Polar Meteorol. Glaciol., **13**, 11-21, 1999

ON THE STRATOSPHERIC OZONE LOSS OVER EUREKA STATION IN THE CANADIAN ARCTIC (II) THE DIFFERENCE BETWEEN 1997/98 AND PREVIOUS YEARS

Michio HIROTA[1], Koji MIYAGAWA[2], Tomohiro NAGAI[3], Toshifumi FUJIMOTO[4], Yukio MAKINO[3], Osamu UCHINO[4], Kazuaki AKAGI[4] and Hans FAST[5]

[1] *Meteorological College, 7-4-81, Asahi-cho, Kashiwa 277-0852*
[2] *Aerological Observatory, 1-2, Nagamine, Tsukuba 305-0052*
[3] *Meteorological Research Institute, 1-1, Nagamine, Tsukuba 305-0052*
[4] *Observations Department, Japan Meteorological Agency, 1-3-4, Ote-machi, Chiyoda-ku, Tokyo 100-8122*
[5] *Atmospheric Environment Service, North York, Ontario, Canada*

Abstract: Monthly average total ozone and monthly average temperature at 50 hPa (T_{50}) over Eureka, both obtained by ECC type ozone sonde observations, were high throughout the winter to early spring of 1997/98 in contrast to those in the former 3 years.

The situation is discussed in relation to the relative location of Eureka with respect to the polar vortex boundary and the chemical ozone loss inside the polar vortex. In 1997/98, Eureka was inside the polar vortex in the lower stratosphere (475 K potential temperature level) only in the middle of December, early to mid-February and early to mid-March. The period was shorter than in the former 3 years. Moreover, daily T_{50} values when the lower stratosphere over Eureka was inside the polar vortex were not so low compared with those in the former 3 years, and PSCs were not observed over Eureka. The year to year variation of the temperatures in the lower stratosphere (T_{50}) over Eureka inside the polar vortex was generally consistent with the variation of the one within the entire polar vortex.

A positive correlation between intravortex potential vorticity (PV) and ozone mixing ratio is expected in the lower stratosphere in the absence of strong chemical ozone loss. In 1997/98, this relation seems to have held during the winter to early spring over Eureka. Also, the total ozone in 1997/98 over Eureka when Eureka was inside the polar vortex in the lower stratosphere was higher than in the former 3 years. These suggest that the chemical ozone loss in 1997/98 inside the polar vortex was small in contrast to the former 3 years.

1. Introduction

Toward winter, cooling of polar stratospheric air in the lack of solar radiation leads to formation of the circumpolar wind belt. This westerly wind belt (polar wind jet) defines the polar vortex. The boundary of the polar vortex is characterized by large gradients in temperature, mixing ratio of trace constituents and potential vorticity, and maximum in polar wind jet speed, and is considered to be a kinematic barrier to large scale transport. The Antarctic polar vortex develops lower temperature and persists longer than the Arctic polar vortex, because planetary wave activity is more frequent

Table 1. Number of ECC type ozone sonde observations at Eureka from September 1993 to March 1998.

	1993	1994	1995	1996	1997	1998	Total
January		8 (7)	15 (15)	12 (11)	13 (6)	13 (7)	61 (46)
February		6 (6)	12 (9)	5 (3)	12 (11)	9 (5)	44 (34)
March		4 (4)	16 (16)	11 (9)	12 (9)	14 (11)	57 (49)
April			4 (4)		7 (6)		11 (10)
May					3 (3)		3 (3)
June					4 (3)		4 (3)
July					5 (5)		5 (5)
August		5 (4)	5 (5)		4 (4)		14 (13)
September	5 (5)	4 (4)	4 (4)		4 (4)		17 (17)
October	4 (2)	4 (4)	4 (2)	5 (4)	4 (2)		21 (14)
November	3 (3)	5 (3)	5 (5)	4 (4)	4 (4)		21 (19)
December	11 (10)	10 (8)	15 (14)	11 (4)	9 (6)		56 (42)
Total	23 (20)	46 (40)	80 (74)	48 (35)	81 (63)	36 (23)	314 (255)

Numbers in parentheses are numbers of total ozone data.

and of larger amplitude in the Northern Hemisphere, which modifies the temperature and dynamical structure of the polar vortex. The cause of the polar stratospheric ozone depletion in winter is this very low temperature in the polar vortex. Polar stratospheric clouds (PSCs) are formed in the cold polar vortex. Then, stable halogen reservoir compounds are converted to active forms on these surfaces and ozone is depleted photochemically with the return of solar radiation. Polar ozone is depleted on a very small scale in the Arctic compared to the Antarctic for the above-mentioned reason (WMO, 1994). However, there were large ozone decreases in the Arctic lower stratosphere in 1994/95 and 1995/96, and, especially, in 1996/97.

