Response to referee #1

We appreciate the positive analysis of the reviewer and his constructive recommendations which contributed to improve the quality of the manuscript. We comment below all of them and have modified the manuscript accordingly when required

1. There is no major new discovery from this analysis of the data. If the authors cannot find one, and I have nothing to suggest, then the manuscript should contain a lot more statements to say "this confirms...". They should also say why this is a major and important new data set by contrasting it with similar data sets of longer duration from Neumayer and South Pole.

The three referees have mentioned the lack of new results related to chemical ozone destruction in the Antarctic region. Vertical ozone profiles are scarce in the Antarctica, especially in the core region in winter and spring. Ozonesoundings from stations well inside the polar vortex during the ozone hole period have been analysed. Results obtained by comparing ozone loss rates in both stations yield valuable information to confirm relevant aspects about transport in the core of the vortex which up to now only chemical-transport models have been provided. We have also included more statements comparing our results with similar previous works.

2. Section 4.1 discusses the lack of seasonal evolution in total ozone column, but we are not shown this evolution, even in the partial ozone column whose annual variability we are shown. This evolution and its error are important quantities, helping to identify descent and chemical depletion as later discussed in analysis of profile data. The manuscript should include a figure of this evolution, and a table of the seasonal trends and their error bars.

Seasonal evolution of partial O3 in the 15-21 km layer was already shown in figure 2. Total column seasonal evolution from ozonesondes are, however, not reliable since, as mentioned in the text, balloon burst altitudes are very variable depending on air temperature, balloon condition and ground handling. O3 integration by extrapolating to the upper stratosphere is carried out for Brewer comparison, but just as Quality Control (according to Ozonesondes Standard Operating Procedures). We are not confident enough for using total ozone from ozonesondes, particularly on cold months. Figure C shows the monthly mean total ozone column obtained form sondes. Grey area indicates one standard deviation.

3. We are not told of any data bases where the individual data values and the various climatologies shown in the paper are lodged or will be lodged, so the rest of us can make use of them. There appears to be no Supplementary Data that might contain the values. This is important primary information and if it is not deposited at NDACC, WODC or a SCAR data centre, it should be. This would also then be a significant improvement to South Pole data, which is only available in summary form.

All individual ozonesounding files are stored in the Nacional Polar Data Centre as the Scientific Committee on Antarctic Research (SCAR) recommends. In addition, Belgrano ozonesounding station is in the way to become part of the NDACC. Data will be stored there soon.

4. Important details, essential in a serious analysis of the data, appear to be absent:

(a) there is very little detail of how ozone loss and loss rates are calculated, in the text or in the captions to Figures 4, 5 or 8 - we are not told from which date to which;
(b) there are no details about how descent rates are calculated (quoted in the Conclusions), from which level to which level, or from which date to which date.
(c) the ozone recovery in the late winter is discussed in the earlier text and in the last paragraph of the Conclusions, but there are no details of how it is calculated, nor from which date to which date.
For any unknown reason, this part was removed in the last version of the manuscript. We have now included it as a new section in the methodology.
5. Section 4.4 misses a major point of my work on the edge region of the vortex, started in Lee et al. (2001) and concluded in Roscoe et al. (2012). The mixing within the core of the vortex is good but not perfect; ozone-poor air takes about 12 days to travel from 78_S to 90_S after the terminator reaches the outside of the vortex core, so we would expect the black curve in Figure 9 to lag the red curve by about 12 days in late August, as shown. This process can be clearly seen in the model calculations of Figure 7 of Lee et al. (2001), reproduced in colour in Figure 1 below. Here, accumulated ozone loss at 70 to 75_S in the vortex core starts soon after the arrival of sunlight there, but mixes to the Pole ahead of the movement of the terminator. At 78_S and poleward, the contours in Figure should be seen as tracer contours, thereby expressing mixing. Contours move from 78_S equivalent latitude to 88_S in just over 10 days, as observed in Figure 9 of the current manuscript. Finally, by the end of September, all the vortex has been exposed to sunlight for over 12 days, so the amounts of ozone loss at 78ºS and 90ºS should be equal, as observed in Figure 9 of the current manuscript. Such a discussion should replace much of the current content of Section 4.4. Minor comments:

We thank the referee#1 for drawing our attention of the Lee et al. 2001 and Roscoe et al. 2012 papers which deal on the poleward transport of O3 depleted air using a 3D chemical-transport model, and for the color plot supplied. Accumulated O3-loss at 480K level model results (figure 5 in Lee et al 2001) agree with our observations in terms of time required for air-masses to move from 78ºS to 90º and in the coincidence in time of both stations to reach the complete destruction, thus providing an explanation to the figure 9 features. Therefore we have followed the referee suggestion of quoting the Lee et al 2001 paper for interpreting the observations. New section 4.4. text is as follows:

