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Analysis of the evolution of the Antarctic ozone hole size

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[1] The Antarctic ozone hole in the stratospheric layer has two basic parameters: depth and size. In this work the evolution of the ozone hole size (OHS) is analyzed using the monthly mean data for September, October, and November during 1982–2003. On the basis of the analysis of subsets of the data series we found signals of a reversal in the OHS trend during the period 1995–2003 for the months of October and November. On the other hand, the trends of the OHS subsets for the month of September show cyclical changes that approximately follow the variations of the geomagnetic *Ap* index and the 10.7-cm solar flux index. The detected beginning of the recovery process is a good test for models in order to match observations.

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1. Introduction

[2] The stratospheric ozone has suffered a substantial decrease in the Antarctic region at least during the last 22 years [e.g., *Stolarski et al.*, 1991; *Bojkov et al.*, 1990; *World Meteorological Organization* (*WMO*), 2003] producing a recurring ozone abundance depletion structure known as the Antarctic ozone hole. Conventionally, it is considered that there is an ozone hole when the ozone abundance is $\leq$220 Dobson units (DU) (1 DU = 0.001 atm cm) in a specific geographic place [e.g., *WMO*, 2003]. It is well known that the main cause of this reduction is ascribed to anthropogenic activity; however, it was originally suggested that the origin of the "hole" could be explained on the basis of solar cycles or purely atmospheric dynamics. These hypotheses became inconsistent with observed features of the Antarctic ozone hole [e.g., *Seinfeld and Pandis*, 1998]. Nevertheless, according to *WMO* [2003] and *Labitzke et al.* [2002] recent modeling studies report increased sensitivity of lower stratospheric ozone to the solar cycle compared with earlier modeling experiments, but any effect is still too uncertain to quantify, remaining somewhat speculative.

[3] The ozone hole has two basic characteristics, depth and size, which are inferred from the ozone abundance data. In addition to the well-established anthropogenic origin as the main cause for the ozone reduction, the ozone abundance is also affected by natural phenomena such as the solar cycle of ultraviolet radiation, volcanic eruptions, temperature interannual changes, atmospheric dynamics, large solar protons events, galactic cosmic rays, and the relativistic electron precipitation [e.g., *Jackman et al.*, 1996, and references therein]. All of them affect the ozone abundance to some extent, though it is not fully clear how these factors affect the ozone hole size (OHS). At present, the Antarctic ozone abundance models fit the observations quite reasonably, though some differences still remain; according to *WMO* [2003, section 3.5.3.1, p. 3.77] "comparisons between models and observations for ozone amounts near 60°S will give poor agreement if the ozone hole area is too small, even though the underlying physics of the model may be correct, and a model with a smaller ozone hole may evolve differently from that of the atmosphere because of transport and chemistry effects relating to radiative effects." Therefore, in order to contribute to the understanding of the evolution and the origin of the discrepancies between the modeled and the observed OHS, the area evolution is analyzed here. The analysis is made on the basis of the monthly average OHS as reported by the National Oceanic and Atmospheric Administration (NOAA) National Weather Services Climate Prediction Center for the years 1982 to 2003 (Southern Hemisphere winter summary 2003, Figures 4b–4c, available at http://www.cpc.ncep. noaa.gov/products/stratosphere/winter_bulletins/sh_03/index.html).

2. Data and Analysis

[4] When the Antarctic OHS is examined with very high resolution (daily data), it is hard to identify any behavior pattern in a long timescale. On the other hand, when data with annual resolution of the typical OHS are examined, the poor time resolution does not allow the recognition of a definite pattern. Therefore we have chosen to work with the monthly average OHS for the months of September, October, and November (Table 1), reported in the NOAA winter Summary 2003, for the period 1982–2003, where data are reported on the basis of the measurements of solar backscattered ultraviolet (SBUV) on Nimbus 7 and SBUV/2 instruments on NOAA Polar Orbiting Satellites. A description of the data sources is available in NOAA winter summary 2003, and for a discussion on the limitations and uncertainties of SBUV and SBUV/2 measurements, see *WMO* [2003, chapter 4, Appendix 4A].