In a previous paper (HIROTA *et al.,* 1998), we reported the results of ECC type ozone sonde observations in winter to early spring at Eureka (80°N, 86°W) from September 1993 to April 1997, and suggested the occurrence of chemical ozone loss in the lower stratosphere over Eureka, especially in 1996/97. This paper reports the difference of the ozone layer and temperature over Eureka between 1997/98 and the previous years, compares them with meteorological conditions over the polar region and discusses the possible cause of the difference. An outline of observations is given in HIROTA *et al.* (1998). The number of ozone sonde observations in each month is shown in Table 1. Column amount of ozone (total ozone) was calculated from the vertical ozone profile when the ozone sonde reached an altitude higher than 17 hPa. Temperature data were also obtained by ozone sonde observations.

2. Results and Discussion

2.1. Year to year variation of total ozone and stratospheric temperature

Seasonal variation of monthly average total ozone over Eureka shows a maximum in early spring and a minimum in autumn (HIROTA *et al.,* 1998), and is similar to the one

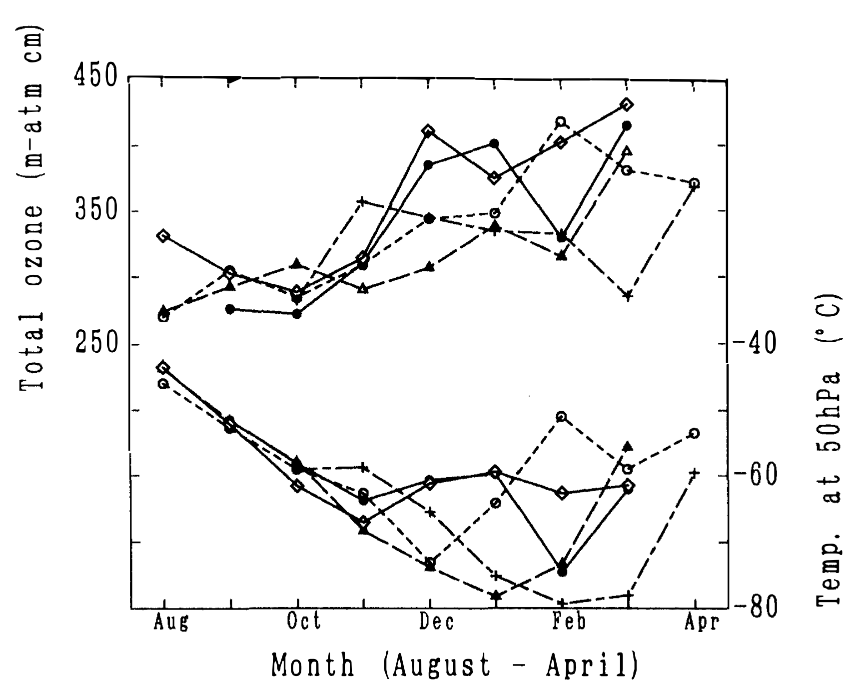


Fig. 1. Monthly average total ozone and temperature at 50 hPa over Eureka.
●: 1993/94, ○: 1994/95, △: 1995/96, +: 1996/97, ◇: 1997/98

at Resolute (74.7°N, 95°W) (FIOLETOV *et al.*, 1997). Monthly averages of total ozone over Eureka are shown in Fig. 1, together with monthly average temperatures at 50 hPa (T_{50}) (19–20 km). T_{50} was chosen because this height is just above the ozone density peak altitude. Figure 1 indicates that the total ozone and T_{50} from December to March since 1993/94 are positively correlated (correlation coefficient is 0.80).

In 1997/98, both total ozone and T_{50} were high throughout from December to March in comparison with those in previous years. They were very similar to those in 1993/94, except for February.

2.2. Meteorological condition of the Arctic vortex

Variation of total ozone over an Arctic site, Eureka during the winter to early spring is basically controlled by two factors. One is relative location of the site with respect to the polar vortex boundary. The other is the chemical ozone loss process inside the vortex.

First, relative location of Eureka with respect to the polar vortex boundary was estimated from isentropic potential vorticity (PV) in the lower stratosphere. PV was calculated from the Japan Meteorological Agency (JMA) objective analysis. In the PV maps at 475 K potential temperature (17–19 km) from December to March, large gradients were usually observed between 30 and $40\times 10^{-6}\,K\,m^2s^{-1}kg^{-1}$, and this region was considered to be the boundary of the polar vortex. This potential temperature was chosen, because this height was close to the ozone density peak altitude. Some examples of PV maps in 1996/97 and 1997/98 are shown in Fig. 2. On 10 February, 14 March and 22 December 1997, and on 8 February and 10 March 1998, Eureka was considered to be inside the polar vortex in the lower stratosphere. On the other hand,

(a)

