Polar Meteorol. Glaciol., **19**, 67–81, 2005

Scientific note

Apparent stratospheric ozone loss rate over Eureka in 1994/95, 1995/96, and 1996/97 inferred from ECC ozonesonde observations

Michio Hirota[1]*, Koji Miyagawa[1], Kazuhiko Nagata[3], Kiyotaka Shibata[2],
Tomohiro Nagai[2], Toshifumi Fujimoto[3], Yukio Makino[4],
Osamu Uchino[5] and Hans Fast[6]

[1] *Aerological Observatory, 1–2, Nagamine, Tsukuba 305-0052*
[2] *Meteorological Research Institute, 1–1, Nagamine, Tsukuba 305-0052*
[3] *Observations Department, Japan Meteorological Agency, 1–3–4,*
Ote-machi, Chiyoda-ku, Tokyo 100-8122
[4] *Hakodate Marine Observatory, Japan Meteorological Agency, Hakodate 041-0806*
[5] *Kobe Marine Observatory, Japan Meteorological Agency, Kobe 651-0073*
[6] *Atmospheric Environment Service, North York, Ontario, Canada*
**Corresponding author. E-mail: mhirota@met.kishou.go.jp*

(Received February 10, 2005; Accepted June 20, 2005)

Abstract: Many ECC-type ozonesondes were launched at the Canadian Arctic Eureka observatory (80°N, 86°W), one of the most northern stations in the Arctic, during winters from 1993/94 to 2001/02, and the temporal evolutions of the vertical ozone profiles were obtained in detail. The lower stratospheric temperature over Eureka was very low inside the polar vortex and the largest ozone loss was observed in 1999/2000, as reported in a previous paper. Similarly, Eureka was often or persistently inside the vortex in the lower stratosphere (around the 470 K isentropic surface level) in the winters of 1994/95, 1995/96, and 1996/97. Very low temperatures were observed inside the vortex in the lower stratosphere over Eureka, as indicated by detection of PSCs by Mie lidar. Observations of tracers (N_2O, total reactive nitrogen species (NO_y), and others) inside the vortex during these winters using an ER-2 aircraft and balloons indicated that the effect of air parcel mixing across the vortex edge was minimal, based on the tracer-tracer relationship (*e.g.*, Y. Kondo *et al.*; J. Geophys. Res., **104D**, 8215, 1999). Therefore, significant decreases of the intravortex ozone mixing ratio in the lower stratosphere were considered to be chemical ozone losses due to chlorine activation of PSCs following diabatic descent. The apparent ozone loss rate inside the vortex over Eureka was estimated for each year. The rates ranged from 0.01 to 0.03 ppmv/day, less than that observed in 1999/2000 (0.04 ppmv/day). The observations were conducted at a single station; however, the apparent ozone loss rate over Eureka inside the vortex each year agrees with loss rates obtained in other studies.

key words: Arctic, stratospheric ozone, ozone loss, PSCs

1. Introduction

The ozone hole in the Antarctic has been observed in early spring since the late

1970s. In contrast, ozone depletion in the Arctic occurs on a much smaller scale in time and space, because the Arctic polar vortex is warmer, less stable, and less persistent than the Antarctic polar vortex. However, there were substantial ozone decreases in the Arctic lower stratosphere in 1994/95, 1995/96, 1996/97, and 1999/2000 (Donovan *et al*., 1995, 1996, 1997; Manney *et al*., 1996a, b, 1997; Hansen *et al*., 1997; Newman *et al*., 1997; Knudsen *et al*., 1998; Rex *et al*., 1997, 1999; WMO, 1999; Santee *et al*., 2000; Schulz *et al*., 2000; Braathen *et al*., 2000; Richard *et al*., 2001; Sinnhuber *et al*., 2000), indicating that polar stratospheric clouds (PSCs) induced severe ozone depletion through chlorine activation not only in the Antarctic but also in the Arctic.

Observations of PSCs by Mie lidar began in 1993 at the Canadian Eureka observatory (80°N, 86°W), one of the most northern stations in the Arctic (Nagai *et al*., 1997a, b), to study the mechanism of ozone loss in the Arctic lower stratosphere. Simultaneous ozonesonde observations are usually conducted there once a week and whenever PSCs are observed. The results of ozonesonde observations at Eureka from winter to early spring in 1999/2000 were reported in a previous paper (Hirota *et al*., 2003). The lidar observations and others (*e.g*., observations of large HNO_3-containing particles by Fahey *et al*., 2001) suggested denitrification in the lower stratosphere inside the vortex in late winter. A substantial apparent ozone loss rate inside the vortex over Eureka was estimated, taking into account the diabatic descent of air masses, after the method of Kreher *et al*. (1999).

The lower stratospheric ozone mixing ratios and temperatures in 1994/95, 1995/96, and 1996/97 inside the vortex over Eureka are investigated in this report, and the apparent ozone loss rates inside the vortex over Eureka are estimated. Details of the ozonesonde observations are described in Hirota *et al*. (2003).

2. Total ozone and stratospheric temperature

The monthly average total ozone over Eureka from winter to early spring in nine winters from 1993/94 to 2001/02 was low in four winters, 1994/95, 1995/96, 1996/97, and 1999/2000, in which the monthly average temperatures in the lower stratosphere (*i.e*., 50 hPa) over Eureka were also low (Fig. 2 in Hirota *et al*., 2003). A correlation between the total ozone and the lower stratospheric temperature was often observed (Chubachi, 1993). The correlation most likely resulted from the ozone depletion inside the vortex induced by chlorine activation of the PSCs that form in the lower stratosphere when the temperature is sufficiently low (Andersen and Knudsen, 2002). The winters in 1994/95, 1995/96, and 1996/97 were chosen for the analysis because of the significant total ozone decrease in the Arctic.

3. Meteorological conditions over Eureka in 1994/95, 1995/96, and 1996/97

The variation of total ozone over an Arctic site depends primarily on the location of the site relative to the polar vortex boundary and the chemical ozone loss within the vortex. The former was determined from the equivalent latitudes of the vortex boundary and Eureka on a 475 K isentrope, calculated each day based on the technique of Nash *et al*. (1996). NCEP/NCAR reanalysis data (Kalnay *et al*., 1996) was used as objective analysis data.