Ozone loss rates from Belgrano have been compared with those obtained for SPS (Hofmann et al., 2009) in order to examine the vortex spatial homogeneity. Calculations have been carried out for the month of September to make data directly comparable. Results (Fig. 8) show larger ozone loss rates at SPS by as much as 25% for the 1999–2007 overlapping period. Such a large difference in OLR between two stations located clearly inside the Antarctic vortex was not an expected result. In order to find where the origin of such differences is, we have compared the evolution of stratospheric temperatures in both stations. 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 not significant compared to the overall period of potential PSCs over both stations, from the end of May to beginning of October (about 16-17 weeks) (not shown). Therefore, they can not justify the differences in ozone loss rates found. Figure 9 displays the mean value of the ozone partial column in layer II but with the SPS data included. In both stations, a slow decline of ozone is observed before the sunlight reaches the stations, being a delayed about 10-12 days in SPS. As we mentioned before this ozone reduction is motivated by transport of ozone-depleted air from lower latitudes where the *ozone had already started.. The delayed observed on SPS is motivated by the time the ozone-poor air takes to travel from 78ºS to 90ºS, according to Lee et al. (2001). These observational results are in excellent agreement with the evolution of losses versus latitude and time computed by the SLIMCAT 3D chemical-transport model for the year 1996 and 480 K isentropic level (Lee et al., 2001). Moreover, the model also shows that accumulated ozone loss becomes equal at a equivalent latitude poleward of -74º by the beginning of October, as found in the observations. Sunrise at a height of 18 km over Belgrano coincides with the change in the slope of the ozone loss rate toward larger values, starting the phase II, where ozone loss rate is almost linear. As long as the sunlight returns to the deep vortex, ozone depletion accelerates by chemical reactions. Therefore, the ozone reduction by mixing of air with less ozone content in SPS gets faster. In SPS sunlight reaches the station 32 days later than in Belgrano. At this time, ozone has been already reduced by almost a half of the pre-ozone hole conditions. Accumulated solar radiation during the first four weeks after sunrise in both stations is quite different. In Belgrano is about 200 hours, while in SPS is 668 hours. Larger rates of accumulated light could lead to activate more halogen compounds in SPS. Santee et al., (2008) found a positive chlorine gradient toward the pole for this season by analysing AURA- MLS data. Therefore, more activated chlorine in SPS could be responsible of the higher ozone loss rate. As a consequence of the larger SPS ozone loss rates, the complete destruction takes place simultaneously at both stations by the beginning of October.*

6. The words “region” and “layer” are used alternately for the same quantity, namely the layers defined in Figure 1. This is dangerous as readers may think you are referring to different things. It is yet more dangerous as “region” can also refer to the horizontal, so is ambiguous. Change “region” to “layer” throughout, including the panel of Fig. 1.

The word “region” has been changed by “layer” throughout when we are referring to the vertical layers defined in Figure 1.

7. Section 4.1 and Figure 2 do not tell us what interpolation is used in Figure 2. Clearly these are not the monthly-mean values defined in Section 4.1 (though the figure caption leaves us guessing as to whether this is what they should be). Furthermore, the character of the figure suggests that some vertical smoothing was also used, but we are not told in either the text or the caption.

For each sonde, mean ozone and mean temperature were calculated in layers of 500 m and monthly profiles were obtained as the mean of these profiles. Figure 2 was obtained from the monthly mean ozone and temperature profiles from surface to 30000 meters in these layers.

8. What is the statement in Section 4.1 that year to year variations “tend to cancel” in a climatology supposed to mean? Such variations are completely absent, by definition.

Sentence has been removed, it was an obvious remark

9. The end of Section 4.1 and paragraph 1 of the Conclusions assert that “By the beginning of March the lower stratosphere remains essentially isothermal”. Apart from the contradiction in the wording “By the beginning, it remains”, which presumably should be “From the beginning”, this is not the case by the normal meaning of isothermal. Isothermal normally refers to the vertical temperature gradient being zero, which is far from the case at the

beginning of March. Presumably the authors mean that the temperature in the lower stratosphere does not change after the beginning of March: if so, they should say so and give an end date; if not they should say what they do mean and ensure that Figure 2 does indeed show it.

It was a language problem. The lower atmosphere is essentially isothermal (vertical gradient near zero) in summer (January to beginning of March) in the 12-30 km layer as can be seen by the almost vertical isotherms on that period. We have tried to make the last sentence of 4.1. more clear:

"From the beginning of January to March the lower stratosphere is progressively cooling-down but remains essentially isothermal in the 12-30 km layer"

10. In paragraph 1 of Section 4.2, the authors mis-state the relevant conclusion of my work in Lee et al. (2001) and Roscoe et al. (2012). They should say that a low but not negligible mixing takes place between the edge region of the vortex and the core, not "inside the vortex" as given. The relevant mixing is of air from lower latitudes than the vortex core. Furthermore, the actual quote is from Roscoe et al. (2012) and said that the mixing is "small but not zero"; in Lee et al. (2001) we did not discuss whether there was non-zero mixing.