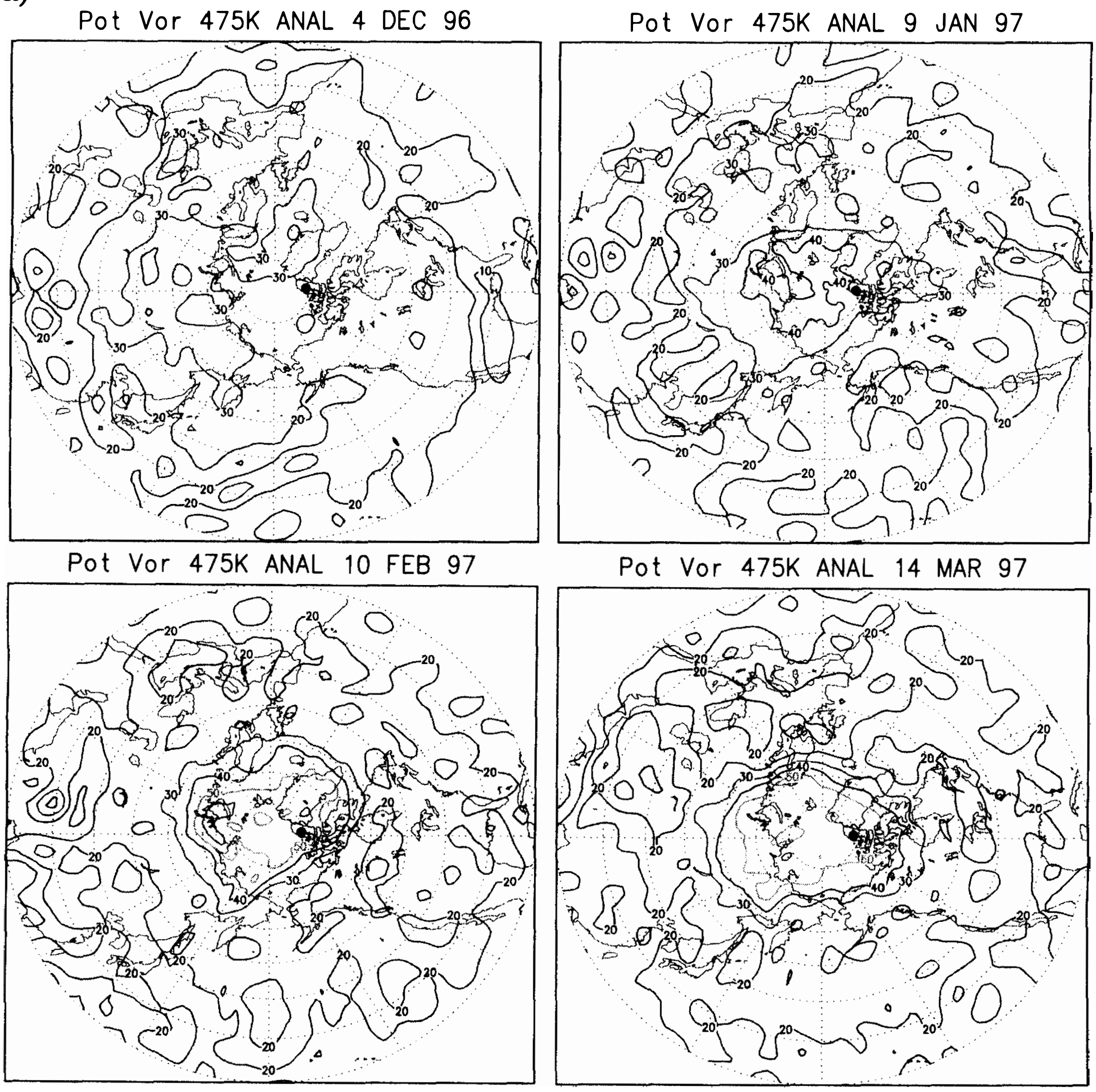


Fig. 2a. 1996/97.

Fig. 2. Potential vorticity map at 475 K potential temperature level over the Northern Hemisphere. Potential vorticity: $\times 10^{-6}$*K m*^{2}*s*$^{-1}$*kg*$^{-1}$*. ● in the maps show the locatiion of Eureka, with 0° longitude at the top and 90° W to the right.*

Eureka was not inside the vortex on 5 January and 27 February 1998. From these maps since 1993/94, Eureka, with a PV value higher than 40×10^{-6}K m^{2}s^{-1}kg^{-1}, was judged to be inside the polar vortex. When the PV value was lower than this value, Eureka was judged to be on the boundary of or outside the polar vortex. This threshold value seems to be appropriate for the 5 winters from 1993/94 to 1997/98.

