res.*, 110, D21311, doi:10.1029/2005JD005917, 2005.
- Son, S. W., Tandon, N. F., Polvani, L. M., and Waugh, D. W.: Ozone hole and Southern Hemisphere climate change, *Geophys. Res. Lett.*, 36, L15705, doi:10.1029/2009GL038671, 2009.
- Sonkaew, T., von Savigny, C., Eichmann, K.-U., Weber, M., Rozanov, A., Bovensmann, H., Burrows, J. P., and Groöb, J.-U.: Chemical ozone losses in Arctic and Antarctic polar win-

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Antarctic ozone
variability inside the
polar vortex**

M. C. Parrondo et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

ter/spring season derived from SCIAMACHY limb measurements 2002–2009, *Atmos. Chem. Phys.*, 13, 1809–1835, doi:10.5194/acp-13-1809-2013, 2013. .

Steinhorst, H. M., Konopka, P., Günther, G., and Müller, R.: How permeable is the edge of the Arctic vortex – model studies of the winter 1999–2000, *J. Geophys. Res.*, 110, D06105, doi:10.1029/2004JD005268, 2005.

Stolarski, R., Schoeberl, M., Newman, P., McPeters, R., and Krueger, A.: The 1989 Antarctic ozone hole as observed by TOMS, *Geophys. Res. Lett.*, 17, 1267–1270, 1990.

Thompson, A. M., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara, M., Kirchoff, V. W. J. H., Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S., Ogawa, T., Johnson, B. J., Vömel, H., and Labow, G.: The 1998–2000 SHADOZ (Southern Hemisphere Additional Ozonesondes) tropical ozone climatology. 1. Comparison with TOMS and groundbased measurements, *Geophys. Res.*, 108, 8238, doi:10.1029/2001JD000967, 2003.

Tilmes, S., Müller, R., Groöß, J. U., Nakajima, H., and Sasano, Y.: Development of tracer relations and chemical ozone loss during the setup phase of the polar vortex, *J. Geophys. Res.*, 111, D24S90, doi:10.1029/2005JD006726, 2006.

Uchino, O., Bojkov, R., Balis, D. S., Akagi, K., Hayashi, M., and Kajihara, R.: Essential characteristics of the Antarctic-spring ozone decline: update to 1998, *Geophys. Res. Lett.*, 26, 1377–1380, 1999.

Waugh, D. W., Randel, W. J., Pawson, S., Newman, P. A., and Nash, E. R.: Persistence of the lower stratospheric polar vortices, *J. Geophys. Res.*, 104, 27191–27201, 1999.

Weatherhead, E. C. and Andersen, S. B.: The search for signs of recovery of the ozone layer, *Nature*, 441, 39–45, doi:10.1038/nature04746, 2006.

Weber, M., Dikty, S., Burrows, J. P., Garny, H., Dameris, M., Kubin, A., Abalichin, J., and Lange-matz, U.: The Brewer–Dobson circulation and total ozone from seasonal to decadal time scales, *Atmos. Chem. Phys.*, 11, 11221–11235, doi:10.5194/acp-11-11221-2011, 2011.

World Meteorological Organization (WMO): Scientific Assessment of Ozone Depletion: 1994, Global Ozone Research and Monitoring Project, Report No. 37, Geneva, Switzerland, 1995.

World Meteorological Organization (WMO): Scientific Assessment of Ozone Depletion: 2006, Global Ozone Research and Monitoring Project, Rep. 50, Geneva, Switzerland, 2007.

World Meteorological Organization (WMO): Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project, Rep. 50, Report No. 52, Geneva, Switzerland, 2010.

WMO: Quality Assurance and Quality Control for Ozonesonde Measurements in GAW, WMO Rep. 201, Geneva, Switzerland, 2011.

5 Yang, E. S., Cunnold, D. M., Newchurch, M. J., Salawitch, R. J., McCormick, M. P., Russell III, J. M., Zawodny, J. M., and Oltmans, S. J.: First stage of Antarctic ozone recovery, *J. Geophys. Res.*, 113, D20308, doi:10.1029/2007JD009675, 2008.