The lower stratosphere over Eureka in 1994/95 was inside the vortex in the first halves of December and January and from the end of February to the beginning of March (Fig. 1). The temperatures inside the vortex at 50 hPa over Eureka were equal to or below the threshold for PSCs formation, *i.e.*, 196 K (the NAT formation temper-

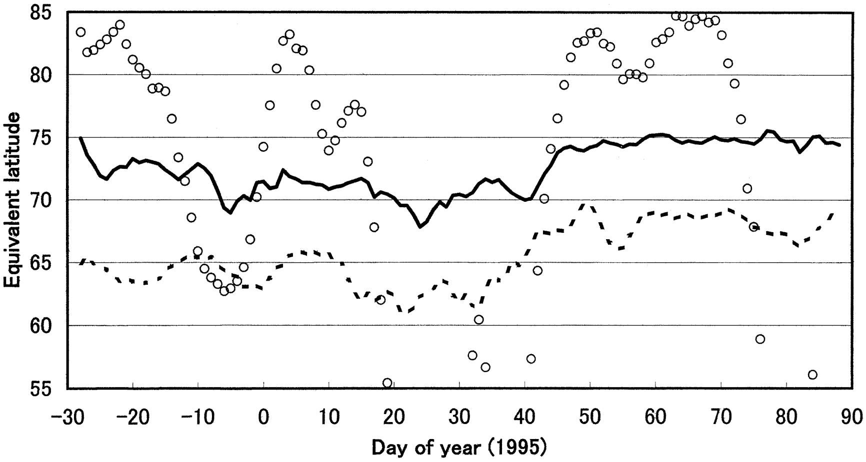

Fig. 1. Equivalent latitudes of the polar vortex boundary region and Eureka on the 475 K isentrope in the Northern Hemisphere in 1994/95.
Solid (dashed) lines indicate the poleward (equatorward) edges of the boundary region of the polar vortex. The circles indicate Eureka. The data shown were smoothed in time with a 5-day running mean.

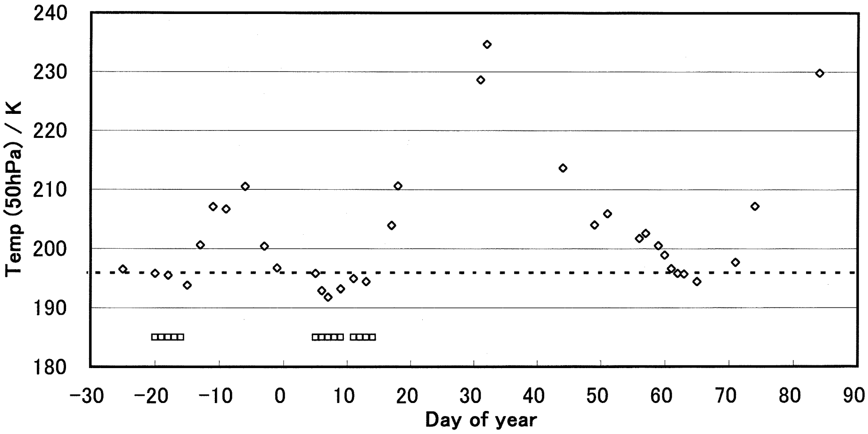

Fig. 2. Temperature at 50 hPa over Eureka in 1994/95.
Dashed line indicates the NAT formation temperature of 195.9 K at 50 hPa (assuming that H_2O = 5 ppmv and HNO_3 = 10 ppbv). The squares indicate the days on which PSCs were observed over Eureka.

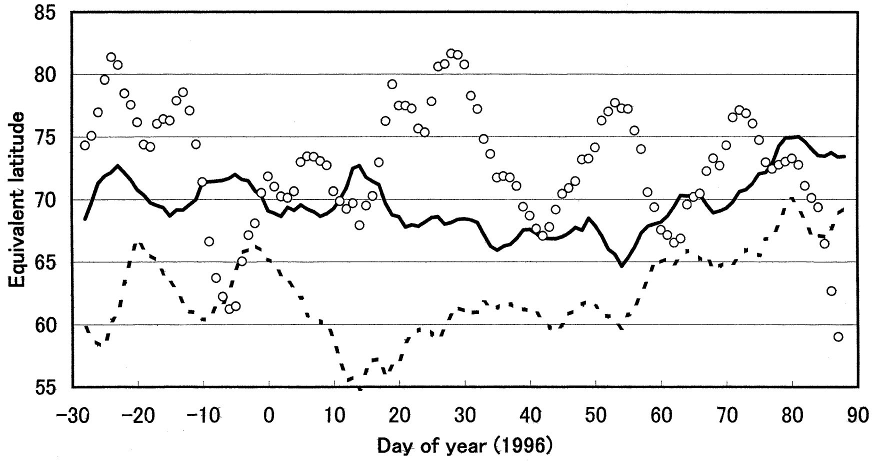

Fig. 3. Equivalent latitudes of the polar vortex boundary region and Eureka on the 475 K isentrope in the Northern Hemisphere in 1995/96. The same symbols as in Fig. 1 are used.

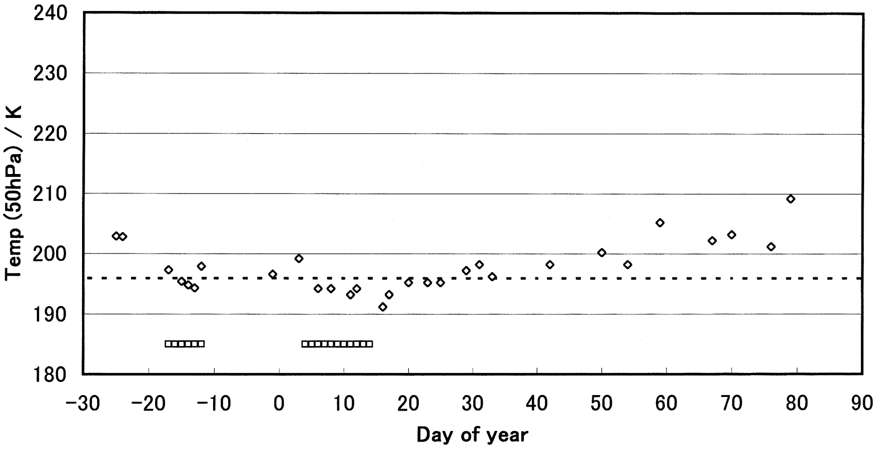

Fig. 4 Temperature at 50 hPa over Eureka in 1995/96. The same symbols as in Fig. 2 are used.

ature, assuming that $H_2O=5$ ppmv and $HNO_3=10$ ppbv (Hanson and Mauersberger, 1988)) (Fig. 2). PSCs were observed over Eureka in the middle of December and the first half of January, and were not observed at the beginning of March.