Then, in relation to the chemical ozone loss, the daily PV at 475 K potential temperature level and daily T_{50} over Eureka are shown in Figs. 3 and 4, respectively. As seen in Figs. 3 and 4, when Eureka was inside the vortex in 1994/95, 1995/96 and 1996/97, T_{50} was often as low as the nitric acid trihydrate (NAT) formation temperature (about -80°C) and actually PSCs were observed, though, in some cases, PSCs

(b)

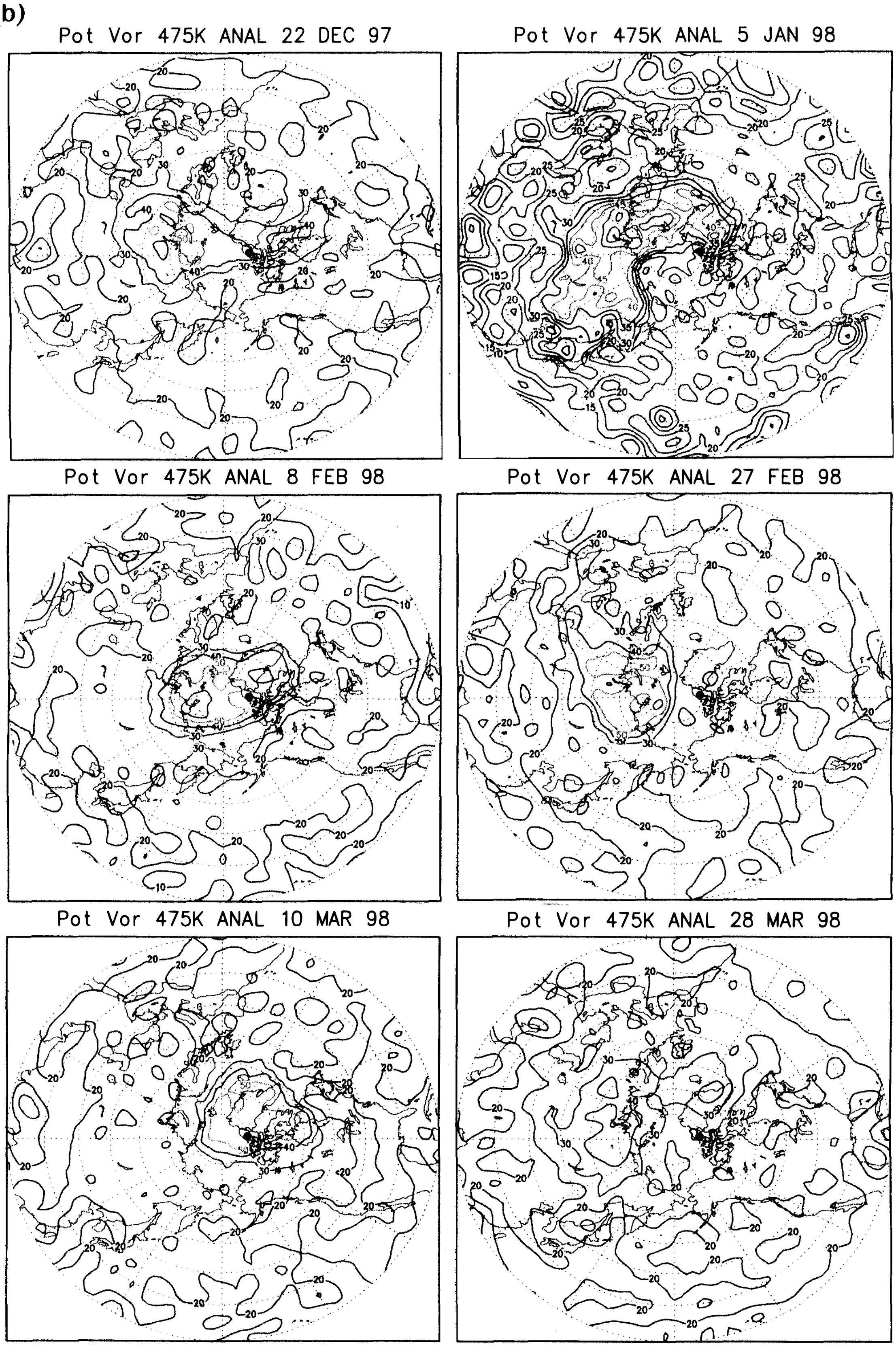
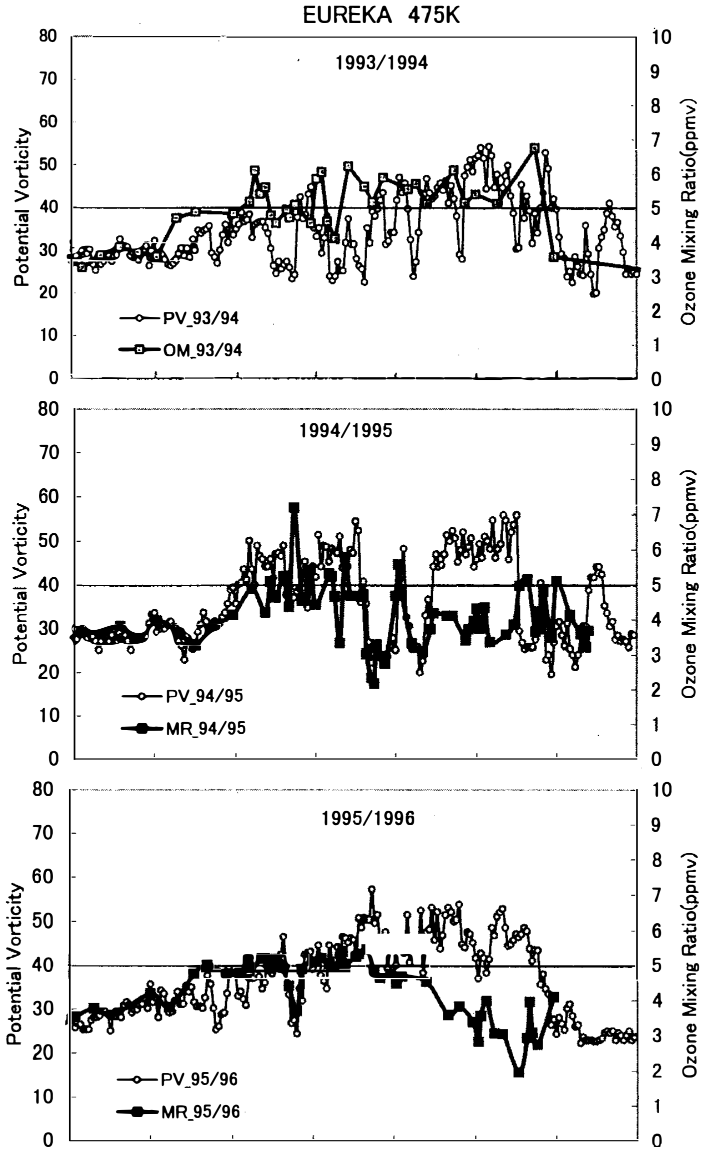


