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QUANTITATIVE CHARACTERIZATION OF THE ANTARCTIC OZONE HOLE

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ABSTRACT

The long-term evolution of the Antarctic ozone hole is studied based on the TOMS data (ver. 6) and the JMA data-set of stratospheric temperature in relation with the possible role of PSCs. The effective mass of depleted ozone in the ozone hole at its annual mature stage reached an historical maximum of 55 Mt in 1991, 4.3 times larger than in 1981. The ozone depletion rate during 30 days before the mature ozone hole does not show any appreciable long-term trend but the inter-annual fluctuations do, ranging from 0.169 to 0.689 Mt/day with the average of 0.419 Mt/day for the period of 1979 - 1991. The depleted ozone mass has the highest correlation with the region below 195 K on the 30 mb surface in June, whereas the ozone depletion rate correlates most strongly with that in August. The present result strongly suggests that the long-term evolution of the mature ozone hole is caused both by the inter-annual change of the latitudinal coverage of the early PSCs, which may control the latitude and date of initiation of ozone decrease, and by that of the spatial coverage of the mature PSCs which may control the ozone depletion rate in the Antarctic spring.

1. INTRODUCTION

The remarkable depletion of the ozone layer (so-called the ozone hole) has been appearing over Antarctica in the spring since the late 1970's. In order to study the complete mechanism for the long-term evolution of the ozone hole, which remains unexplained (Turco et al., 1989), it is required to establish quantitative measures which enable us to express the intensity of the ozone hole appropriately. In this paper, we tentatively define the quantitative measures to characterize the ozone hole evolution (hereafter called the ozone hole indexes) and examine the cause of the long-term evolution of the ozone hole.

2. DEFINITION OF OZONE HOLE INDEXES

The area of the ozone hole is defined as the area enclosed by the contour of 220 m atm-cm, south of 50°S. The threshold of 220 m atm-cm is taken as the value which had never appeared before 1980 as mentioned by Newman et al. (1991) and confirmed with the total ozone data at Amundsen-Scott station archived in the Word Ozone Data Centre. The depth of the ozone hole is defined as the daily minimum total ozone south of 50°S. Another ozone hole index expressing the volume of the ozone hole is needed to complete the expression of the ozone hole intensity. The depleted mass of ozone, which is used in place of the volume of the ozone hole, is defined as the deficit of ozone mass in the area south of 50°S from the long-term global average of total ozone of 300 m atm-cm.

The daily values of these three ozone hole indexes are calculated using the daily grid data (ver. 6) of Total Ozone Mapping Spectrometer (TOMS) for the period from 1 August to 31 December for the years from 1979 to 1991, except for the period from 1 November to 31 December 1991 (unavailable at present). In the calculation, unavailable grid points due to the polar night are assumed to have the same total ozone value as the most southern available value that day.

Based on the daily values thus calculated, the annual peak values, that is, the annual maximum area of the ozone hole, the annual minimum of total ozone in the ozone hole and the annual maximum of depleted ozone mass in the ozone hole are taken as the annual representative indexes of the ozone hole in its annual mature stage (hereafter called the mature ozone hole).

3. QUANTITATIVE CHARACTERIZATION OF THE OZONE HOLE

Figure 1 shows the ozone hole indexes in the mature ozone hole from 1979 to 1991. In Fig. 1, the ozone depletion rate in the developing stage of the ozone hole is also shown, which is calculated by the linear least square fitting to the daily values of depleted ozone mass during the 30 days before its peak date.

In Fig. 1, it is seen that the long-term evolution of the mature ozone hole became apparent in 1982. In 1991, the depth, area and depleted ozone mass in the mature ozone hole reached historical extremes which were 108 m atm-cm, 17.4×10^6 km^2 and 55 Mt, respectively. When these values are compared with those in 1981, it can be seen that, over the last 10 years, the minimum total ozone in the mature ozone hole has decreased by about 47%, the area has increased by about 13 times, and the depleted ozone mass has increased by about 4.3 times.