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Table 1. Average Area of the Antarctic Ozone Hole Determined by the Area Enclosed by the 220-DU Total Ozone Contour During the Months of September, October, and November as Detected by SBUV on Nimbus 7 and the SBUV/2 Instruments on NOAA Polar Orbiting Satellites[a]

	Area, × 10^6 km^2		
Year	September	October	November
1982	2.6	2.7	1.1
1983	5.2	6.4	0.5
1984	7.4	7.4	1.2
1985	10.2	11.6	4.2
1986	8.3	7.9	0.2
1987	15.1	16.5	10.0
1988	6.4	3.0	0.0
1989	14.5	14.7	1.9
1990	16.8	14.9	8.5
1991	17.8	15.2	2.8
1992	16.9	14.8	6.8
1993	5.1	18.2	9.3
1994	20.5	15.7	3.7
1995	11.1	18.9	9.4
1996	20.1	17.4	11.4
1997	18.3	19.2	7.5
1998	25.3	20.6	12.4
1999	21.4	19.5	12.8
2000	25.0	16.2	3.0
2001	23.0	19.2	11.2
2002	10.8	5.6	0.2
2003	25.8	16.7	2.6

[a] Data correspond to the period 1982–2003 as reported by NOAA winter summary (where the description of data sources is available). See *WMO* [2003, chapter 4, Appendix 4A] for a discussion on the limitations and uncertainties of SBUV (solar backscattered ultraviolet) and SBUV/2 measurements. DU stands for Dobson unit (1 DU = 0.001 atm cm).

[5] Data for the years 1980–1981 are not considered here because in that reference there are no data available for September and November. As a first step of analysis we have computed the general trend of the OHS time series by the least squares method to determine lines of minimum dispersion. The slope of the line estimates the trend of the OHS growth in the studied period (1982–2003). The results for each month considered in the analysis are presented in Figure 1. In Figure 1 we can observe that during the month of September the OHS grows more rapidly in the time, in comparison with the months of October and November. In fact, the month of November shows small OHS growth rates in the studied period. No signals of the beginning of full ozone recovery can be seen from Figure 1 (full ozone recovery means return to the ozone levels in 1980), since the slopes are systematically positive; however, it is well known that the effective equivalent stratospheric chlorine (EESC) peaked in 1997 and then decreased in 1998 up to the present [e.g., *WMO*, 2003]. Consequently, a reduction in the Antarctic ozone hole parameters (depth and size) is expected. In fact, according to *WMO* [2003, section 1.8.3] "EESC provides a rough estimate of the timescale for ozone recovery." Hence, using the date of the systematical decrease of the EESC in 1998 as a time reference (departure point), from which a negative trend in the OHS is expected (OHS reduction), we have searched for the beginning of recovery in recent years analyzing the OHS trend (slope of the best fitting line) for the 6-year period (1998–2003). Then, we compared this trend with the slopes of the previous 6-year subsets (Table 2) to identify the changes in the trends that take place in lapses of 6 years within the timeframe.

[6] This subset analysis allows us to detect slope changes in short subperiods, which are more useful to detect screened changes in the behavior of OHS data than the analysis of the complete data set (1982–2003), because the bulk of the 2-decade data has a strong weight on the final trend. Furthermore, the analysis of the trend of 6-year subsets is better in order to find a long-term behavior, because it reduces the data "noise" produced by the yearly fluctuations of the OHS.

[7] To show the changes in the trends of the 6-year subsets, a plot of the slopes of the adjusted lines is illustrated in Figure 2. The error bars correspond to the standard error of the slopes according to the least squares method. The value corresponding to 2003 represents the slope of the 1998–2003 subset; the value for 2002 represents the slope of the 1997–2002 subset and so on.