Yela, M., Parrondo, C., Gil, M., Rodriguez, S., Araujo, J., Ochoa, H., Deferrari and Diaz, S.: The September 2002 Antarctic vortex major warming as observed by visible spectroscopy and ozone soundings, *Int. J. Remote Sens.*, 26, 3361–3376, 2005.

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic ozone
variability inside the
polar vortex

M. C. Parrondo et al.

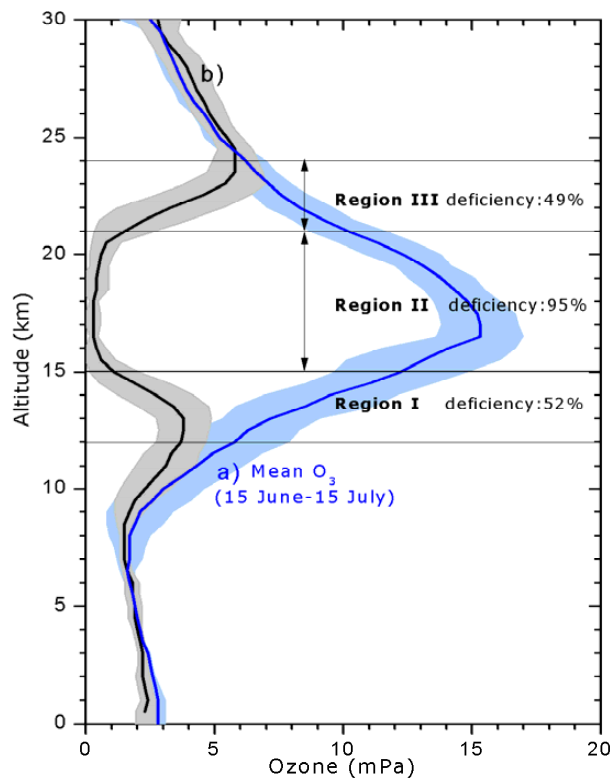


Fig. 1. Ozone mean profiles **(a)** Winter profile typical of pre-O₃ hole conditions (blue line). **(b)** October-mean profile when depletion is at maximum (black line). Shaded areas indicate one standard deviation. Three regions of study are shown.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