The lower stratosphere over Eureka in 1995/96 was inside the vortex from the beginning to the middle of December and from the middle of January to the middle of March, except for the beginning of March (Fig. 3). The temperatures inside the vortex at 50 hPa over Eureka were equal to or below 196 K in the middle of December and the first half of January, and PSCs were observed over Eureka in these periods (Fig. 4). Although the lower stratospheric temperature was also low around 25 January, PSCs were not observed.

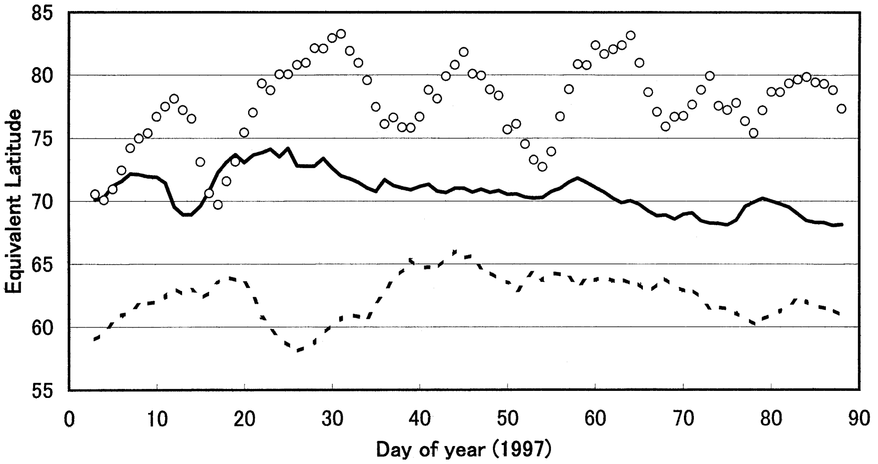

Fig. 5. Equivalent latitudes of the polar vortex boundary region and Eureka on the 475 K isentrope in the Northern Hemisphere in 1996/97. The same symbols as in Fig. 1 are used.

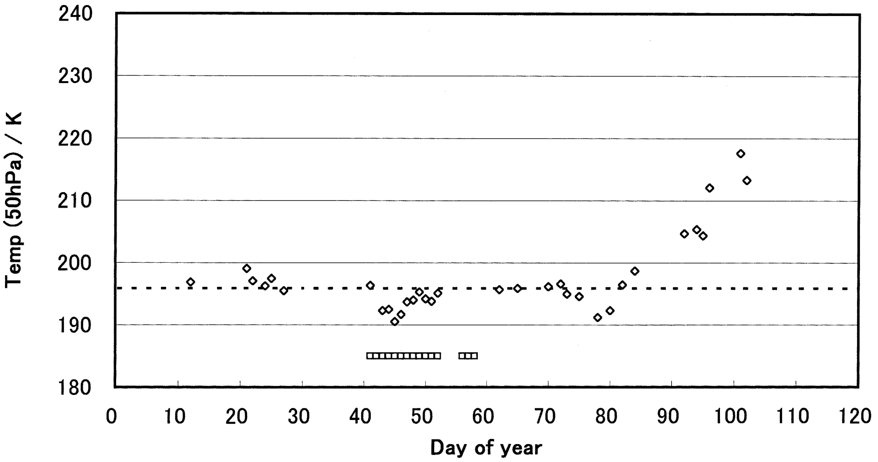

Fig. 6. Temperature at 50 hPa over Eureka in 1996/97. The same symbols as in Fig. 2 are used.

The lower stratosphere over Eureka in 1996/97 was inside the vortex from the end of January to the end of March (Fig. 5). The temperatures inside the vortex at 50 hPa over Eureka were equal to or below 196 K through the middle of March (Fig. 6). PSCs were observed over Eureka from the middle to the end of February. Donovan *et al.* (1997) observed PSCs as late as 18 March, after our lidar observations for the winter had been terminated.

4. Chemical ozone loss

The ozone loss rate in an air parcel inside the polar vortex can be accurately estimated using the Match method (*e.g*., Von der Gathen *et al*., 1995; Rex *et al*., 1999). However, we did not use the Match method in this study and assumed a uniform ozone mixing ratio on each isentrope. Thus, the apparent ozone loss rates over Eureka when Eureka was inside the vortex were calculated taking into account the diabatic descent of air masses (Kreher *et al*., 1999). The diabatic descent rates were obtained as the sum of the longwave and solar radiative heating rates on several isentropes from NCEP/NCAR reanalysis data. The heating rates were interpolated onto several isentropes from those on standard isobaric surfaces (Kalnay *et al*., 1996)) and integrated over the polar region (70 to 90°N) to obtain the mean descending motion. However, the variation of the ozone mixing ratio inside the polar vortex also depends on isentropic mixing of the vortex air with extravortex air (Plumb *et al*., 2000). The effect of air parcel mixing across the vortex edge can be estimated from the tracer-tracer relationship, and was considered minimal in 1999/2000 (Richard *et al*., 2001). A significant ozone loss rate was suggested in the lower stratosphere inside the vortex during the winter of 1999/2000 (Hirota *et al*., 2003). The intravortex ozone mixing ratio on the 475 K isentrope decreased by about 2.2 ppmv, from 3.1 ppmv on the 497 K isentrope (4 February) to 0.9 ppmv on the 475 K isentrope (29 March), following diabatic descent. The apparent ozone loss rate inside the vortex over Eureka during this period was 0.041±0.008 ppmv/day (90% confidence interval). The apparent loss rate was substantial in the air masses that reached the isentropes around 475 K to 460 K on 29 March, and smaller at upper altitudes. The apparent loss rate over Eureka inside the vortex was in good agreement with loss rates obtained in other studies, as indicated in Table 1.

Table 1. Ozone loss in the lower stratosphere inside the Arctic polar vortex in 1999/2000.