We have taken into account Lee et al. (2001) and Roscoe et al. (2012) works. The paragraph is now:

"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 low but not negligible mixing takes place between the edge region of the vortex and the core (Roscoe et al., 2012)".

11. The final sentence in Section 4.2 is not obvious from Figure 3, where there is no height information. Instead it can be better seen in Figure 2. The final sentence of Section 4.2 is an important point because some past workers have asserted that such an increase in the total or partial ozone column before the final warming in the lower stratosphere is evidence of de-activation of chlorine compounds allowing a chemical recovery, rather than almost exclusively caused by the descent of vortex collapse as shown by Figure 2.

We have eliminated this sentence as it was clearly a feature of figure 2.

12. Section 4.3 paragraph 2 asserts that Figure 5 shows the main pattern in interannual variability of ozone loss rate is observed at all levels. This is only true if 2002 is included. Hence the follow-on conclusion that loss rates are mainly affected by deep vortex structure is only true of 2002, as expected in that year, and that in other years loss rates are NOT affected by deep vortex structure, contrary to the assertion.

Year 2002 is a clear example to assert that the anomalous behaviour of the polar vortex is reflected on ozone loss rates lower than the mean rate obtained for the 13 years in each layer. We want to highlight that year to year variability of ozone loss rate at each layer shows a similar pattern. This fact can observed from the standardized anomalies series of ozone loss rate at each layer plotted in figure B. The sign (positive/negative) of the anomalies are normally quite similar each year at all layers. Of course, several factors influence the year to year ozone loss rate as the behaviour of the stratospheric polar vortex, and it seems that all affect in the same direction in each layer.

13. What evidence is there that stratospheric minor warmings, in the plural, occur at higher altitude in Antarctica (p15673 line6)? There is evidence of one in July 2010 cited later on p15673, and to my knowledge that is all.

Minor warmings in the winter South Hemisphere are not as common as in the North Hemisphere but are not exceptional. There is information of minor warmings in 2004 and in 1998. Laat and Weele (2011) asses "The strongly reduced Antarctic ozone hole destruction in 2010 and 2004 is directly related to SSWs occurring during the polar winter.

14. The paper is contradictory about whether ozone loss rate is positive or negative if ozone is being lost, starting on p15673 line 17 (negative), extending to Figure 4 righthand vertical axis (positive), and other figure axes (negative). It is clearly a positive quantity if ozone is being lost, so text and figures should be amended accordingly.

We have to unify the criterion for the ozone loss rate. We consider a positive quantity when ozone has been lost during the period considered. Right-hand vertical axis in figure 4 does not change. Text and figures 5, 7 and 8 have changed accordingly.

15. Surely, the argument in p15674 lines 10 to 18 that more winter ozone should be correlated with less ozone loss is incorrect. More total ozone in winter implies that more descent has occurred during the previous year's meridional transport by the Brewer-Dobson circulation. This would lead to more HCl being brought down to altitudes of PSCs, for conversion to reactive chlorine, and so to more ozone loss. This was Joe Farman's rationalisation for his famous $10 bet in 1988 as to whether the ozone loss that year would be small or large, a bet that he won.

The old figure 7 could lead confusion as the ozone loss rate were negatives. New figure 7 clearly shows that largest O3 rates are correlated to more ozone in winter which is in agreement with referee comment.

16. Ozone recovery was also identified from station data by Kuttippurath et al., ACP 2013, a paper he was nice enough to put my name on. This should perhaps be included in the last paragraph of Section 4.3.

The paper was not yet published when this manuscript was submitted. We have included it now.

17. The caption to Figure 1 does not say over what years these are mean profiles (presumably the 13 years of data but we are not told), nor over what period is "winter" (the text says 15 June to 15 July but we should be reminded). Nor does it say how the standard deviations are calculated – are they the standard deviations of the monthly means within the 13-year average, or the means of the standard deviations of the neardaily values within each month, or some other quantity?

We have completed the caption of figure 1. The new caption in figure 1 stands as::

Mean ozone profiles obtained from 13 years (1999-2011) at Belgrano station. a) Winter profile typical of pre-O_3 hole conditions for the period 15th June to 15th July (blue line). b) October-mean profile when ozone depletion is at maximum (black line). Shadowed areas *indicate one standard deviation of the monthly means within the 13-year average. The three layers of study are shown.*

18. If the ozone loss (DU) and the ozone loss rate (DU/day) in Figure 4 are measured over the same date intervals, why do the numbers written above each bar not scale with the red points? If they are not over the same date intervals, why not?