Fig. 2b. 1997/98.



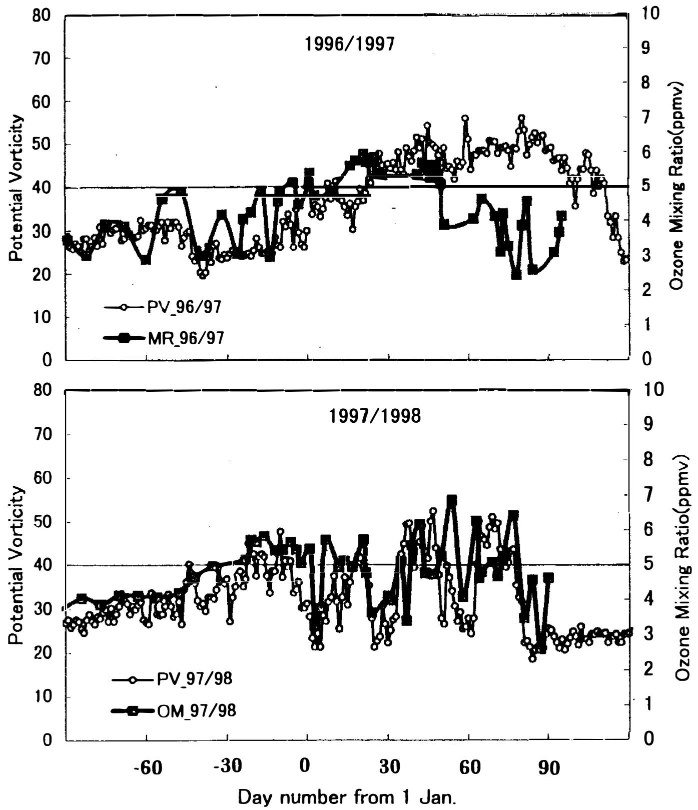


Fig. 3. Potential vorticity and ozone mixing ratio at 475 K potential temperature level over Eureka. ○: *Potential vorticity:* $\times 10^{-6}$ $K\,m^2s^{-1}kg^{-1}$. ■: *Volume mixing ratio of ozone: ppmv.* —: *Potential vorticity* $= 40 \times 10^{-6}$ $K\,m^2s^{-1}kg^{-1}$.