Method		Period	Isentrope	Loss rate	Total loss
Present work		4 Feb. to 29 March	497 to 475 K	0.041±0.008 ppmv/day	2.2 (3.1 to 0.9) ppmv
UARS MLS	Santee *et al*. (2000)	Early February	to 465 K	0.04±0.01 ppmv/day	
Ozonesonde (Match)	Braathen *et al*. (2000)	10 Jan. to 31 March	to 475 K		2.53±0.17 ppmv
Ozone-tracer correlations	Richard *et al*. (2001)		around 450 K	0.046±0.006 ppmv/day	
3D model	Sinnhuber *et al*. (2000)	By the end of March	450 K		2.5 ppmv (70%)

a) 1994/95

The temperatures above Eureka during the periods when Eureka was inside the polar vortex in the lower stratosphere were the coldest vortex temperatures at 50 hPa (Donovan *et al*., 1995). PSCs were frequently observed by lidar from mid-December to the end of January over Ny-Ålesund (79°N, 12°E) between 15 and 22 km (Shibata *et* *al.*, 1997), corresponding to the low temperature in mid-December 1994 and mid-January 1995. No PSCs were observed thereafter, similar to the observations over Eureka, though the lidar observations lasted until 11 March. These suggest that the HNO_3 in the lower stratosphere was depleted after the end of January. Sugita *et al.* (1998) observed significant loss of total reactive nitrogen (NO_y) between 18 and 22 km; the greatest denitrification was on the 475 K isentrope (19 ± 0.5 km), based on balloon-borne *in situ* measurements of NO_y and nitrous oxide (N_2O) made from Kiruna (68°N, 21°E) on 11 February 1995. They also observed, but with significant uncertainty, that the NO_y value between 23 and 28 km generally agreed with the unperturbed value of NO_y and indicated that the sampled air masses were transported from the upper stratosphere over middle latitudes to high latitudes, where they descended inside the polar vortex. These observations suggest that the air masses between 18 and 28 km descended inside the vortex, and significant loss of NO_y occurred, corresponding to the very low temperature in the lower stratosphere.

The meteorological conditions over Eureka inside the vortex were similar to those in the Scandinavian Arctic, suggesting that the air masses over Eureka in the lower stratosphere inside the vortex experienced very cold temperatures favorable for denitrification and that the effect of air mass mixing across the vortex edge was small. The apparent ozone loss rates were calculated under these assumptions. The intravortex ozone mixing ratio on the 470 K isentrope decreased by about 0.2 ppmv from 2.5 ppmv on the 490 K isentrope (13 February) to 2.3 ppmv on the 470 K isentrope (15 March), following diabatic descent. The lower stratosphere over Eureka was not inside the polar vortex until 13 February. The apparent loss rate inside the vortex during this period was found to be 0.009 ± 0.012 ppmv/day (90% confidence interval) by fitting a straight line to all ozonesonde data between 13 February and 15 March, as depicted in Fig. 7. The ozone mixing ratios on intermediate dates were interpolated onto the isentrope determined by the diabatic descent rate. The apparent ozone loss rate was much lower than that in 1999/2000. The apparent ozone loss rates in the air masses, which reached the isentropes between 470 K and 440 K on 15 March, are also depicted in Fig. 8. The error bar indicates the 90% confidence interval. The apparent loss rate increased with decreasing altitude from 480 K to 440 K, and that at 440 K was 0.031 ± 0.008 ppmv/day (90% confidence interval). A similar vertical profile of the ozone loss in the Arctic winter of 1994/95 was reported by Rex *et al.* (1999). The loss rates inside the vortex reported by other groups are listed in Table 2. The ozone loss from 1 January on the 515 K isentrope to 20 March on the 450 K isentrope obtained by the Match method (Rex *et al.*, 1999) corresponds to an average loss rate of 0.025 ± 0.004 ppmv/day, which agrees with the apparent loss rate observed on the 450 K isentrope (15 March) in this study (0.028 ± 0.005 ppmv/day).

b) 1995/96

PSCs were observed over Ny-Ålesund and Andoya (69°N, 16°E) for a longer period than over Eureka, *i.e.*, from 1 January to 29 February, and were not observed in March (Rex *et al.*, 1997). The very low HNO_3 observed by UARS/MLS from 17 to 20 February between Greenland and Norway was due to the presence of PSCs in that area (Santee *et al.*, 1996). The measurements of tracers made on the ER-2 on 1 February 1996 (Hintsa *et al.*, 1998) indicated dehydration and substantial denitrification (60%)

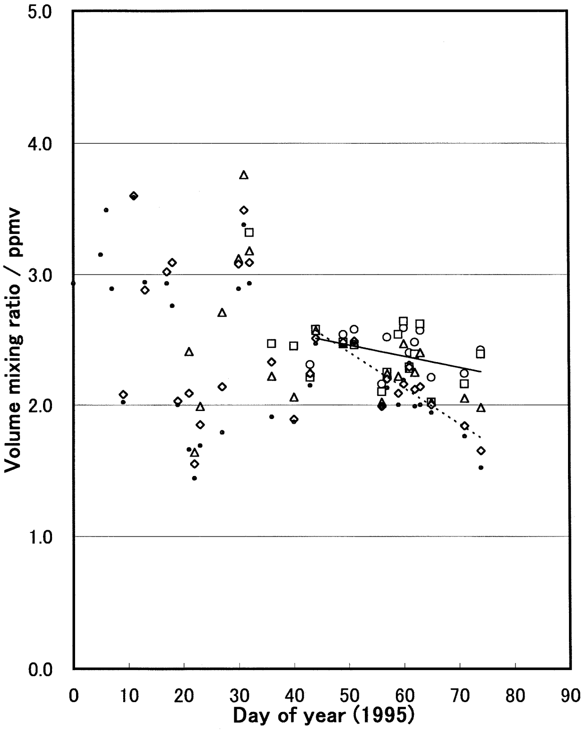

Fig. 7. *Ozone mixing ratio (ppmv) in the air parcel that departed the 500 K isentrope on 1 February (day 32 of 1995), continued to diabatically descend, and reached the 470 K isentrope on 15 March (day 74 of 1995), together with those from 460 K to 440 K on 15 March inside the polar vortex over Eureka.*

Circles 480 K, Squares 470 K, Triangles 460 K, Diamonds 450 K, Dots 440 K.

Solid (dotted) lines indicate linear decreasing trends from 13 February to 15 March for 470 K (450 K).