In contrast to these quantities, the ozone depletion rate does not show any appreciable long-term trend but the inter-annual fluctuations do range from 0.169 to 0.689 Mt/day with the average of 0.419 Mt/day for the years from 1979 to 1991. It is interesting to note that in 1990, the depleted ozone mass in the mature ozone hole was 48 Mt which was only 5% lower than that in 1989 whereas the depletion rate in 1989 was 3 times larger than that in 1990 which was the largest in the years from 1979 to 1991. Daily plots of ozone hole indexes (Fig. 2) clearly suggest that the initiation of ozone decrease in 1990 was earlier than in 1989. Thus, the long ozone-decrease duration due to an early start of ozone decrease causes the large depleted ozone mass in the mature ozone hole, even with the small depletion rate in 1990. Similarly an early start in ozone depletion was also evident in 1991 and the depletion rate was the second historical maximum, about 10% smaller than in 1989. This resulted in the historical maximum of the depleted ozone mass in the mature ozone hole in 1991.

4. RELATION BETWEEN THE PRIOR STRATOSPHERIC TEMPERATURE AND THE INTENSITY OF THE MATURE OZONE HOLE

The process leading to the ozone hole formation is strongly related with the occurrence of polar stratospheric clouds (PSCs). On PSCs particles, chlorine reservoirs (HCl, $ClONO_2$ etc.) undergo heterogeneous conversion, emitting chlorine gas (Cl_2) and fixing HNO_3 in the PSCs particles (Solomon et al., 1986; McElroy et al., 1986). During winter, Cl_2 is accumulated in the Antarctic stratosphere. In spring when the sunlight returns to the Antarctic stratosphere, Cl_2 is photolyzed to produce a large quantity of reactive chlorines forming the ozone hole. The fixing of HNO_3 in PSCs particles which are eventually removed from the stratosphere by their gravitational settling is also important to form the ozone hole, inhibiting the fixing of chlorine in its more stable reservoirs. Satellite observations indicate an onset of PSCs formation at approximately 195 K. The temperatures of 195 K and 187 K are thought to be the threshold of the onset of Type-I PSCs (mainly of nitric acid trihydrate solid particles) and Type-II PSCs (mainly of water solid particles) formation, respectively (Turco et al., 1989). The minimum stratospheric

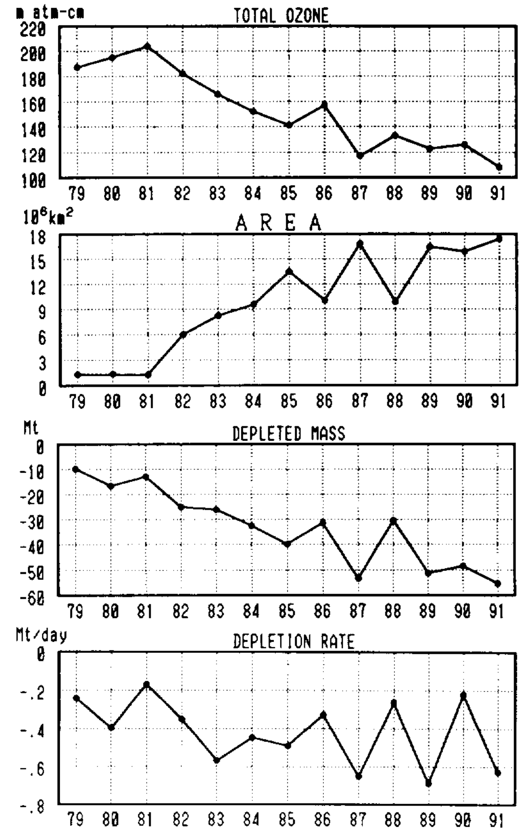

Fig. 1. The long-term change of the minimum total ozone, area enclosed by the 220 m atm-cm contour and depleted ozone mass in the mature ozone hole and the ozone depletion rate.