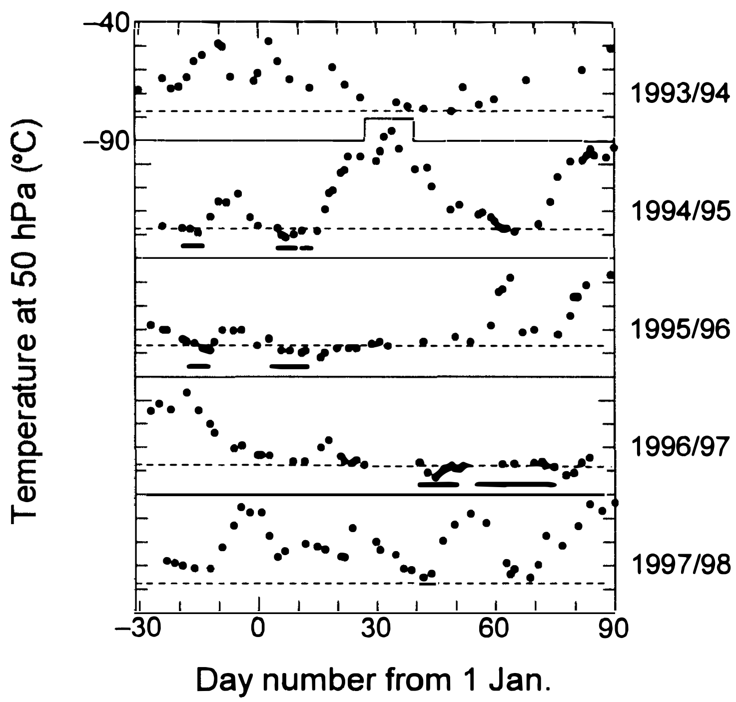


Fig. 4. Temperature at 50 hPa over Eureka. • : A NAT formation temperature of $-77.2°C$ at 50 hPa (H_2O=5 ppmv, HNO_3=10.5 ppbv). —: Period when PSCs were observed over Eureka.

were observed at higher temperature than the NAT formation temperature (NAGAI *et al.,* 1997a, b). The periods when PSCs were observed are shown in Fig. 4.

Corresponding to the situations in the lower stratosphere over Eureka, those over the polar region from 1993/94 to 1996/97 were as follows. In 1993/94, averaged minimum temperatures in the lower stratosphere (465 K) inside the polar vortex were generally warmer than in 1992/93 and 1994/95, except for the short period from late February to early March (MANNEY *et al.,* 1996). PSCs were not observed over Eureka, though Eureka was inside the vortex during this period. In 1994/95, lower stratosphere daily minimum temperatures (50 hPa) over the north polar region (65–90°N) reached record low values in December and January, and again during March after a warming event in February (National Oceanic and Atmospheric Administration (NOAA), 1995). T_{50} values when Eureka was inside the vortex were in good agreement with averaged minimum temperatures (50 hPa) inside the vortex (DONOVAN *et al.,* 1995). In 1995/96, Eureka was generally inside the vortex from December to the middle of March, and NOAA (1996) again reports record low temperatures in the lower stratosphere over the north polar region from December to early March. In 1996/97, the polar vortex was undeveloped into early January (4 December 1996 and 9 January 1997 in Fig. 2a), but clearly defined by the middle of January, and Eureka remained inside the vortex from late January to early April; T_{50} was low continuously from February to March. An unusually cold, polar-centered vortex (10 February and 14 March 1997 in Fig. 2a) remained in a relatively undisturbed state from January to late April (NOAA, 1997; NEWMAN *et al.,* 1997). These results indicate that the temperatures in the lower stratosphere inside the polar vortex were generally consistent with those over Eureka inside the polar vortex.

In 1997/98, Eureka was inside the polar vortex in the lower stratosphere only in the middle of December, early to mid-February, and early to mid-March. The period when Eureka was inside the polar vortex was short compared with those in the former 3 years. The higher total ozone and T_{50} in 1997/98 presented in 2.1 was partly due to this fact. JAPAN METEOROLOGICAL AGENCY (1998) reports that the polar vortex (at 30 and 100 hPa) in 1997/98 generally shifted toward the European side in December because of the strong Aleutian high, though Eureka in the lower stratosphere was on the edge of the polar vortex on 22 December 1997 as shown in Fig. 2b. The vortex was weak and over the European side in January, and was over the Barents Sea in February (5 January, and 8 and 27 February 1998 in Fig. 2b). In March, the vortex at 100 hPa was strengthened and shifted over northern Greenland, and the vortex at 30 hPa shifted over the Svalbard Islands (10 March 1998 in Fig. 2b). These meteorological conditions seem to be consistent with the relative location of Eureka with respect to the polar vortex boundary.

2.3. Total ozone and temperature inside the vortex

As shown in Fig. 4, daily T_{50} values in 1997/98 when Eureka was inside the polar vortex were not so low compared with those in the former 3 years, and PSCs were not observed over Eureka. Table 2 shows the average total ozone and average T_{50}, and the correlation between daily values in each year over Eureka in which Eureka was inside the polar vortex in the lower stratosphere, starting from 1993/94. The number of the data in each month is very low (no data in January 1998, and only one data point each in December 1993, January 1994 and March 1996), average values between December and March are shown. It is evident that the total ozone values in 1994/95, 1995/96 and 1996/97 are lower than in 1993/94 and 1997/98. Similar variation can be seen in T_{50}. The higher total ozone and T_{50} in 1997/98 presented in 2.1 was also due to the fact that these two quantities were higher even within the vortex.