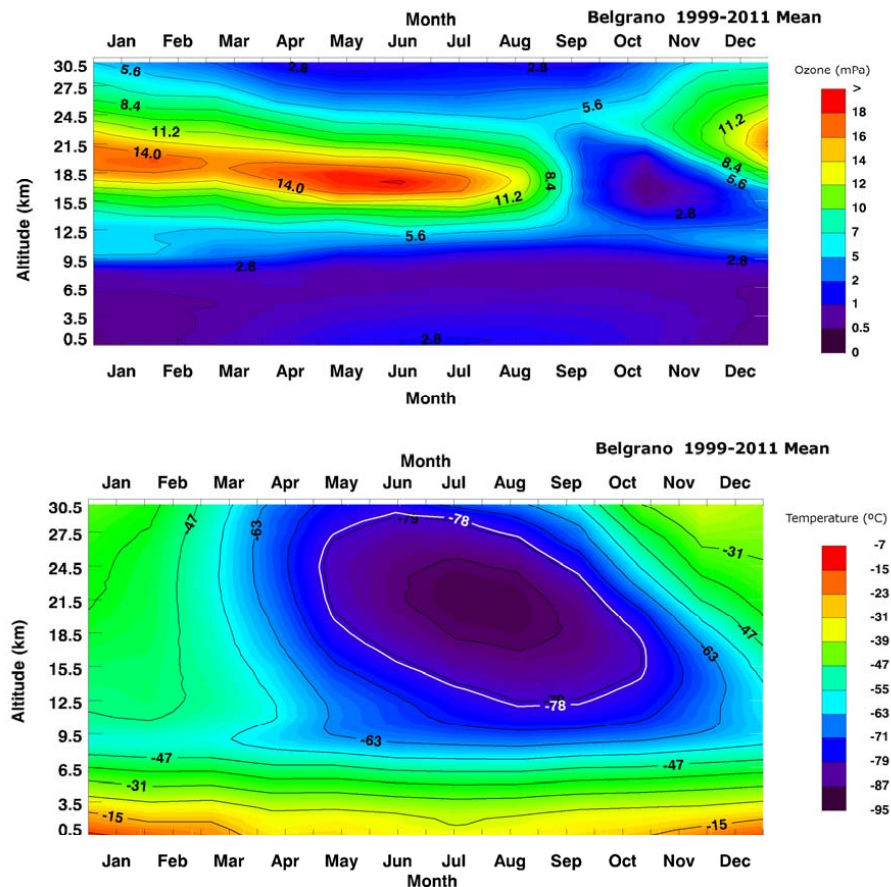


Fig. 2. Time-height cross-sections of ozone (upper panel) and temperature (lower panel) over Belgrano. Isothermal of -78°C is plotted in white, defining approximately the boundaries of time and height where PSC formation is possible.

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

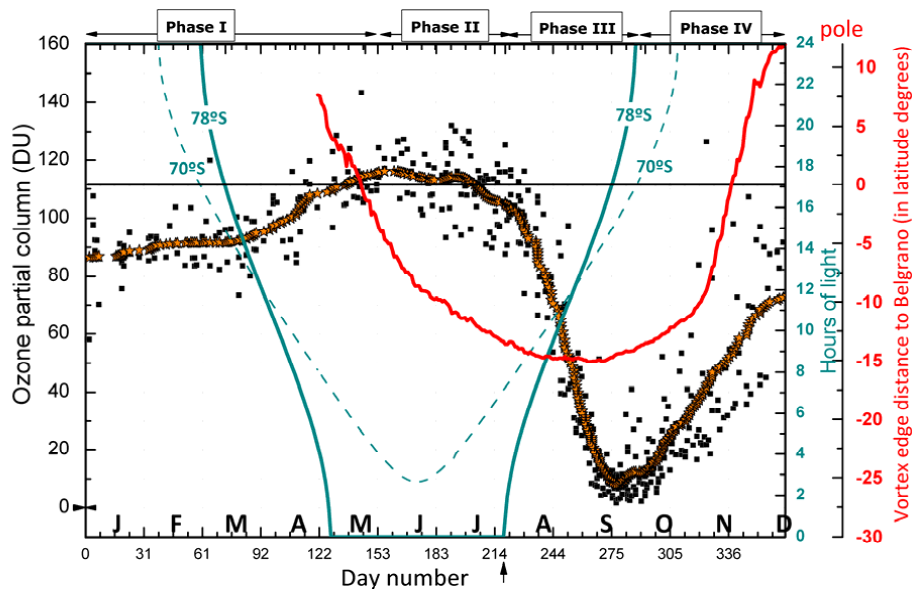


Fig. 3. Seasonal evolution of the 1999–2011 mean ozone in the layer 15–21 km (30-points running mean as orange stars). Daily mean distance from the vortex edge to Belgrano in terms of equivalent latitude computed for the same period (red solid line). Negative values means Belgrano inside the vortex. Hours of light at 78° S (thick blue line) and 70° S (dashed blue line) in the stratosphere (25 km).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