[8] The slope of the OHS is negative for the considered subset periods 1997–2002 and 1998–2003 for all the analyzed months (Figure 2 and Table 2). However, for October and November it is negative since the subset period 1995–2000 up to the subset 1998–2003. In other words, the last four 6-year subsets for the months of October and November have negative slopes, which implies a regular tendency to the reduction of the OHS that begins at a certain year in the subset period 1995–2000. Besides, for the month of September the OHS reduction begins at a certain year between the subset period 1997–2002. However, taking into account that the previous results and subsequent implications may be influenced by the abnormal small OHS during 2002 [e.g., *Sinnhuber et al.*, 2003], we have proceeded to estimate the importance of these abnormal values of OHS. We have computed the OHS trends under two

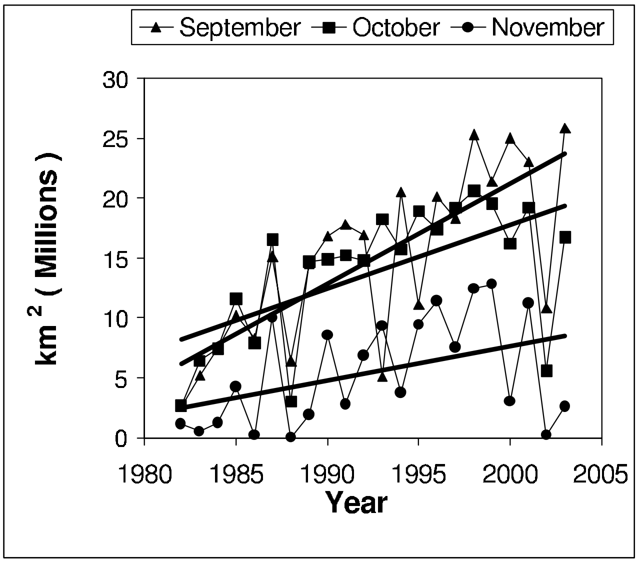

Figure 1. Ozone hole size (triangles, squares, and dots) and the global trends (1982–2003) for September, October, and November (bold lines) based on monthly average data, as reported in National Oceanic and Atmospheric Administration National Weather Services home page (see Table 1).

Table 2. Trends of the Ozone Hole Size (OHS) During the Considered Subsets in the Analysis, on Basis to the Monthly Average Data, as Reported by the NOAA National Weather Service Home Page (Winter Summary 2003)

	Slope, × 10^6 km^2/yr		
Six-Year Subset	September	October	November
1982–1987	2.131	2.220	1.331
1983–1988	0.777	0.189	0.569
1984–1989	0.883	0.551	0.020
1985–1990	1.226	0.669	0.474
1986–1991	1.734	1.240	0.297
1987–1992	1.300	0.809	−0.029
1988–1993	0.049	2.189	1.586
1989–1994	−0.171	0.414	0.440
1990–1995	−0.920	0.711	0.277
1991–1996	0.271	0.594	1.291
1992–1997	1.217	0.651	0.443
1993–1998	2.954	0.600	0.826
1994–1999	1.294	0.740	1.446
1995–2000	2.297	−0.166	−0.654
1996–2001	0.877	−0.031	−0.403
1997–2002	−1.166	−2.157	−1.426
1998–2003	−0.894	−1.663	−2.246

additional assumptions: (1) omitting the 2002 OHS values and (2) using the interpolated values (between 2001 and 2003 data) instead of the reported data. The results of such analysis are summarized in Table 3 and can be described as follows:

[9] Omitting the OHS 2002 values, the October and November trends remain negative, while September becomes positive but with a decreasing tendency. Using an interpolated value for OHS 2002, we again obtain negative trends for October and November; September becomes positive but with a decreasing value.

[10] Looking to the three scenarios of Table 3, we can appreciate that the confidence of negative values for the slopes of October and November is at least 82% (from 1995 to 2003), whereas that for September is at the most 56% (from 1997 to 2003), which occurs when the reported abnormal value for 2002 is considered. So the negative tendency of the slopes in October and November does not depend on the values employed for the 2002 OHS. On the other hand, for the month of September the negative tendency is sensitive to the value used for the 2002 data, but the slope changes of the 6-year OHS subsets show a kind of cyclic behavior in the three analyzed cases.