Table 2. Average total ozone, average temperature at 50 hPa (T_{50}), and correlation between daily total ozone and T_{50}, when Eureka was inside the polar vortex in the lower stratosphere (at 475 K).

Year	Ozone sonde observations*	Average total ozone**	Average T_{50}**	Correlation: slope (m-atm cm/°C)	Correlation: correlation coefficient
1993/94	10	347 (47)	−69.6 (7.9)	2.0	0.35
1994/95	24***	319 (48)	−73.4 (7.5)	4.7	0.74
1995/96	19	326 (32)	−76.1 (6.3)	1.3	0.26
1996/97	21	311 (45)	−78.7 (2.2)	2.5	0.12
1997/98	10	376 (59)	−69.4 (5.5)	9.3	0.87

*: Ozone sonde observations, when the ozone sonde reached an altitude higher than 17 hPa.

**: Standard deviations are shown in parentheses.

***: Data on 31 January, 1 February and 24 March are omitted, because total ozone values were very high, though the PV values were high instantaneously.

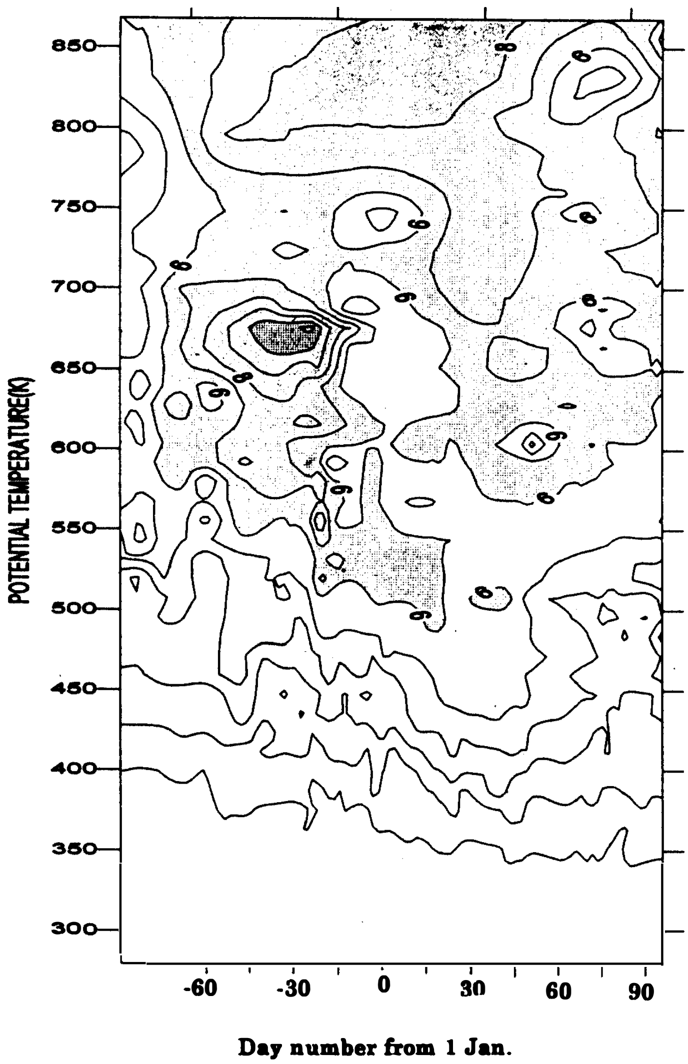


Fig. 5. Ozone mixing ratio (ppmv) over Eureka in 1996/97.

NOAA (1998) reports a similar situation, *i.e.*, that the Arctic polar vortex in the winter of 1997/98 was cold in December, but after a warming event in January warmer and less stable than in previous years. As mentioned before, in December, the polar vortex shifted toward the European side and T_{50} over Eureka was rather warm.

2.4. Chemical ozone loss

Figure 3 shows PV at the 475 K potential temperature level, together with ozone mixing ratio at the same level over Eureka. In the lower stratosphere (475 K level) inside the polar vortex, a positive correlation between PV and ozone mixing ratio is expected in the absence of strong chemical ozone loss, because the distribution of ozone in the lower stratosphere is largely controlled by dynamics (PLUMB and KO, 1992; DONOVAN *et al.*, 1995, 1996). As shown in Fig. 3, this relation between intravortex PV and ozone mixing ratio seems to hold in the first half of each observation period in 1994/95, 1995/96 and 1996/97. In the latter half, the ozone mixing ratio decreased from that expected from the PV change. This would be due to the formation of PSCs in the lower stratosphere inside the very cold vortex and the increase of active chlorine compounds in the presence of PSCs. Actually, enhanced chlorine monoxide (ClO) was observed in these years by UARS Microwave Limb Sounder or a ground-based FTIR system (Manney *et al.,* 1996; Donovan *et al.,* 1996, 1997). For example, as shown in Fig. 5, ozone mixing ratio in the lower stratosphere (around 475 K) in 1996/97 increased through the end of February due to the diabatic descent of air (Donovan *et al.,* 1997), and then decreased abruptly probably due to the chemical ozone loss. These results indicate that there were chemical ozone loss in 1994/95 (Manney *et al.,* 1996; Bird *et al.,* 1997), 1995/96 (Donovan *et al.,* 1996) and especially in 1996/97 (Donovan *et al.,* 1997; Newman *et al.,* 1997). If the chemical ozone loss process is working inside the polar vortex, positive correlation between total ozone and T_{50}, expected from the diabatic descent of air, would be weakened. This relation is suggested by the difference between 1997/98 and the former 3 years over Eureka, as shown in the fifth and sixth columns of Table 2.