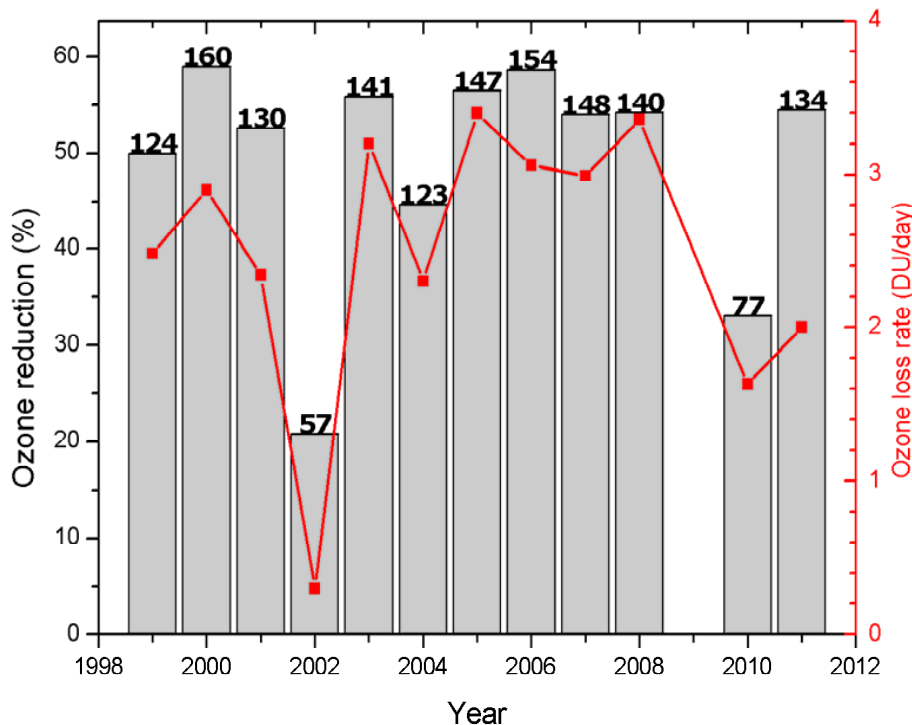


Fig. 4. Time series of ozone loss rate (red line and right scale) for the total column and ozone loss with respect the ozone in August in percent (bars and left scale). The total amount of ozone depleted is shown on the top of the bars.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

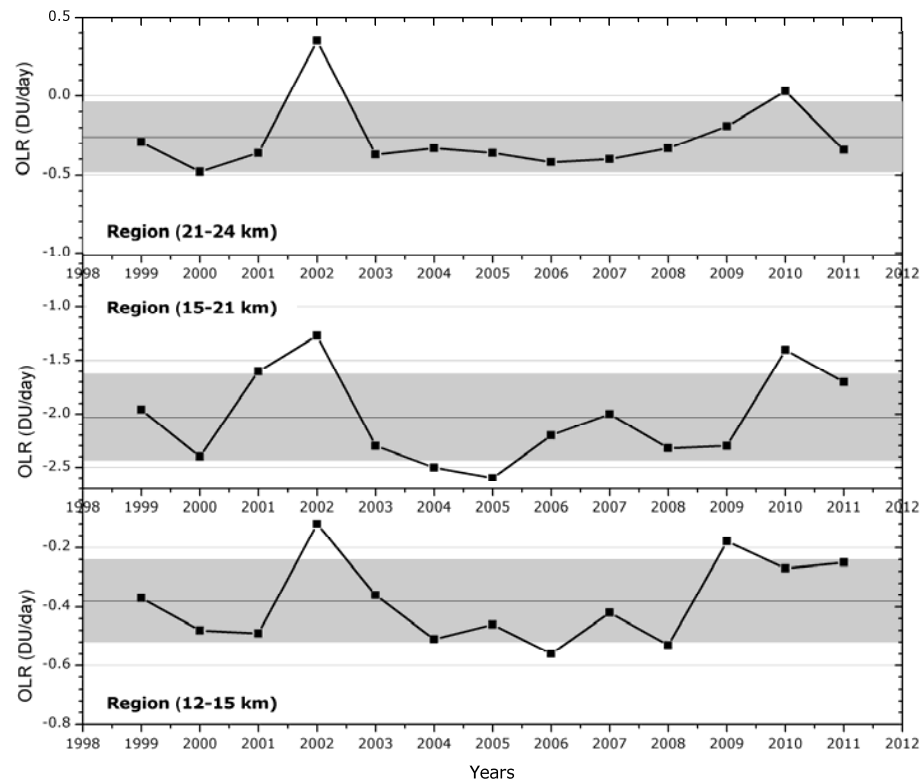


Fig. 5. Inter-annual evolution of the ozone loss rate in the 21–24 km layer (upper plot), 15–21 km (middle plot) and 12–15 km (lower plot). Grey shadowed areas indicate one standard deviation.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

