Evolution of ozone depletion on Antarctic and Sub-Antarctic regions (1979-2012)

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ABSTRACT

At the middle eighties, strong stratospheric ozone depletion during spring was discovered over Antarctica. Since then, the scientific community has put large efforts in performing studies directed to evaluate the magnitude and consequences of this depletion and to take the necessary measures to revert the situation to the scenarios before 1970. In 1987, the Montreal Protocol established a list of ozone depleting products and faced out policies. As consequence of these restrictions on ozone depleting substances, the ozone layer should start to recover in the 21st century. In order to study the evolution of the Antarctic ozone depletion, we analyzed the ozone hole area and mass deficit and seasonal total ozone column (TOC) minimum. We also performed a seasonal and bi-monthly analysis for TOC time series (1979-2012), at twenty Antarctic and Sub-Antarctic stations. The number of days inside the vortex (TOC below 220DU) per season (September-December) and for September-October and November-December were analyzed, fitting the time series with a second degree polynomial According to this study, ozone hole area would have peaked between 2001 and 2002 ($R=0.91$, $p<0.01$), while the minimum TOC would have occurred between 2000 and 2001($R=0.91$, $p<0.01$). Mass deficit is only provided since 2005 and it showed a decrease since then, although ot statistically significant as consequence of the short time series. From the 20 analyzed stations, 80% showed that the number of days per season inside the vortex peaked between 2000 and 2003 and for 55% of the stations the number of days inside the vortex for September-October peaked between 1999 and 2004.

Ozone Depletion, Antarctica, Ozone Hole, Stratospheric Ozone

1. INTRODUCTION

At the early seventies, the first studies alerting on the possibility of depletion in the ozone layer, because of anthropogenic emissions, appeared. In 1971, H. S. Johnston warned about the possibility that, an increase in the number of commercial supersonic airplanes could damage to the ozone layer[1] and in 1974, M. Molina and S. Rowland alerted on the effect that chlorofluorocarbons (CFC) could have on this layer[2]. Later, in the middle eighties, an analysis of ground measurements performed by the British Survey, revealed strong stratospheric ozone depletion, during spring, at Halley Bay, Antarctica, which was called the “ozone hole”[3].

After that discovery, the scientific community put large efforts in performing atmospheric and biological studies, including human health, directed to evaluate the consequences of this phenomenon, and in taking the necessary measures to revert the present situation to scenarios before 1970[4-14].

In 1985, the Vienna Convention to Protect the Ozone Layer was held. This meeting produced a general international agreement, which allowed the beginning of negotiations to take specific measures on the compounds that caused ozone depletion. In 1987, the Montreal Protocol established a list of ozone depleting products and faced out policies. The measures proposed in the Montreal Protocol were, then, strengthened by the Amendments of London (1990), Copenhagen (1992) and Montreal (1997).

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Satellite and ground based data indicate that ozone destruction inside the polar vortex has been increasing since late seventies and probably earlier. Destruction rate was larger until the middle nineties, slowing down in the last decade. In the mid-1990s ozone depleting substances (ODSs) started to decline, globally, in the troposphere and, later in the stratosphere[14]. As a consequence, TOC would increase, but, unfortunately, natural variability, observational uncertainty and temperature decreases due to climate change, would make it difficult to attribute the TOC increae to decreases in ODSs. According to models, recovery of the ozone layer would start around year 2010, but, because of the modulation imposed by natural variability, the recovery trend would not be detected immediately[12].

In this paper, we analyze different parameter to evaluate the evolution and present situation of ozone depletion over Antarctic and Sub-Antarctic regions.

2. DATA AND METHODOLOGY

Two parameters are usually considered to evaluate the "ozone hole": a) Area, which is defined by the area with total ozone column bellow 220DU and, b) Minimum TOC between 60 and 90ºS. In this analysis, the mean ozone hole size for 07 September–13 October, the minimum of mean TOC for 21 September–16 October for the period 1979-2012[15] and Mass deficit (2005-2012)[16] time series have been fitted with a second degree polynomial, and the first derivative equalized to zero, in order to determine when the time series showed its maxima or minima, depending on the parameter under consideration.