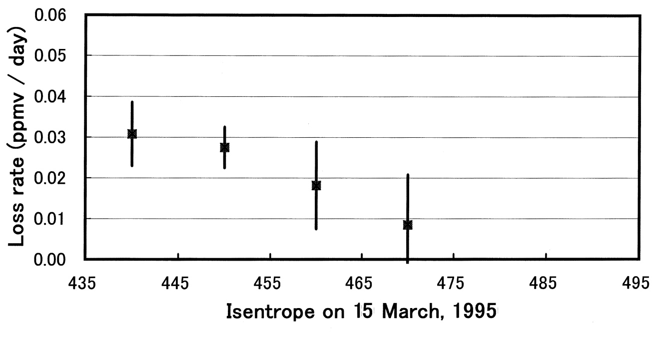

Fig. 8. *Ozone loss rates (ppmv/day) in descending air parcels that departed the 490, 482, 473, and 465 K isentropes on 13 February (day 44 of 1995) and reached the 470, 460, 450, and 440 isentropes on 15 March (day 74 of 1995).*

The error bars indicate 90% confidence intervals.

Table 2. Ozone loss in the lower stratosphere inside the Arctic polar vortex in 1994/95.

Method		Period	Isentrope	Loss rate	Total loss
Present work		13 Feb. to 15 March	to 470 K	0.009±0.012 ppmv/day	0.2 (2.5 to 2.3) ppmv
			to 440 K	0.031±0.008 ppmv/day	0.9 (2.6 to 1.7) ppmv
Ozonesonde (Match)	Rex *et al.* (1999)	1 Jan. to 20 March	515 to 450 K		2.0±0.3 ppmv (60%)
Airborne Lidar	Wirth & Renger (1996)	3 Feb. to 26 March	420–520 K		50%
UARS MLS	Manney *et al.* (1996)	21 Dec. to 3 Feb.	465 K		30%
O_3 Lidar	Donovan *et al.* (1995)	Early Jan. to mid-Feb.	below 500 K		15%
		Mid-Feb. to mid-March			15%

on the 450 to 465 K isentrope (18 to 19 km). The area of ice saturation temperatures circled nearly twice inside the vortex from 21 January to 1 February; over 25% of the polar vortex at this altitude was estimated to have been dehydrated in this event (Hintsa *et al.*, 1998).

PSCs were observed for a longer period over the Scandinavian Arctic than over Eureka; however, the apparent ozone loss rates were calculated assuming similar conditions over Eureka inside the vortex, as in 1994/95. Excluding the two observations in early March, the intravortex ozone-mixing ratio on the 470 K isentrope decreased by about 1.8 ppmv from 3.2 ppmv on the 495 K isentrope (20 January) to 1.4 ppmv on the 470 K isentrope (16 March), following diabatic descent. The apparent loss rate inside the vortex during this period was found to be 0.032±0.017 ppmv/day (90 % confidence interval) by fitting a straight line, as depicted in Fig. 9. The apparent ozone loss rates in the air masses, which reached the isentropes between 480 K and 440 K on 16 March, are also shown in Fig. 10. The apparent loss rate was almost constant from 480 K to 440 K. The loss rates inside the vortex reported by other groups are listed in Table 3. Rex *et al.* (1997) used the Match method and reported an ozone loss of 2.4±0.3 ppmv from 1 January to 9 April (~470 K isentrope), which corresponds to a loss rate of 0.024±0.003 ppmv/day. This agrees well with the result obtained by UARS/MLS (Manney *et al.*, 1996b) and is a little lower than the apparent loss rate obtained in this study.

c) 1996/97

Kondo *et al.* (1999) indicated that the air masses in a narrow altitude region of the 435 to 460 K isentropes (around 18.5 km in altitude) were denitrified on 25 February and that isentropic mixing of the air masses inside the vortex with the extravortex air did not occur below the 500 K isentrope, based on balloon-borne in situ measurements of NO_y and N_2O up to 29 km over Kiruna (68°N, 21°E) in February 1997. The column amounts of ClO over Eureka were measured by a Fourier transform infrared (FTIR) spectrometer in late winter, and the measured ClO columns were converted into

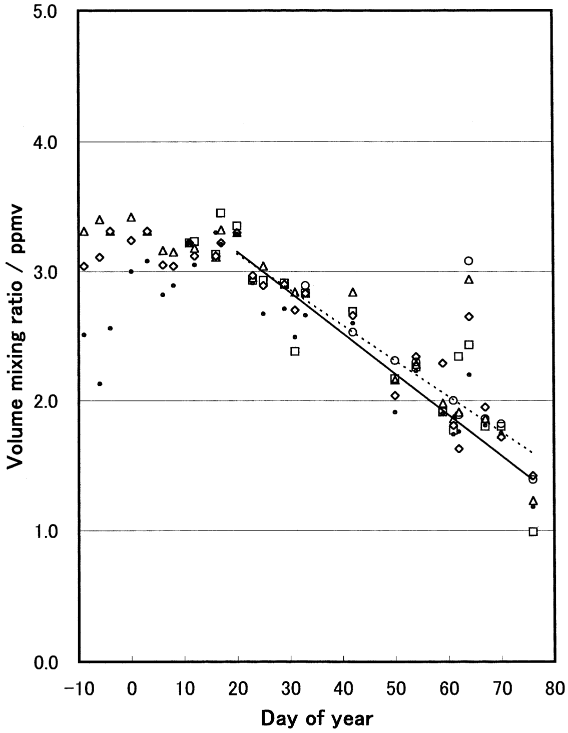

Fig. 9. *Ozone mixing ratio (ppmv) in the air parcel that departed the 511 K isentrope on 22 December (day −9 of 1996), continued to diabatically descend, and reached the 470 K isentrope on 16 March (day 76 of 1996), together with those from 480 K to 440 K on 16 March inside the polar vortex over Eureka. The same symbols as in Fig. 7 are used.*
Solid (dotted) lines indicate linear decreasing trends from 20 January to 16 March for 470 K (450 K).