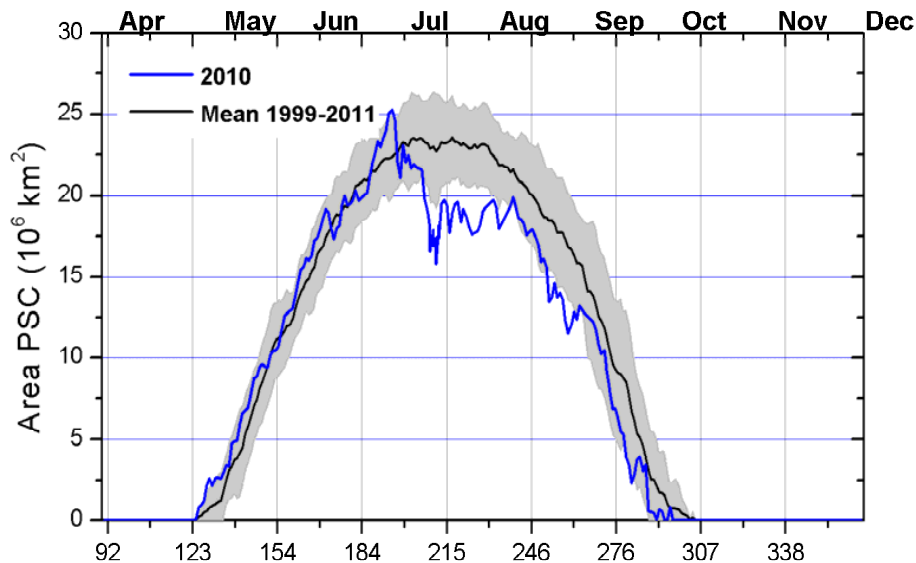


Fig. 6. Mean Area of potential polar stratospheric clouds (PSC-I) formation based on ECMWF analysis temperature for the period 1999–2011 (black line). Grey area represents one standard deviation. Area for the year 2010 is shown in blue line.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Antarctic ozone
variability inside the
polar vortex**