In addition, with the aims of obtaining more detailed information, we analyzed total ozone column at 20 Antarctic and Sub-Antarctic stations (Figure 1) for the period September 1st to December 31st for each season, from 1979 to 2012 (all stations except Byrd, which includes data 1979-2011. Data for TOC was obtained from TOMS (Total Ozone Mapping Spectrometer) on board of satellite Nimbus-7 (NASA)[17] from 1978 up to 1993, TOMS/METEOR-3 from 1993 to 1994[17] and TOMS/Earth Probe from 1996 to 2004)[18] Level 2, in all cases. Data since January 2005 is from the OMI instrument (KNMI/NASA) onboard the Aura satellite[19]. For compatibility, data OMTO3d Level 2 has been used, which was processed in a manner similar to the TOMS data from earlier satellites. Daily average values were calculated when more than one value per day were provided by the satellite.

The limit of the ozone hole (vortex) is considered when TOC is bellow 220DU. In order to analyze the evolution of the Antarctic ozone depletion, at each of the stations, the number of days inside the vortex was accounted for a) the season (September-December), b) September- October (S-O) and c) November-December (N-D). Data was then normalized for the total number of measured days. Only months with more than 80% of data were considered.

The time series resulting from normalized seasonal number of days bellow 220DU for all years, was fitted with a 2nd degree polynomial equation. The first point of the time series was the year previous to the first non zero value. Then, the year when the curve maximized was obtained.

Residuals were analyzed using Durbin-Watson test[20] and, in addition, visually inspected.

The same procedure was followed to analyze the time series for S-O and N-D.

3. RESULTS

The time series of mean ozone hole area for 07 September–13 October and the minimum of mean TOC for 21 September–16 October, for the period 1979-2012[15] are shown in Figure 2 a and b. Mass deficit time series (2005-2012)[16] is shown in Figure 2 c.