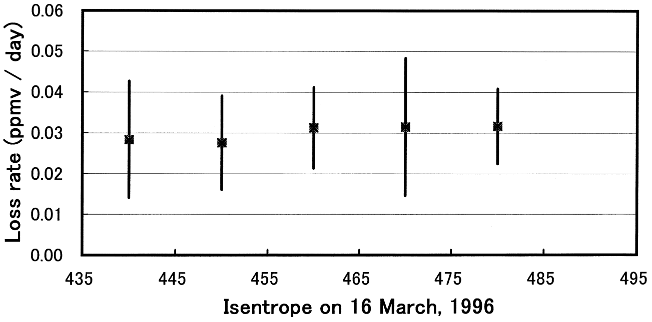

Fig. 10. *Ozone loss rates (ppmv/day) in descending air parcels that departed the 507, 495, 483, 472, and 461 K isentropes on 20 January (day 20 of 1996) and reached the 480, 470, 460, 450 and 440 isentropes on 16 March (day 76 of 1996).*
The error bars indicate 90% confidence intervals.

Table 3. Ozone loss in the lower stratosphere inside the Arctic polar vortex in 1995/96.

Method		Period	Isentrope	Loss rate	Total loss
Present work		20 Jan. to 16 March	to 470 K	0.032±0.017 ppmv/day	1.8 (3.2 to 1.4) ppmv
UARS MLS	Manney *et al.* (1996b)	29 Jan. to 3 March	465 K	0.022 ppmv/day (0.8%/d)	
Ozone-tracer correlations	Müller *et al.* (1997)	Late Jan. to 10 April	450 K		3.3 ppmv (>70%)
			400–480 K		60%
Ozonesonde (Match)	Rex *et al.* (1997)	20 Jan. to 9 April	around 470 K		2.4±0.3 ppmv (64%)
Ozonesonde (Match)	Braathen *et al.* (2000)	1 Jan. to 3 April	to 475 K		2.22±0.33 ppmv (72%)
Lidar	Hansen *et al.* (1997)	7 Jan. to 26 March	475 K		60%
Lidar	Donovan *et al.* (1996)	Mid-Jan. to mid-March	450 K	1.1–1.3%/d	50–55%

layer-averaged mixing ratios between 14 and 22 km in altitude. The mixing ratio decreased from 1.6 ppbv on 27 February to 0.7 ppbv by 20 March (Donovan *et al.*, 1997). Donovan *et al.* (1997) reported that the FTIR measurements of ClO made in late February were in agreement with the ClO measured by UARS/MLS at this time on the 465 K isentrope (Santee *et al.*, 1997). The vortex average ClO was also somewhat high at 0.8 to 0.9 ppbv in late February on the 465 K isentrope. These findings suggest that chlorine activation occurred widely in the lower stratosphere inside the vortex.

The intravortex ozone mixing ratio in the lower stratosphere decreased from the end of January to the end of March (Fig. 11). The mixing ratio on the 470 K isentrope decreased by 1.9 ppmv from 3.8 ppmv on the 487 K isentrope (24 January) to 1.9 ppmv on the 470 K isentrope (25 March), following diabatic descent. The apparent loss rate over Eureka inside the vortex during this period was found to be 0.031±0.017 ppmv/day (90% confidence interval) by fitting a straight line, as depicted in Fig. 11. The apparent ozone loss rates in the air masses, which reached the isentropes between 480 K and 440 K on 25 March, are also shown in Fig. 12. The apparent loss rate was almost constant between the 480 K and 440 K isentropes. The loss rates inside the vortex reported by other groups are listed in Table 4. Schultz *et al.* (2000) used the Match method and reported that the ozone loss rate was 0.025 to 0.045 ppmv/day from the end of January to the end of March between the 400 K and 550 K isentropes. A loss rate of 0.025±0.006 ppmv/day (0.9±0.2%/day) was observed on the 465±10 K isentrope level between 16 February and 2 March. Manney *et al.* (1997) reported a slightly higher loss rate (1.3 %/day).

The observations presented here are limited in the sense that they were conducted at a single station (Eureka); however, the lower stratospheric temperatures and PSCs appearances over the Scandinavian Arctic inside the vortex displayed a trend generally similar to those over Eureka. Therefore, the observations over Eureka can be considered to be representative of the vortex as a whole in 1994/95, 1995/96, and 1996/97.

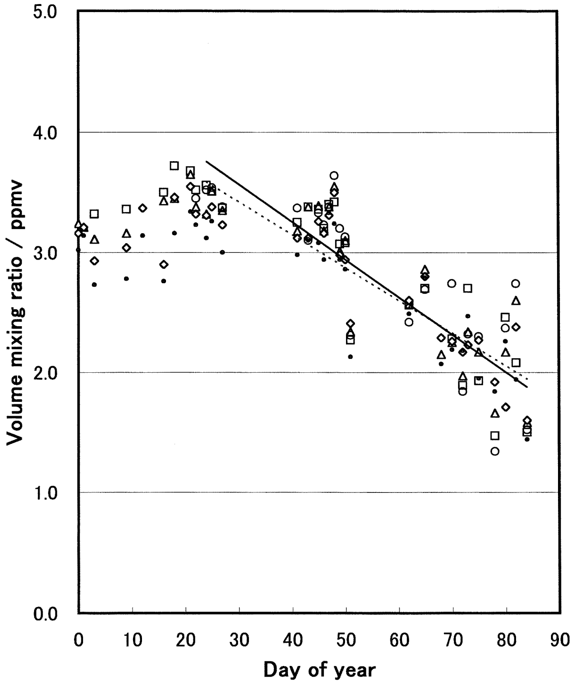

Fig. 11. Ozone mixing ratio (ppmv) in the air parcel that departed the 487 K isentrope on 31 December (day 0 of 1997), continued to diabatically descend, and reached the 470 K isentrope on 25 March (day 84 of 1997), together with those from 480 K to 440 K on 25 March inside the polar vortex over Eureka. The same symbols as in Fig. 7 are used. Solid (dotted) lines indicate linear decreasing trends from 24 January to 25 March for 470 K (450 K).

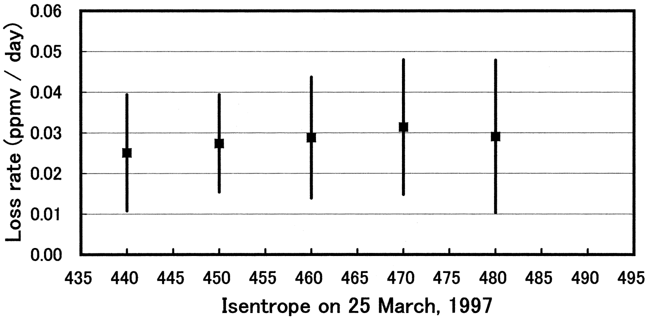

Fig. 12. Ozone loss rates (ppmv/day) in descending air parcels that departed the 499, 487, 476, 464, and 453 K isentropes on 24 January (day 24 of 1997) and reached the 480, 470, 460, 450, and 440 isentropes on 25 March (day 84 of 1997). The error bars indicate 90% confidence intervals.