M. C. Parrondo et al.

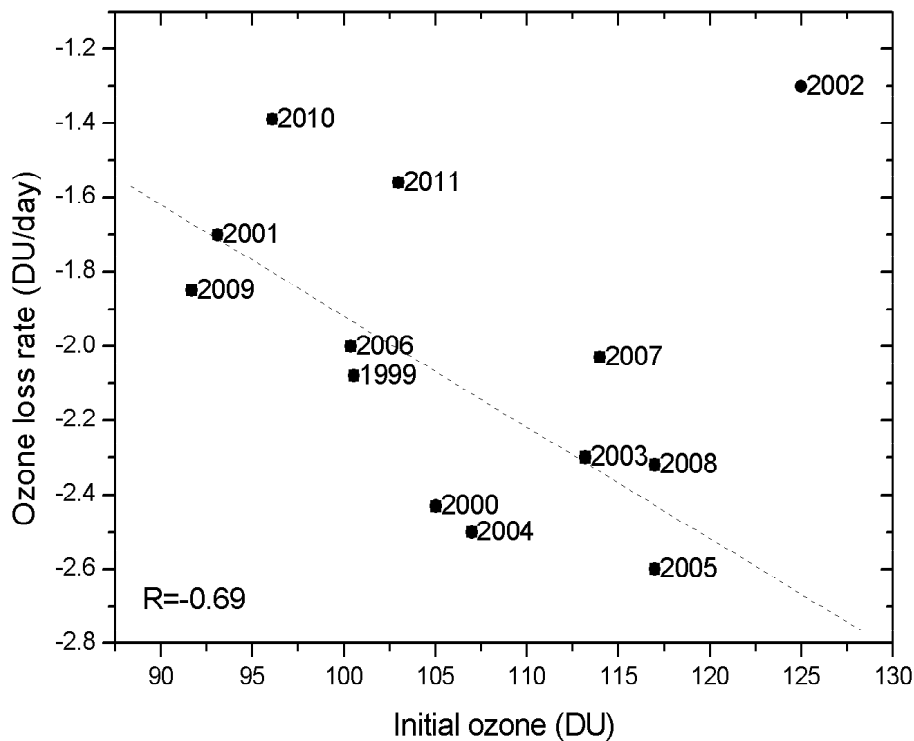


Fig. 7. Ozone loss rate versus the amount of ozone present when the direct ozone depletion starts for all years of measurements.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

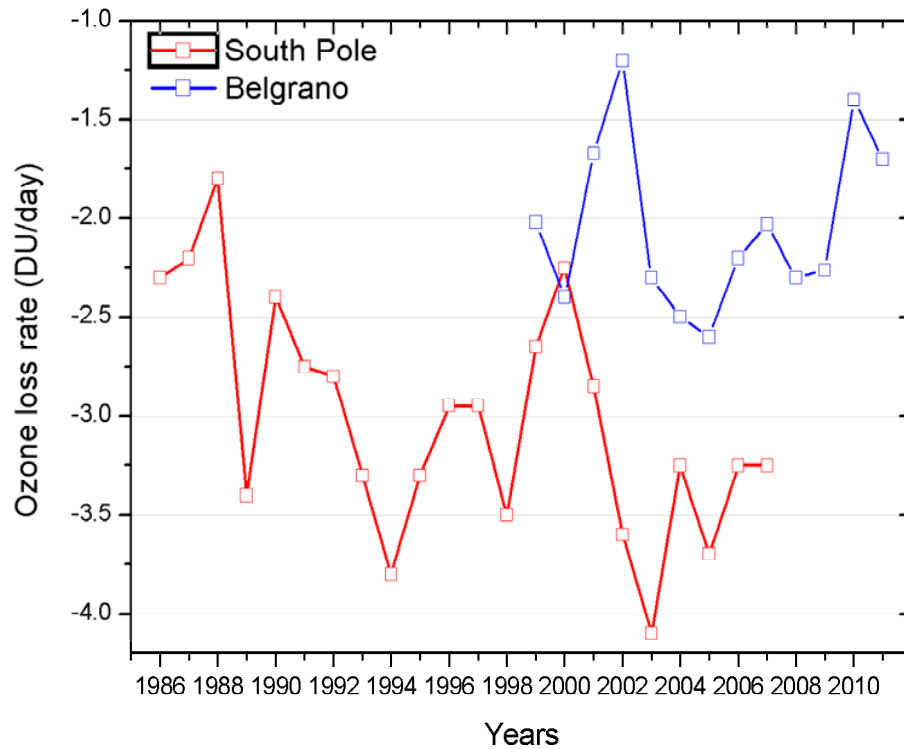


Fig. 8. Time series of ozone loss rate at Belgrano (blue line) and at South Pole (red line) stations.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