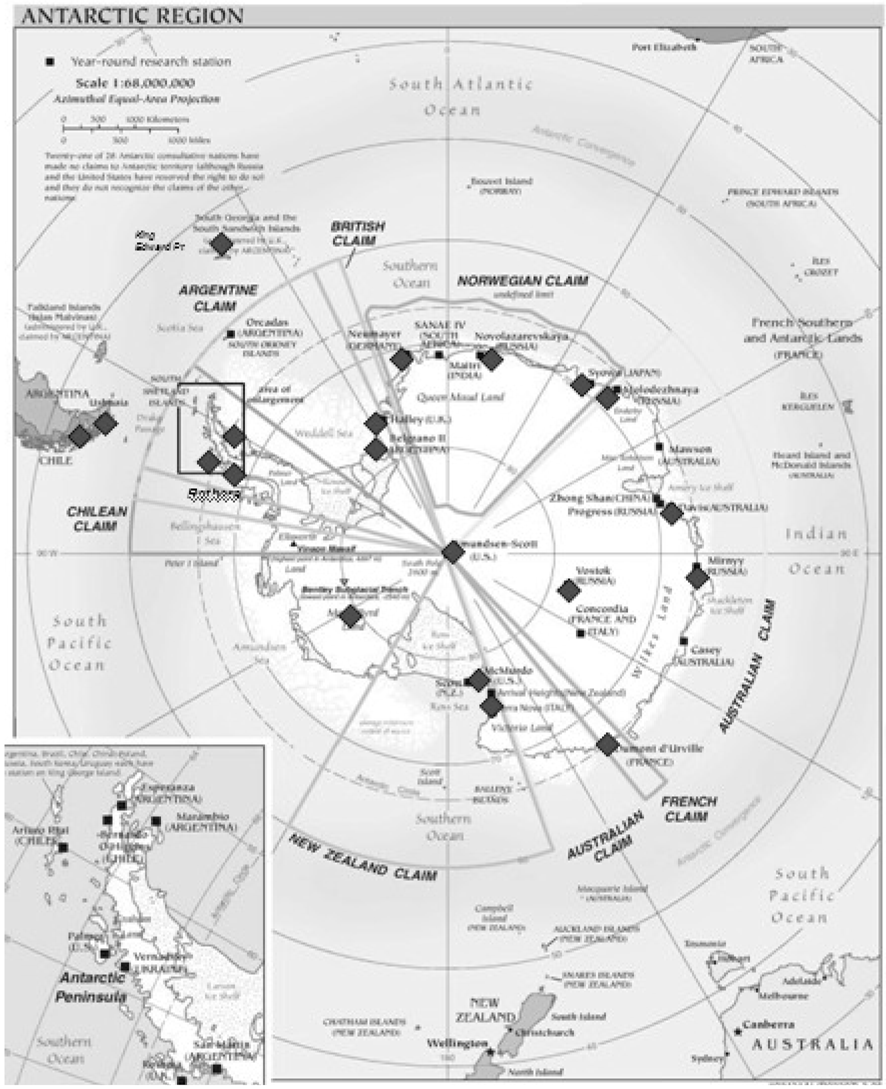
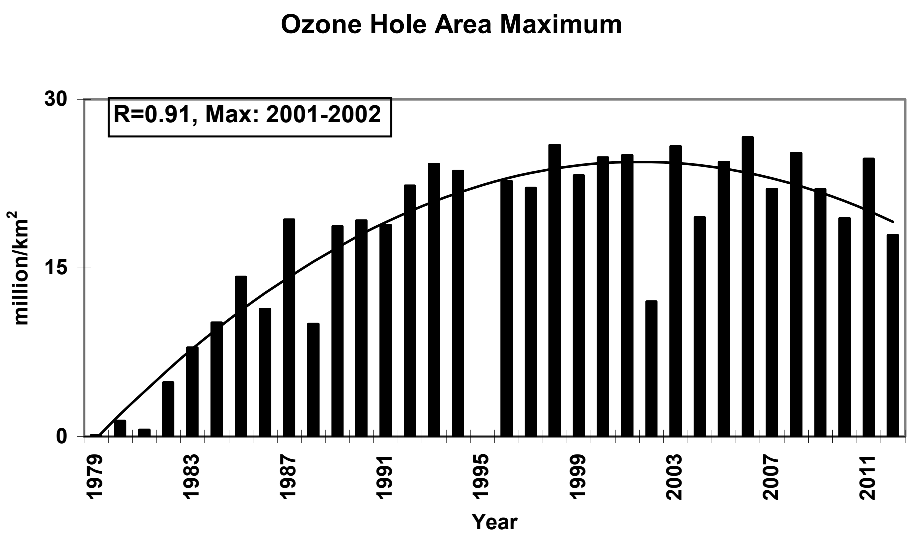


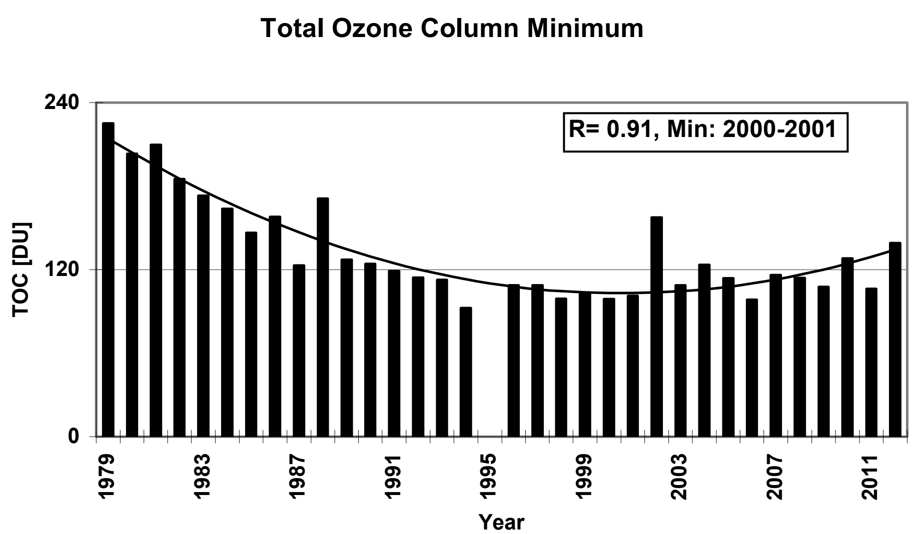
Figure 1: Antarctic and sub-Antarctic stations considered in the analysis.