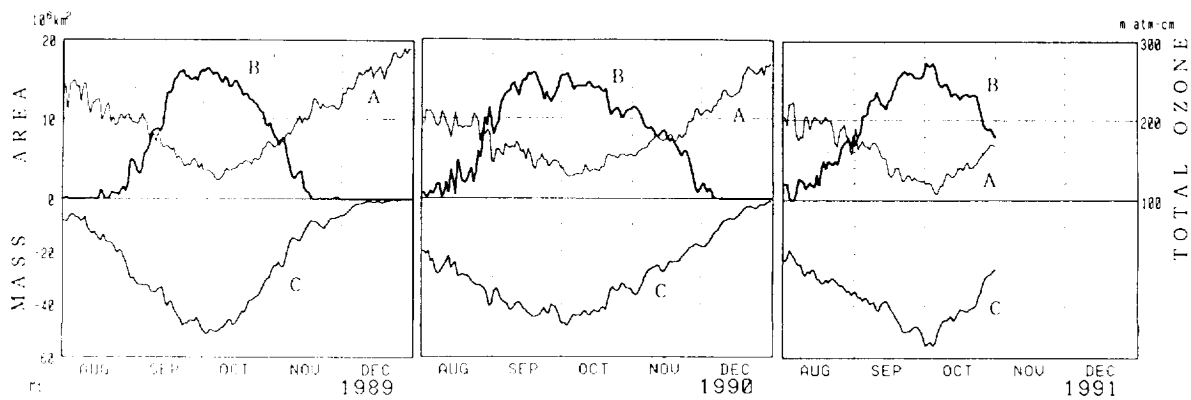

Fig. 2. The daily plot of the minimum total ozone (A), area enclosed by the 220 m atm-cm contour (B) and depleted ozone mass (C).

temperature or the area enclosed by a given temperature contour on a stratospheric isobaric surface may be considered as a parameter expressing the intensity or areal coverage of PSCs. In this section, the correlation between the ozone hole indexes in the mature ozone hole and the stratospheric temperature before the mature ozone hole is examined to consider the possible cause of the long-term evolution of the ozone hole in relation to the role of PSCs.

The temperature data used in this study is the analyzed stratospheric grid data (5° mesh) of monthly mean temperature edited by the Japan Meteorological Agency, available for the isobaric surfaces of 10, 30 and 50 mb. From this grid data, the following three types of parameters are calculated; the minimum temperature in the Southern Hemisphere, the areas enclosed by the 195 K contour, and that by the 187 K contour on the 10, 30 and 50 mb surfaces, for the months of June, July, August and September.

Then, the correlation coefficients are calculated between the ozone hole indexes and the temperature parameters, and between the ozone depletion rate and the temperature parameters. Since there are 13 data points for each quantities for the period 1979 to 1991, the correlation is considered to be statistically significant with 99% confidence when the correlation coefficient is larger than 0.7. Table 1 shows the resultant correlation coefficients for the 30 mb surface.

The 50 mb surface, which is located in the main part of the ozone layer and also the main part of the ozone depleting layer in the ozone hole, exhibits no significant correlation between the temperature parameters and the ozone hole indexes including the ozone depletion rate. The 10 mb surface, which is located at about 10 km above the main part of ozone layer, does show a few significant correlations as follows; between the minimum total ozone and the area below 195 K for the months from June to August; between the depleted ozone mass and the area below 195 K in July; between the depleted ozone mass and the minimum temperature in August and between the depletion rate and the minimum temperature in September.

However a numbers of significant correlations are seen between the temperature parameters on the 30 mb surface and the ozone hole indexes including the ozone depletion rate. The 30 mb surface is located near the top of the ozone depleting layer in the ozone hole. The highest correlation coefficients (0.79-0.85) are obtained between the ozone hole indexes and the area below 195 K on the 30 mb surface in June, although correlation coefficients higher than 0.7 are also seen in July. The ozone depletion rate has the highest correlation coefficient (0.86) with the area below 195 K on the 30 mb surface in August. In September, it is the second highest (0.74).

Figure 3 shows the scatter diagram between the depleted ozone mass in the mature ozone hole and the area below 195 K on 30 mb surface in June. The numbers attached to the plotted points indicate the years. The distribution of years in the diagram

Tab. 1. Correlation coefficients between temperature parameters and ozone hole indexes.