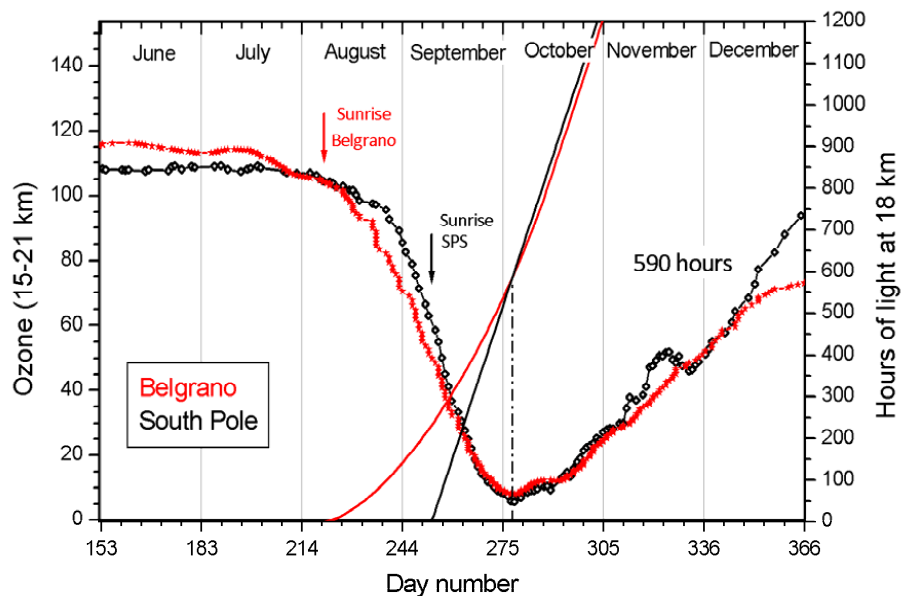


Fig. 9. 1999–2009 mean values of the ozone partial column for the 15–21 km layer (left scale) for Belgrano (red stars) and SPS (black diamonds). Solid lines represent the accumulated hours of light for both stations (same colour code, scale at the right side).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic ozone variability inside the polar vortex

M. C. Parrondo et al.

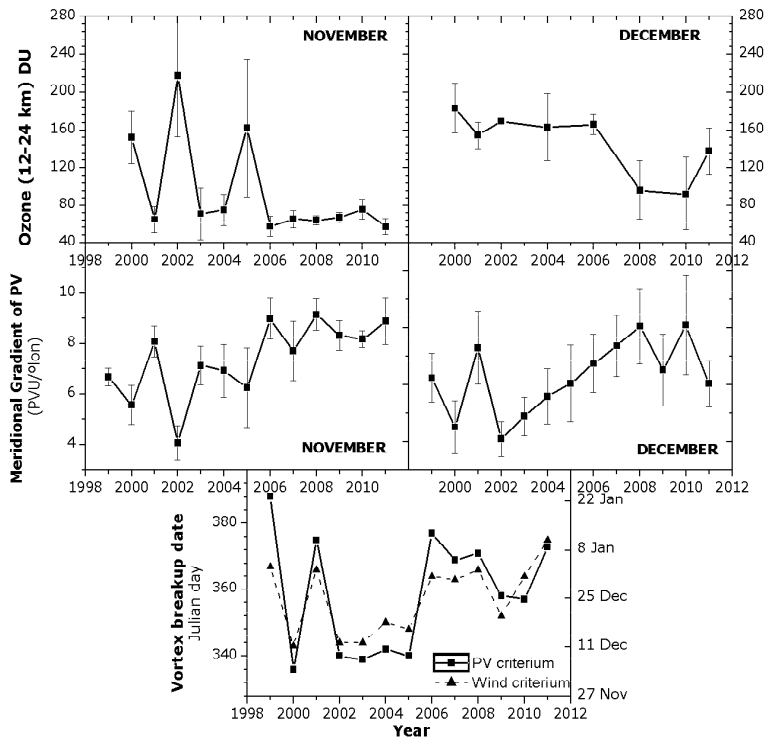


Fig. 10. Top panel shows integrated ozone column in the region 12–24 km in November and December. The vertical error bars indicate one standard deviation. Mean meridional gradient (60° – 90° S) of potential vorticity at the isentropic level of 475 K is displayed in mid-panel. Lowest graph presents the day of the final breakdown of the Antarctic polar vortex from 1999 to 2011 based on Black et al. (2006) (squares) and Waugh et al. (1999) (triangles) definitions.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