The area of the "ozone hole" has increased rapidly from the early eighties up to the middle nineties, with large year-to-year variability, reaching a maximum of 26.6 million km^2 in 2005 (Figures 2a). Nevertheless this maximum did not differ considerably of values observed in 1998 (25.9 million km^2) or 2003 (25.8 million km^2). Minimum total ozone column showed a fairly mirroring behaviour, with a minimum value of 92.3DU in 1994 (Figure 2b), also showing large variability. A second degree polynomial fitting was used to better understand the evolution in time. According to these fitting, the maximum of area would have occurred between 2001 and 2002 ($R=0.91$, $p<0.01$), while the minimum TOC would have occurred between 2000 and 2001 ($R=0.91$, $p<0.01$). Durbin-Watson and visual test of the residues confirm the validity of the results. Mass deficit is provided only since 2005[16] (Figure 2c) and, the second degree fitting curve showed a maximum between 2005 and 2006, although the result is not statistically significant as consequence of the reduced number of years of the time series.

The results for seasonal analysis of the Antarctic and Sub-Antarctic stations provided in Figure 1 are shown in Table 1 and summarized in Figure 3. In the table, "Year Peak" means the year when the seasonal number of days bellow 220DU maximized, according to the first derivative of the second degree polynomial, R: is the square root of the coefficient of determination, p is the probability that the result was obtained by chance and "Residuals" is "YES" only if the Durbin-Watson and the visual analysis show no autocorrelation of the residuals. When p>=0.05, in the table, the result was considered statistically not significant (N.S.). Results in Table I Figure 3 show that for 16 stations (80%) the seasonal number of days bellow 220DU peaked between 2000 and 2003, one in 2005-2006 and only for three stations the result was statistically not significant.



a)



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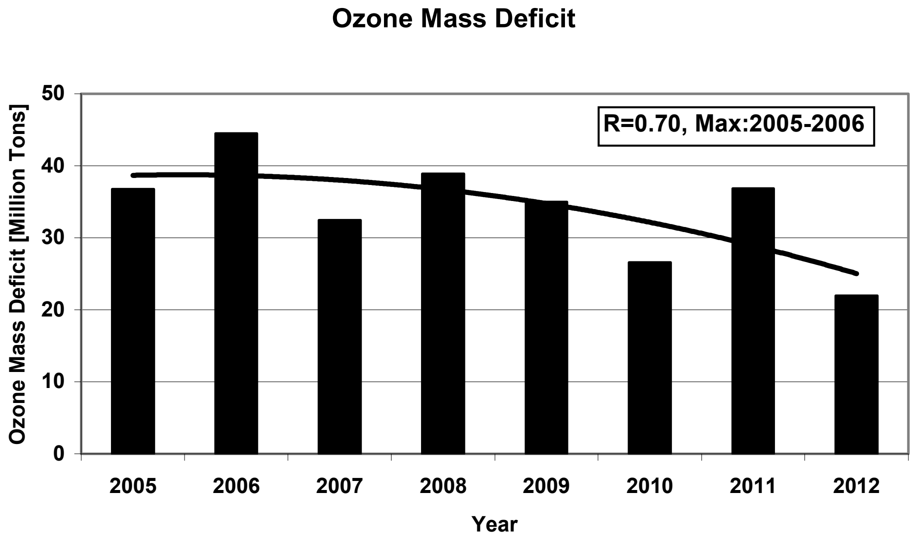

c)

Figure 2: a) Mean ozone hole area for 07 September–13 October, b) Minimum of mean TOC for 21 September–16 October, c) Mass deficit