TEMPERATURE PARAMETERS			OZONE HOLE INDEXES			DEPLETION RATE
			MIMIMUM TOTAL OZONE	AREA OF OZONE HOLE	DEPLETED MASS	
30mb	MINIMUM OF TEMPERATURE	JUN	0.73	-0.61	0.58	0.05
		JUL	0.52	-0.51	0.51	0.35
		AUG	0.39	-0.43	0.45	0.42
		SEP	0.16	-0.17	0.25	0.65
	AREA BELOW 195 K	JUN	-0.85	0.82	-0.79	-0.29
		JUL	-0.68	0.74	-0.78	-0.42
		AUG	-0.49	0.59	-0.64	-0.86
		SEP	-0.43	0.46	-0.53	-0.74
	AREA BELOW 187 K	JUN	-0.57	0.49	-0.44	0.13
		JUL	-0.73	0.74	-0.74	-0.43
		AUG	-0.63	0.66	-0.70	-0.64
		SEP	-	-	-	-

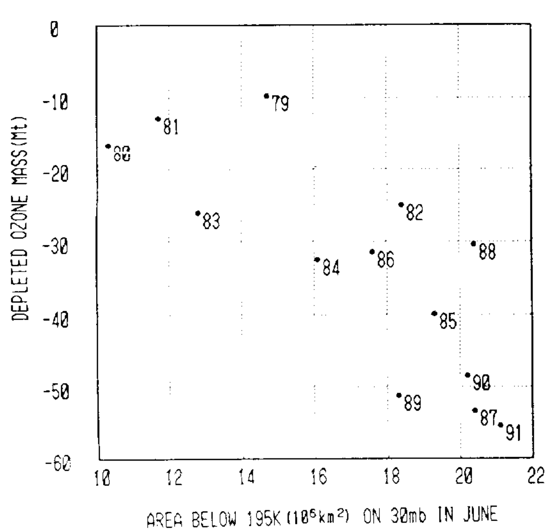

Fig. 3. The scatter diagram of the depleted ozone mass in the mature ozone hole and the area below 195 K on 30 mb surface for June.

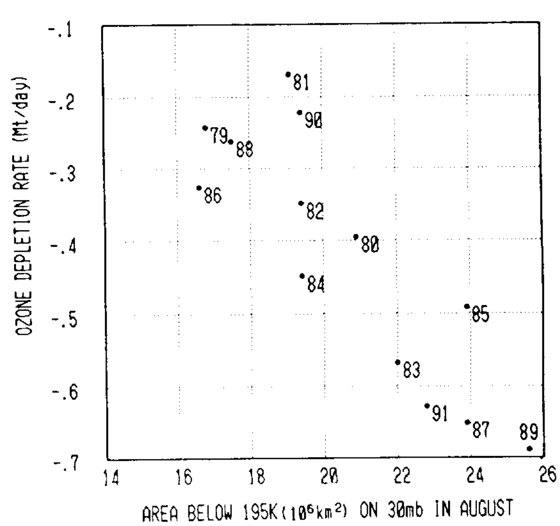

Fig. 4. The scatter diagram of the ozone depletion rate and the area below 195 K on 30 mb surface for August.

suggests that the high correlation seen in the diagram results mainly from the simultaneous long-term trend of the depleted mass in the mature ozone hole and the area below 195 K on the 30 mb surface in June, but also partly from the simultaneous oscillation of the two variables. This is not the case for the scatter diagram between the depletion rate and the area below 195 K on the 30 mb surface in August, shown in Fig. 4. This suggests that the high correlation results mostly from simultaneous inter-annual oscillations of the two variables.

5. DISCUSSION

The important findings of the present analysis are that the long-term evolution of the mature ozone hole is highly correlated with the area below 195 K on the 30 mb surface near the top of ozone depleting layer in June, which is about four months before the mature ozone hole. Since the temperature of 195 K means the threshold of the onset of Type 1 PSCs formation, the area below 195 K is considered to express the possible area covered with Type 1 PSCs.