The numbers written above each bar indicated the total amount of ozone depleted using sonde data for the period from day 220 (8th of August) to 277 (4th October). However not each year we had a data the first and last day of the period, therefore the interval was not the same every year. We have recalculated the total amount of ozone depleted covering the same interval each year. Data have been obtained using the linear regression model of the linear fitting. Figure 4 has been update using these new data.

19. Why is 2009 data absent in Figure 4 yet present in Figure 5 and Figure 7?

In figure 4 data are based on total integrated column obtained from each sonde. Only when the sonde reaches altitudes over 17 hPa integration is reliable (Claude et al., 1987). In 2009 not enough sondes fulfilled the mentioned condition to evaluate ozone loss in total column.

In figure 5 and 7, lower heights are needed to get data for this figures, referring to layers I,II and III.

20. Figure 10 is far too small, its caption does not say why data is missing from December's upper panel in some years, it does not remind us that the layer 12-24 km is layers I+II+III of Fig 1, it does not say that what the standard deviation is of, the vertical axis of the middle panel says the units are PVU/_lon when they are PVU/_lat, and there are five other points in the figure and its caption worthy of editorial comment below.

Figure 10 has been improved according with referees remarks. Text in the caption has also been modified.

Editorial comments:
p15664 lines8 & 9 – should surely come after lines 10 & 11, not before. Done
p15664 line 26 – insert "place" after "took", replace "rises" by "rose". Done
p15664 line 26 – replace "up to" by "by" – one cannot have a quantity "up to" a range. Done
p15665 line 1 – delete "late" – 1985 is not the late 1980s. Done
p15665 line 21 – delete "in". Done
p15666 line 9 – insert "the" before "polar" Done.
p15668 line 24 – replace "deviation" by "deviations". Done
p15668 line 25 – replace "provide" by "provides" Done.
p15670 line 1 – insert "the" before "next". Done
p15670 line 19 – insert "in" before "summer". Done, the other referee suggests during
p15672 line 6 – insert "at the end of this phase" after "residual". Done
p15672 lines 6&7 – move the sentence "Typical.. values" to follow the next sentence. Done
p15672 line 17 – insert "to" after "respect". Done
p15672 line 21 – delete "about" or the range – "about 140 to 160" is a tautology. Done
p15672 line 24 – Charlton et al. (2005) is concerned with downward propagation of the 2002 sudden warming to the Antarctic troposphere, rather than the fact of the warming. There are many other 2005 papers that attest to the fact of the warming.

Two references have been included:

Newman, P. A., and E. R. Nash, 2005: The unusual Southern Hemisphere stratosphere winter of 2002. J. Atmos. Sci., 62, 614–628.

Roscoe, H. K., J. D. Shanklin, and S. R. Colwell, 2005: Has the Antarctic vortex split before 2002? *J. Atmos. Sci.*, **62,** 581–588.

p15673 line 5 – replace the ambiguous "contribution" by the unambiguous "standard deviation".

We have replaced contribution by the coefficient of relative variation defined as the standard deviation divided by the mean in % why is the data shown in the text.

p15674 line 4 – "ozone depleting substances" normally refers to the halon and CFC precursors, e.g. in the Montreal Protocol and its amendments. You mean the activated halogen compounds.

p15674 line 4 –delete "ODS" as the acronym is not used elsewhere. Done

p15674 line 5 – delete "sunlight available – this cannot influence year to year variability.

We agree with the referee, this factor has been deleted.

p15674 line 9 – insert "2002" – not all readers will realise which year is anomalous. Done

p15674 line 25 – replace "there is" by "". Done

p15674 line 28 – replace "larger" by "longer". Done

Fig. 3 caption – what are the black dots – the individual points for 13 years?

A new sentence has been inserted.

Figure 3. Seasonal evolution of the 1999-2011 mean ozone in the layer 15-21 km (30-points running mean as orange stars). Individual data from ozonesondes for 13 years are shown in black squares. 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 78ºS (thick blue line) and 70ºS (dashed blue line) in the stratosphere (25 km).

Fig. 4 caption – insert "(DU)" after "depleted"; replace "shown" by "written". Done

Fig. 6 caption – are these from ECMWF-Operational analyses, ERA-Interim reanalyses, or a mixture?

Temperature data used are ECMWF-Operational analyses truncated to T106 horizontal resolution (1.125º×1.125º)

Fig.7 caption – this must include the statement from the text that the R=-0.69 that is written in the figure panel only applies to data without 2002. Done

Fig. 10 caption – replace “Top panel shows” by “Top panels show”; replace “region” by “layer”; move “mid-panel” to start of third sentence and say “Middle panels show ...”; replace “Lowest graph presents” by “Lowest panel shows”; replace “Julian day” in the vertical axis of the lowest panel by “day of year” – Julian day is days since 1 January 4713 BC (see https://en.wikipedia.org/wiki/Julian_day).

Done