However, as shown in Fig. 3, the decrease of ozone mixing ratio was not clear in 1997/98, because the polar vortex came and went over Eureka, and seemed to be rather small in comparison with those in the former 3 years. Also, the total ozone in 1997/98 over Eureka when Eureka was inside the polar vortex in the lower stratosphere were higher than in the former 3 years (Table 2). This would be due to that the polar vortex in 1997/98 was warmer in the lower stratosphere than in the former 3 years. Actually, PSCs were not observed over Eureka. This suggests the less efficient activation of chlorine species and suggests that the chemical ozone loss in 1997/98 inside the polar vortex was small in contrast to the former 3 years.

Similar situations were seen in 1993/94 except for early March, when the ozone mixing ratio was lower than that expected from the PV change. Manney *et al.* (1995) report chemical ozone loss from late February to early March in 1993/94. This suggests that PSCs were formed somewhere in the vortex except for Eureka, and total ozone over Eureka was considerably lower than in 1997/98 (Table 2). Positive correlation between total ozone and T_{50} was rather low compared with that in 1994/95, partly because the data in 1993/94 were relatively concentrated in February and March.

Acknowledgments

The authors thank reviewers for helpful comments on the manuscript. This work was supported by the Institute for Space and Terrestrial Science, York University, Canada, the Atmospheric Environment Service of Canada and the Science and Technology Agency of Japan.

References

Bird, J.C., Pal, S.R., Carswell, A.I., Donovan, D.P., Manney, G.L., Harris, J.M. and Uchino, O. (1997): Observations of ozone structures in the Arctic polar vortex. J. Geophys. Res., **102 D**, 10785–10800.

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., DAVIES, J., DUCK, T.J., KAMINSKI, J. W., MCELROY, C.T., MITTERMEIER, R.L., PAL, S.R., SAVASTIOUK, V., VELKOV, D. and WHITEWAY, J.A. (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.

FIOLETOV, V.E., KERR, J.B., WARDLE, D.I., DAVIES, J., HARE, E.W., MCELROY, C.T. and TARASICK, D.W. (1997): Long-term ozone decline over the Canadian Arctic to early 1997 from ground-based and balloon observations. Geophys. Res. Lett., **24**, 2705-2708.

HIROTA, M., MIYAGAWA, K., NAGAI, T., FUJIMOTO, T., MAKINO, Y., UCHINO, O. and FAST, H. (1998): On the stratospheric ozone loss over Eureka Station in the Canadian Arctic. Polar Meteorol. Glaciol., **12**, 19-28.

JAPAN METEOROLOGICAL AGENCY (1998): Monthly report on climate system, December 1997- March 1998 (in Japanese).

MANNEY, G.L., ZUREK, R.W., FROIDEVAUX, L. and WATERS, J.W. (1995): Evidence for Arctic ozone depletion in late February and early March 1994. Geophys. Res. Lett., **22**, 2941-2944.

MANNEY, G.L., FROIDEVAUX, L., WATERS, J.W., SANTEE, M.L., READ, W.G., FLOWER, D.A., JARNOT, R.F. and ZUREK, R.W. (1996): Arctic ozone depletion observed by UARS MLS during the 1994-95 winter. Geophys. Res. Lett., **23**, 85-88.

NAGAI, T., UCHINO, O., ITABE, T., SHIBATA, T., MIZUTANI, K., FUJIMOTO, T. and HIROTA, M. (1997a): 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.

NAGAI, T., UCHINO, O., ITABE, T., SHIBATA, T., MIZUTANI, K. and FUJIMOTO, T. (1997b): 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.

NATIONAL OCEANIC and ATMOSPHERIC ADMINISTRATION (NOAA) (1995-1998): Northern hemisphere winter summary 1994-95～1997-98.

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. and KO, M.K.W. (1992): Interrelationships between mixing ratios of long-lived stratospheric constituents. J. Geophys. Res., **97 D**, 10145-10156.

WORLD METEOROLOGICAL ORGANIZATION (WMO) (1994): Scientific assessment of ozone depletion: 1994. Global Ozone Research and Monitoring Project-Report No. 37, WMO.

(Received January 12, 1999; Revised manuscript accepted September 24, 1999)