[11] In order to provide a timescale of the OHS trend evolution and seeking the origin of such a cyclical disturbance in the ozone abundance, we contrast in Figure 3 the OHS slope behavior of the month of September with the corresponding solar 10.7-cm flux and the geomagnetic index *Ap* (available at http://web.dmi.dk/fsweb//projects/wdcc1/indices.html). In Figure 3, note that the change of the slopes of the 6-year subsets follows approximately the variations of these monthly indices, except for the 1993–1998 subset. Also, we have computed the slopes using different subset period lengths (5 and 7 years), and the high value for 1993–1998 slope remains far from the solar indices pattern (Figure 4), implying that this high value in the slope does not depend on the subset period length used.

[12] These activity indices were selected as a first option because the variation of both are in the same timescale, they are available as equivalent indices (monthly) in the same time period, and there is a direct input of energy (by means of photons, fast particles, and electric fields) to the Antarctic atmospheric system. Such an energy input can potentially raise the temperature, affecting the physical conditions required for a substantial chemical ozone loss. It should be noted that there may be other factors influencing the OHS not taken into account here, such as variations in the planetary wave flux, which has an impact on the processes of transport and loss of polar ozone [*Weber et al.*, 2003].

3. Discussion

[13] The analysis of sensitivity applied in relation to the abnormal 2002 OHS value shows that our results with the

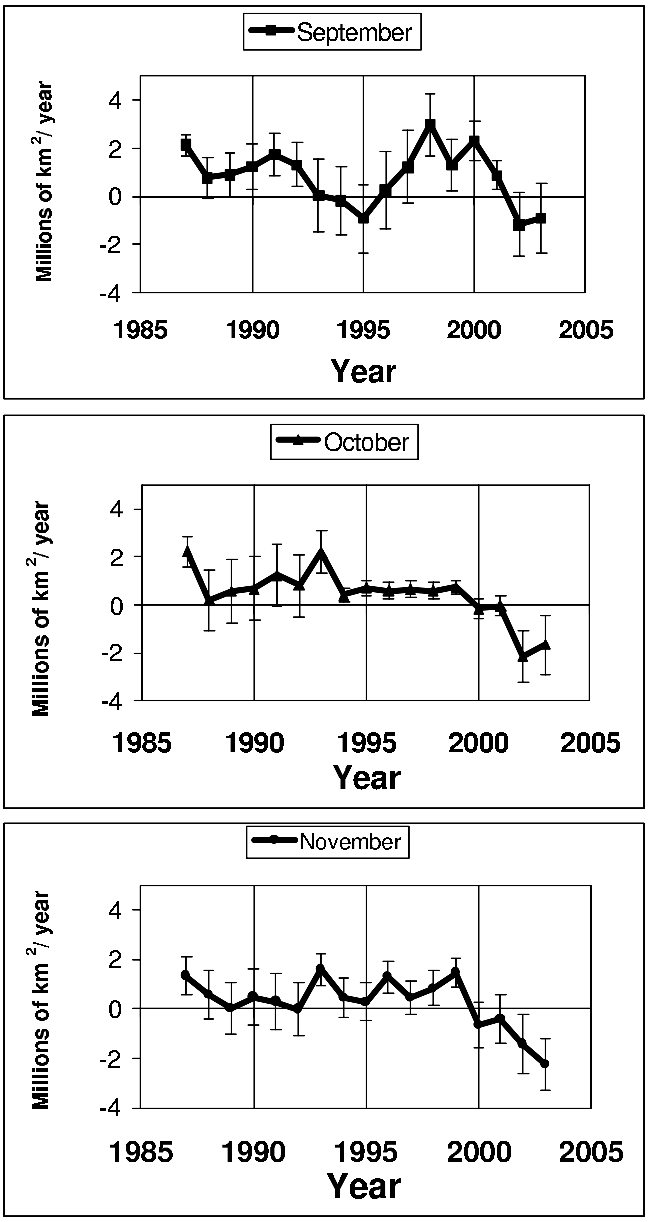

Figure 2. Changes in the slopes of the lines adjusted in each 6-year subset of the monthly average ozone hole size (OHS). (top) September, (middle) October, and (bottom) November, according to subset periods used in Table 2.