Station	Year Peak	R	p	Residuals
Amundsen Scott	2000-2001	0.65	<0.01	YES
Arrival Heights	2001-2002	0.67	<0.01	YES
Belgrano	2000-2001	0.81	<0.01	YES
Byrd	2000-2001	0.77	<0.01	YES
Davis	2002-2003	0.66	<0.01	YES
Dumont dUrville		N.S.		
Halley Bay	2000-2001	0.83	<0.01	YES
King Edward Point		N.S.		
Marambio	2001-2002	0.82	<0.01	YES
Mc Murdo	2001-2002	0.66	<0.01	YES
Mirny	2002-2003	0.51	<0.05	YES
Molodeznaya	2002-2003	0.75	<0.01	YES
Neumayer	2002-2003	0.74	<0.01	YES
Novolazarevskaya	2002-2003	0.77	<0.01	YES
Palmer	2001-2002	0.75	<0.01	YES
Punta Arenas		N.S.		
Rothera	2000-2001	0.78	<0.01	YES
Syowa	2002-2003	0.76	<0.01	YES
Ushuaia	2005-2006	0.57	<0.02	YES
Vostok	2000-2001	0.72	<0.01	YES

Table 1: Results seasonal analysis. Station, year when the seasonal number of days bellow 220DU maximized, square root of the determination coefficient (R), p and Durbin-Watson and visual analysis of residuals. N.S. means that the ANOVA denotes $p \geq 0.05$

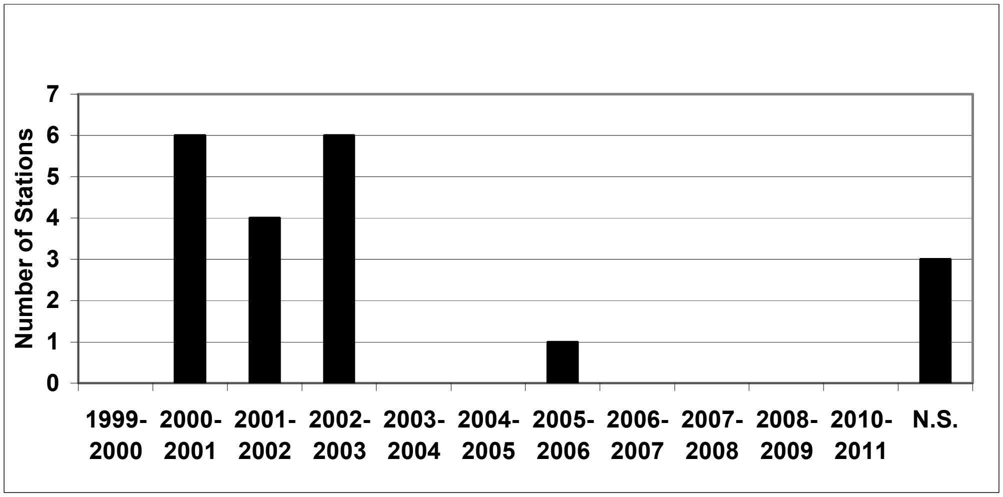

Figure 3: Number of station versus year when the seasonal maximum number of days bellow 220DU occurred. N.S.means that the ANOVA denotes p≥0.05

Station	Year Peak	R	p	Residuals
Amundsen Scott	1998-1999	0.69	<0.01	NO
Arrival Heights	2000-2001	0.68	<0.01	YES
Belgrano	2000-2001	0.86	<0.01	NO
Byrd	1999-2000	0.82	<0.01	YES
Davis	2002-2003	0.67	<0.01	YES
Dumont dUrville		N.S.		
Halley Bay	2000-2001	0.88	<0.01	NO
King Edward Point		N.S.		
Marambio	2001-2002	0.82	<0.01	YES
Mc Murdo	2000-2001	0.68	<0.01	YES
Mirny	2001-2002	0.50	0.05	YES
Molodeznaya	2003-2004	0.79	<0.01	YES
Neumayer	2002-2003	0.78	<0.01	NO
Novolazarevskaya	2003-2004	0.82	<0.01	NO
Palmer	2001-2002	0.81	<0.01	YES
Punta Arenas		N.S.		
Rothera	2000-2001	0.84	<0.01	YES
Syowa	2003-2004	0.81	<0.01	YES
Ushuaia	2002-2003	0.54	<0.01	YES
Vostok	2000-2001	0.64	<0.01	NO