Table 4. Ozone loss in the lower stratosphere inside the Arctic polar vortex in 1996/97.

Method		Period	Isentrope	Loss rate	Total loss
Present work		24 Jan. to 25 March	to 470 K	0.031±0.017 ppmv/day	1.9 (3.8 to 1.9) ppmv
Ozonesonde (Kiruna)	Kreher *et al.* (1999)	1 Feb. to 25 March	475±10 to 460±10 K	0.018–0.021 ppmv/day	0.95–1.11 ppmv
Ozonesonde (Match)	Schultz *et al.* (2000)	End of Jan. to end of March	400–550 K	0.025–0.045 ppmv/d	
		16 Feb. to 2 March	465±10 K	0.025±0.006 ppmv/day (0.9±0.2%/d)	
			450, 475 K		0.9±0.2 ppmv
UARS MLS	Manney *et al.* (1997)	20 Feb. to 26 Feb.	465 K	1.3%/d	
Ozonesonde	Knudsen *et al.* (1998)	6 Jan. to 6 April	to 475 K		1.24 ppmv (35%)
			to 450 K		1.59 ppmv (43%)
			to 425 K		1.45 ppmv (46%)

5. Summary

Many ECC-type ozonesondes were launched at the Canadian Arctic Eureka observatory (80°N, 86°W), one of the most northern stations in the Arctic, in winters from 1993/94 to 2001/02, and the temporal evolutions of the vertical ozone profiles were obtained in detail.

Eureka was often or persistently inside the vortex in the lower stratosphere (around the 470 K isentropic surface level) in the winters of 1994/95, 1995/96 and 1996/97, similar to 1999/2000. Very low temperatures were observed in the lower stratosphere when Eureka was inside the vortex, in accordance with the detection of PSCs by Mie lidar.

Significant apparent decreases of the intravortex ozone mixing ratio over Eureka in the lower stratosphere were considered to be chemical ozone loss due to chlorine activation on PSCs, following diabatic descent, under the assumption that the effect of air mass mixing across the vortex edge was minimal, based on other studies of the tracer-tracer relationship in the periods of our ozonesonde observations. The apparent ozone loss rate inside the vortex over a single station in Eureka was estimated for each year. The results ranged from 0.01 to 0.03 ppmv/day, which was less than that observed in 1999/2000, and were in agreement with the ozone loss rates obtained in other studies.

Acknowledgments

This work was supported by the Institute for Space and Terrestrial Science, York University, Canada; the Meteorological Service of Canada; and the Science and Technology Agency of Japan.

References

Andersen, S.B. and Knudsen, B.M. (2002): The influence of vortex ozone depletion on Arctic ozone trends. Geophys. Res. Lett., **29** (21), 2013, 10.1029/2001GL014595.

Braathen, G.O., Muller, M., Sinnhuber, B.-M., von der Gathen, P., Kryo, E. and other 6 authors (2000): Ozone decrease and PSC incidence in the Arctic vortex during the twelve winters from 1988–89 to 1999–2000. Proceedings of the Quadrennial Ozone Symposium-Sapporo, 115–116.

Chubachi, S. (1993): Relationship between total ozone amounts and stratospheric temperature at Syowa, Antarctica. J. Geophys. Res., **98D**, 3005–3010.

Donovan, D.P., Bird, J.C., Whiteway, J.A., Duck, T.J., Pal, S.R. and Carswell, A.I. (1995): Lidar observations of stratospheric ozone and aerosol above the Canadian high arctic during the 1994–95 winter. Geophys. Res. Lett., **22**, 3489–3492.

Donovan, D.P., Bird, J.C., Whiteway, J.A., Duck, T.J., Pal, S.R., Carswell, A.I., Sandilands, J.W. and Kaminski, J.W. (1996): Ozone and aerosol observed by lidar in the Canadian Arctic during the winter of 1995/96. Geophys. Res. Lett., **23**, 3317–3320.

Donovan, D.P., Fast, H., Makino, Y., Bird, J.C., Carswell, A.I. and other 9 authors (1997): Ozone, column ClO, and PSC measurements made at the NDSC Eureka observatory (80°N, 86°W) during the spring of 1997. Geophys. Res. Lett., **24**, 2709–2712.

Fahey, D.W., Gao, R.S., Carslaw, K.S., Kettleborough, J., Popp, P.J. and other 22 authors (2001): The detection of large HNO_3-containing particles in the winter Arctic stratosphere. Science, **291**, 1026–1031.

Hansen, G., Svenøe, T., Chipperfield, M.P., Dahlback, A. and Hoppe, U.-P. (1997): Evidence of substantial ozone depletion in winter 1995/1996 over Northern Norway. Geophys. Res. Lett., **24**, 799–802.

Hanson, D. and Mauersberger, K. (1988): Laboratory studies of the nitric-acid trihydrate: Implications for the south polar stratosphere. Geophys. Res. Lett., **15**, 855–858.

Hintsa, E.J., Newman, P.A., Jonsson, H.H., Webster, C.R., May, R.D. and other 9 authors (1998): Dehydration and denitrification in the Arctic polar vortex during the 1995–1996 winter. Geophys. Res. Lett., **25**, 501–504.

Hirota, M., Miyagawa, K., Yoshimatsu, K., Shibata, K., Nagai, T., Fujimoto, T., Makino, Y., Uchino, O., Akagi, K. and Fast, H. (2003): Stratospheric ozone loss over Eureka in 1999/2000 observed with ECC ozonesondes. J. Meteorol. Soc. Jpn., **81**, 295–304.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D. and other 17 authors (1996): The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc., **77**, 437–471.

Knudsen, B., Larsen, N., Mikkelsen, I.S., Morcrette, J.-J., Braathen, G.O. and other 10 authors (1998): Ozone depletion in and below the Arctic vortex for 1997. Geophys. Res. Lett., **25**, 627–630.

Kondo, Y., Koike, M., Engel, A., Schmidt, U., Mueller, M. and other 8 authors. (1999): NO_y-N_2O correlation observed inside the Arctic vortex in February: Dynamical and chemical effects. J. Geophys. Res., **104D**, 8215–8224.