Table 3. Comparison of the Behavior of the OHS Trends Under Different Assumptions on the Abnormal Data in 2002 and the Corresponding Statistical Confidence of a Negative Tendency

	OHS, × 10 km^2	Six-Year Subset	Slope, × 10^6 km^2/yr	Confidence of the Negative Tendency, %
		September		
Using the current value of OHS 2002				
2002	10.8	1997–2002	−1.166	56[a]
2003	25.8	1998–2003	−0.894	56[a]
Using an interpolated value for OHS 2002				
2002	24.4	1997–2002	0.777	-
2003	25.8	1998–2003	0.271	-
Suppressing the value of OHS 2002				
2003	25.8	1997–2003	0.847	-
		October		
Using the current value of OHS 2002				
2002	5.6	1997–2002	−2.157	93.2[b]
2003	16.7	1998–2003	−1.663	93.2[b]
Using an interpolated value for OHS 2002				
2002	17.95	1997–2002	−0.393	85.2[b]
2003	16.7	1998–2003	−0.604	85.2[b]
Suppressing the value of OHS 2002				
2003	16.7	1997–2003	−0.509	82.1[b]
		November		
Using the current value of OHS 2002				
2002	0.2	1997–2002	−1.426	97.7[b]
2003	2.6	1998–2003	−2.246	97.7[b]
Using an interpolated value for OHS 2002				
2002	6.9	1997–2002	−0.469	94[b]
2003	2.6	1998–2003	−1.671	94[b]
Suppressing the value of OHS 2002				
2003	2.6	1997–2003	−1.054	91.44[b]

[a] Considering the negative slope found from 1997 to 2003 (see also Table 2).
[b] Considering the negative slope found from 1995 to 2003 (see also Table 2).

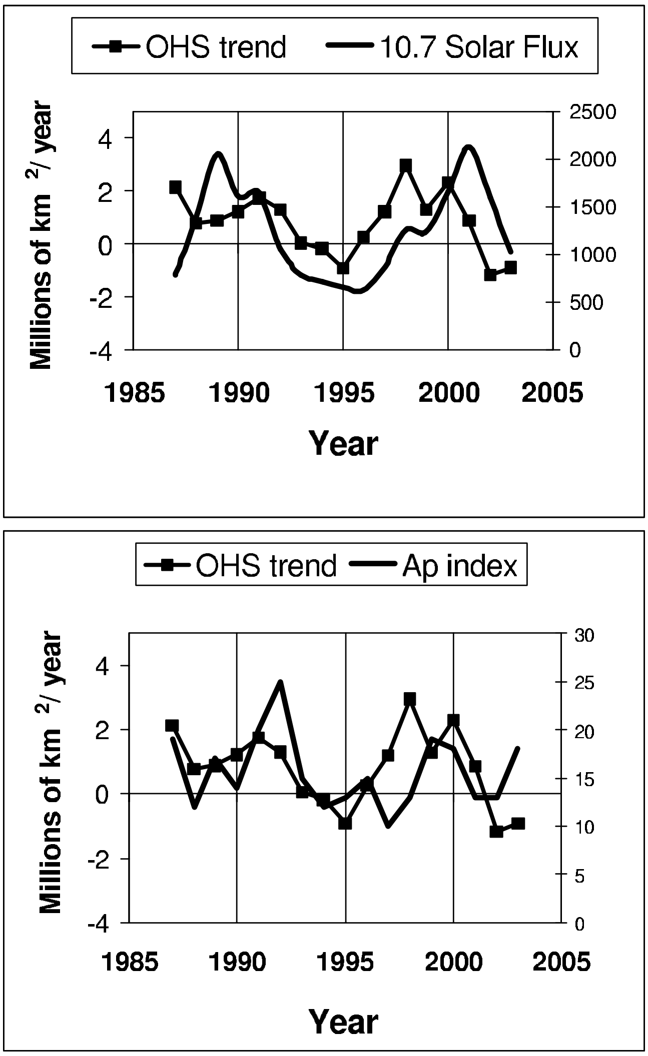

Figure 3. Changes in the slopes of 6-year subsets of the monthly average OHS data compared to the monthly means of the 10.7-cm solar flux index and the geomagnetic *Ap* index during the month of September.