Table 2: Results September-October analysis. Station, year when the seasonal number of days bellow 220DU maximized, square root of the determination coefficient (R), p and Durbin-Watson and visual analysis of residuals. N.S. means that p≥0.05

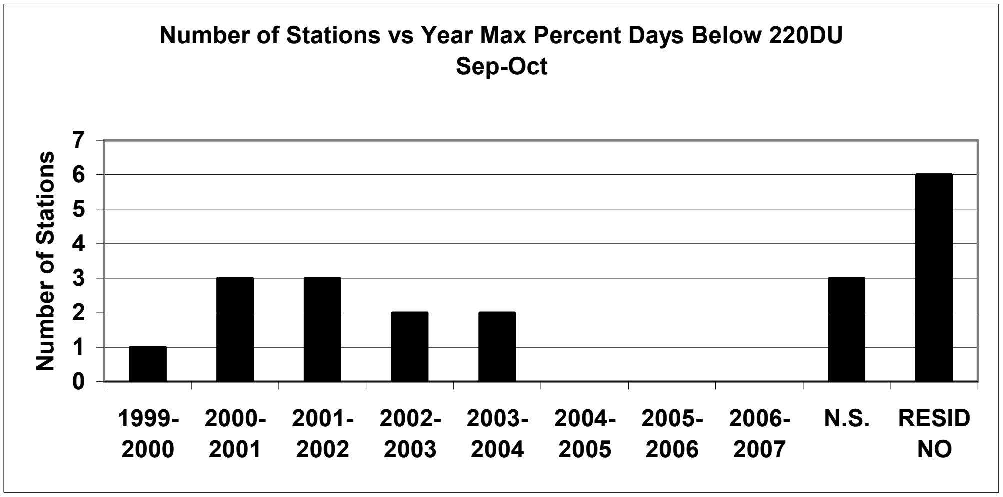

Figure 4: Number of station versus year when the seasonal maximum number of days bellow 220DU occurred. N.S. means that the ANOVA denotes $p \geq 0.05$ and RESID NO means that the residuals show autocorrelation.

The results for September-October (S+O) are shown in Table 2 and Figure 4. Although 17 stations showed results statistically significant ($p<0.05$), after the residuals analysis, six of the stations exhibited residuals autocorrelation. The final results showed that 11 stations (55%) presented a maximum of days bellow 220DU in S+O between 1999 and 2004.

For November-December (N+D), results were either statistically not significant ($p>0.05$) or the residuals analysis showed some auto correlation.

4. CONCLUSIONS

According to the analysis performed in this paper, the maximum of the ozone hole area would have occurred between 2001 and 2002 ($R=0.91$, $p<0.01$), while the minimum TOC would have occurred between 2000 and 2001 ($R=0.91$, $p<0.01$). Mass deficit of ozone inside the vortex would have a maximum between 2005 and 2006, although the result I this case is not statistically significant as consequence of the reduced number of years in the time series.

The seasonal analysis of 20 stations distributed in Antarctic and Sub-Antarctic regions showed that for 80% of the stations, the seasonal number of days bellow 220DU peaked between 2000 and 2003, one in 2005-2006 and only for three stations the result was statistically not significant.

For September-October, the number of days bellow 220DU would have peaked between 1999 and 2004, in 55% of the stations. For the other stations and for November-December, the results were either statistically not significant or the analysis of the residuals showed some autocorrelation.

It should be pointed out that, from this study, it cannot be determined if the observed results have a cause-effect relation with the decrease in ozone depleting substances (ODSs)..

The results are robust to present and it is expected be more robust as the time series become longer. Nevertheless, as consequence of the large inter-annual variability in the analyzed parameters, it is recommended to continue this analysis with future data to confirm that the evolution of the ozone hole follows the trend observed here.

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