Kreher, K., Bodeker, G.E., Kanzawa, H., Nakane, H. and Sasano, Y. (1999): Ozone and temperature profiles measured above Kiruna inside, at the edge of, and outside the Arctic polar vortex in February and March 1997. Geophys. Res. Lett., **26**, 715–718.

Manney, G.J., Froidevaux, L., Waters, J.W., Santee, M.L., Read, W.G., Flower, D.A., Jarnot, R.F. and Zurek, R.W. (1996a): Arctic ozone depletion observed by UARS MLS during the 1994–95 winter. Geophys. Res. Lett., **23**, 85–88.

Manney, G.J., Santee, M.L., Froidevaux, L., Waters, J.W. and Zurek, R.W. (1996b): Polar vortex conditions during the 1995–96 Arctic winter: Meteorology and MLS ozone. Geophys. Res. Lett., **23**, 3203–3206.

Manney, G.J., Froidevaux, L., Santee, M.L., Zurek, R.W. and Waters, J.W. (1997): MLS observations of Arctic ozone loss in 1996–97. Geophys. Res. Lett., **24**, 2697–2700.

Müller, R., Crutzen, P.J., Grooß, J.-U., Brühl, C., Russell III, J.M., Gernandt, H., McKenna, D.S. and Tuck, A.F. (1997): Severe chemical ozone loss in the Arctic during the winter of 1995–96. Nature, **389**, 709–712.

Nagai, T., Uchino, O., Itabe, T., Shibata, T., Mizutani, K. and Fujimoto, T. (1997a): Polar stratospheric clouds observed at Eureka (80°N, 86°W) in the Canadian Arctic during the 1994/1995 winter. Geophys. Res. Lett., **24**, 2243–2246.

Nagai, T., Uchino, O., Itabe, T., Shibata, T., Mizutani, K., Fujimoto, T. and Hirota, M. (1997b): Lidar observations of the PSCs and stratospheric aerosols over Eureka in Canadian Arctic. Advances in Atmospheric Remote Sensing with Lidar, ed. by A. Ansmann *et al*. Berlin, Springer, 505–508.

Nash, E.R., Newman, P.A., Rosenfield, J.E. and Schoeberl, M.R. (1996): An objective determination of the polar vortex using Ertel's potential vorticity. J. Geophys. Res., **101D**, 9471–9478.

Newman, P.A., Gleason, J.F., McPeters, R.D. and Stolarski, R.S. (1997): Anomalously low ozone over the Arctic. Geophys. Res. Lett., **24**, 2689–2692.

Plumb, R.A., Waugh, D.W. and Chipperfield, M.P. (2000): The effects of mixing on tracer relationships in the polar vortices. J. Geophys. Res., **105D**, 10047–10062.

Rex, M., Harris, N.R.P., von der Gathen, P., Lehmann, R., Braathen, G.O. and other 19 authors (1997): Prolonged stratospheric ozone loss in the 1995–96 Arctic winter. Nature, **389**, 835–838.

Rex, M., von der Gathen, P., Braathen, G.O., Harris, N.R.P., Reimer, E. and other 20 authors (1999): Chemical ozone loss in the Arctic winter 1994/95 as determined by the Match Technique. J. Atmos. Chem., **32**, 35–59.

Richard, E.C., Aikin, K.C., Andrews, A.E., Daube, B.C., Jr., Gerbig, C. and other 8 authors (2001): Severe chemical ozone loss inside the Arctic polar vortex during winter 1999–2000 inferred from in situ airborne measurements. Geophys. Res. Lett., **28**, 2197–2200.

Santee, M.L., Manney, G.L., Read, W.G., Froidevaux, L. and Waters, J.W. (1996): Polar vortex conditions during the 1995–96 Arctic winter: MLS ClO and HNO_3. Geophys. Res. Lett., **23**, 3207–3210.

Santee, M.L., Manney, G.L., Froidevaux, L., Zurek, R.W. and Waters, J.W. (1997): MLS observations of ClO and HNO_3 in the 1996–97 Arctic polar vortex. Geophys. Res. Lett., **24**, 2713–2716.

Santee, M.L., Manney, G.L., Livesey, N.J. and Waters, J.W. (2000): UARS microwave limb sounder observations of denitrification and ozone loss in the 2000 Arctic late winter. Geophys. Res. Lett., **27**, 3213–3216.

Schultz, A., Rex, M., Steger, J., Harris, N.R.P., Braathen, G.O. and other 29 authors (2000): Match observations in the Arctic winter of 1996/97: High stratospheric ozone loss rates correlate with low temperatures deep inside the polar vortex. Geophys. Res. Lett., **27**, 205–208.

Shibata, T., Iwasaka, Y., Fujiwara, M., Hayashi, M., Nagatani, M., Shiraishi, K., Adachi, H., Sakai, T., Susumu, K. and Nakura, Y. (1997): Polar stratospheric clouds observed by lidar over Spitsbergen in the winter of 1994/1995: Liquid particles and vertical "sandwich" structure. J. Geophys. Res., **102D**, 10829–10840.

Sinnhuber, B.-M., Chipperfield, M.P., Davies, S., Burrows, J.P., Eichmann, K.-U. and other 6 authors (2000): Large loss of total ozone during the Arctic winter of 1999/2000. Geophys. Res. Lett., **27**, 3473–3476.

Sugita, T., Kondo, Y., Nakajima, H., Schmidt, U., Engel, A., Oelhaf, H., Wetzel, G., Koike, M. and Newman, P.A. (1998): Denitrification observed inside the Arctic vortex in February 1995. J. Geophys. Res., **103D**, 16221–16233.

Von der Gathen, P., Rex, M., Harris, N.R.P., Lucic, D., Knudsen, B.M. and other 10 authors (1995): Observational evidence for chemical ozone depletion over the Arctic in winter 1991–92. Nature, **375**, 131–134.

Wirth, M. and Renger, W. (1996): Evidence of large scale ozone depletion within the arctic polar vortex 94/95 based on airborne LIDAR measurements. Geophys. Res. Lett., **23**, 813–816.

World Meteorological Organization (WMO) (1999): Scientific Assessment of Ozone Depletion: 1998. Global Ozone Research and Monitoring Project - Report, **44**, WMO.