reported data values are not very much affected. That is, even ignoring the 2002 value or with an interpolated value, the tendency to negative values for the October and November slopes is conserved, confirming in this way that the hole is undergoing a closing, whereas September becomes positive under the two alternative assumptions worked out in section 2. However, the same cyclical behavior in the trend is preserved. This cycle-like tendency behavior suggests the quasiperiodic contribution of additional factors. The fact that this effect is only found for the month of September reduces the possibility that the effect should be a consequence of systematic errors in the measurements. Otherwise, the same behavior of the slopes should be found in all the analyzed months.

[14] We have shown that the cyclic-like behavior is not affected whether or not the abnormal 2002 OHS values are taken into account. However, the negative tendency in the September trends (1997–2003) has a low level of confidence; in fact, the slopes become positive omitting OHS 2002 or using an interpolated value for that year. This indicates that it is highly probable that the OHS for September has not reached the maximum yet because it is still increasing (the trend remains positive for the last subset 1998–2003).

[15] With respect to the comparison with the considered solar activity and geomagnetic indices, it should be mentioned they do not follow exactly the variations in the slopes of the month of September. There is a deviation in the case of the 1993–1998 slope; however, it provides a referential timescale for the cyclical-like behavior.

4. Conclusions

[16] The evolution in the OHS during the months of October and November shows signs of a reversal OHS trend that we interpreted as the first steps of the processes toward the full ozone recovery, since it has not returned to its 1980 level yet. In these months the OHS tends to decline from a certain year between 1995 and 2000. This conclusion considered the so-called abnormal value of OHS during 2002, has at least 93% of confidence, and is not affected by omitting or replacing the abnormal value, in which case the confidence is at least 82%. The evidence of OHS evolution during September indicates that very probably the OHS has not reached the maximum yet, because the negative tendency found since 1997–2003 has a low confidence (at the most 56%) and it is very sensitive to the considered 2002 OHS value.

[17] The changes of the trends in the 6-year subsets of the OHS for the months of September show a cyclic-like behavior in the past 22 years that is not affected by the 2002 OHS considered value. These changes follow approximately the corresponding monthly variations of the geomagnetic *Ap* index and the 10.7-cm solar flux index, providing a timescale of such a variation. This coincidence encourages delving more deeply into understanding the possible underlying phenomena.

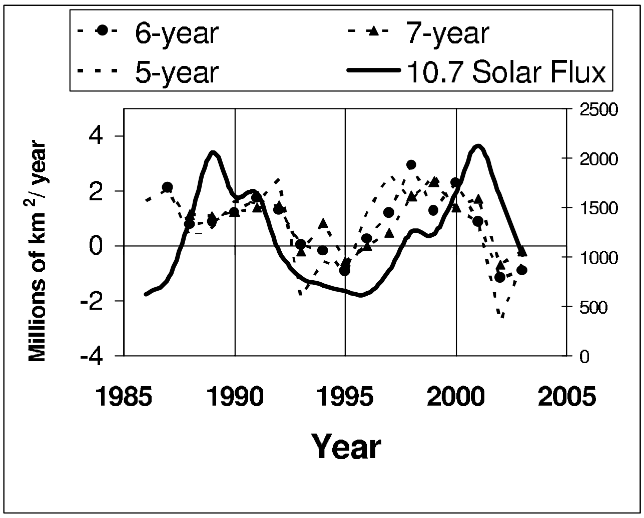

Figure 4. Changes in the slopes of the September OHS monthly average data for subsets of different period lengths (5, 6, and 7 years with dashed, dot, and triangle curves, respectively) in comparison to the 10.7-cm solar flux index.

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