The large spatial coverage of Type 1 PSCs in the winter would cause the large spatial distribution of photolyzable chlorines such as Cl_2 spreading to the relatively lower latitudes in the polar vortex. Since the lower latitudes in the polar vortex receive the solar light earlier than the higher latitudes in the late winter and early spring, the destruction of ozone molecules by reactive chlorines produced by the photolysis of Cl_2 etc. would initiate earlier there. Thus, large spatial coverage of PSCs in the winter would lead to the earlier onset of the ozone hole formation. The early onset of the ozone hole formation tends to lead to the larger depleted ozone mass in the mature ozone hole, as was the case in 1990 and 1991.

In late August 1991, the total ozone observed at Amundsen-Scott (archived in WODC) were mostly larger than the provisional values of total ozone observed at Halley and Faraday (Dr. Shanklin, private communication), Arrival Heights (Dr. Clarkson, Private communication) and Syowa, suggesting the ozone decrease started from the lower latitude in the polar vortex, leading to an earlier onset in ozone hole formation in 1991. This fact may support the present speculation.

Since the main decrease of the ozone amount occurs below the 30 mb surface from August to September, the subsidence current in the polar vortex is required to exist from June to August in order to explain the highest correlation between the area below 195 K on 30 mb surface in June and the observed ozone depletion. The required subsidence air current is approximately same in magnitude as the descending velocity of PSCs detected by McCormick et al. (1985).

On the other hand, the ozone depletion rate in the ozone hole is considered to be approximately proportional to the total amount of reactive chlorine which would depend on the total surface area of the PSCs particles available for the heterogeneous production of the photolyzable chlorines. The large area below 195 K is also considered to be the region where a large amount of the total surface area of PSCs particles exists, if the particles have grown well in size. According to the satellite observations, the maximum extinction by PSCs is observed from July to August (McCormick et al., 1989). Thus, the existing high correlation between the ozone depletion rate and the area below 195 K on 30 mb surface in August may be reasonable when the size of PSCs particles is taken into account.

6. CONCLUDING REMARKS

The present analysis strongly suggests that the existing long-term evolution of the mature ozone hole is caused by the possible year-to-year change of the spatial coverage of PSCs in both their early- and mature-stages, which is controlled by the stratospheric temperature field, while the effect of the global trend in chlorofluorocarbons concentration also plays an important role in the ozone hole evolution. The year-to-year change in the temperature field in the Antarctic stratosphere may be caused by the change in the planetary wave activity in the Southern Hemisphere as demonstrated by Newman and Randel (1989), even in June and August. Also, the long-term trend in the stratospheric concentration of the green-house gases may be responsible for the change in the temperature field in the Antarctic stratosphere, as demonstrated by Shine (1988).

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REFERENCES

McCormick, M. P., P. Hamill, and U. O. Farrukh, 1985: Characteristics of polar stratospheric clouds as observed by SAM II, SAGE, and lidar. J. Meteor. Soc. Jpn., 63, 267-276.

McCormick, M. P., C. R. Trepte, and M. C. Pittes 1989: Persistence of polar stratospheric clouds in the southern polar region. J. Geophys. Res., 94, 11241- 11251.

McElroy, M. B., R. J. Salawitch, S. C. Wofsyand, and J. A. Logan, 1986: Reduction of Antarctic ozone due to synergistic interaction of chlorine. Nature, 321, 759-762.

Newman, P., R. Stolarski, M. Schoeberl, R. McPeters, and A. Krueger, 1991: The 1990 Antarctic ozone hole as observed by TOMS. Geophys. Res. Lett., 18, 661-664.

Newman, P. A., and W. J. Randel, 1988 : Coherent ozone-dynamical changes during the southern hemisphere spring, 1979-1986. J. Geophys. Res., 93, 12585-12606.

Shine K. P., 1988: Comment on "Southern hemisphere temperature trends: a possible greenhouse effect?" Geophys. Res. Lett., 15, 843-844.

Solomon, S., R. R. Garcia, Rowland. F. S., and D. J. Wuebbles, 1986: On the depletion of Antarctic ozone. Nature, 321, 755-758.

Turco, R. P., O. B. Toon, and P. Hamill, 1989: Heterogeneous physicochemistry of the polar ozone hole. J. Geophys. Res., 94, 16493-16510.