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Detection of air within the northern hemisphere polar vortex at Wakkanai and at Tsukuba, Japan

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Abstract: Intensive ozonesonde observations were conducted at Wakkanai (45.4°N, 141.7°E), the northernmost city of Japan, during the period 15th to 24th February 2001. Air in the polar vortex passed over Wakkanai on 19th February 2001 on the 700 K isentropic surface. An increase of potential vorticity and a decrease of ozone mixing ratio on the 700 K isentropic surface over Wakkanai were observed on the same day, 19th February 2001. On the other hand, on the 450 K isentropic surface the air in the polar vortex passed over Tsukuba (36.1°N, 140.1°E), Japan, where the Aerological Observatory and the Meteorological Research Institute are located, on 20th February 2001. Decrease of the ratio of observed HCl (hydrogen chloride) to HCl estimated from HF (hydrogen fluoride) and increases of the potential vorticity and ozone mixing ratio on the 450 K isentropic surface were observed over Tsukuba on 20th February 2001. These facts indicate that the polar vortex passed over Tsukuba on the 450 K isentropic surface on 20th February 2001. Observations show that the polar vortex on the 700 K isentropic surface existed over Europe and Siberia on 14th February 2001 moved eastward, and reached Wakkanai, Japan on 19th February 2001. Observations also show that the polar vortex on the 450 K isentropic surface found over Europe and Siberia on the 14th moved eastward and reached Wakkanai, Japan between 15th and 20th February 2001 and covered Tsukuba, Japan on 20th February 2001. The ozone mixing ratio derived from ozonesonde data shows the possibility of decrease of ozone mixing ratio with ozone destructive chemical reactions in the northern hemisphere polar vortex on the 450 K isentropic surface.

key words: ozone, polar, vortex, Wakkanai, Tsukuba

1. Introduction

Ozone in the atmosphere is essential not only for human beings but also to most life on the earth, because it controls the intensity of the harmful ultraviolet radiation in sunlight. So it is important to study how the ozone layer in the atmosphere is controlled.

The stratospheric polar vortex in the northern hemisphere is formed during winter. Ozone destruction occurs in the polar vortex over the northern hemisphere (Terao *et al.,* 2002; Hirota *et al.,* 2003) as well as in the southern hemisphere (Chubachi, 1984; Farman *et al.,* 1985).

Here, we address the question of whether the air in the polar vortex affects the ozone layer over Japan or not. In order to give an answer to this question, we conducted extensive observations of the vertical distribution of ozone at Wakkanai, the northernmost city of Japan, using an Electrochemical Concentration Cell (ECC) type ozonesonde (Komhyr, 1969) from 15th to 24th in February 2001 (Chubachi *et al.,* 2002). The obtained data were analyzed to study the ozone layer in the winter northern hemisphere. In addition, observations were conducted at the Meteorological Research Institute in Tsukuba, Japan to measure the integrated amount of HCl in the atmospheric column using a Fourier Transform Infrared spectrometer (FTIR) (Makino *et al.,* 2000). The ozonesonde data of other stations in the northern hemisphere were also used. The results obtained from the analyses are shown in this paper.

2. Data set

Vertical ozone profiles at Wakkanai were obtained from the observations (Chubachi *et al.,* 2002). In addition, ozonesonde data were obtained from WOUDC (World Ozone and Ultraviolet radiation Data Center). TOMS (Total Ozone Mapping Spectrometer) version 7 data were obtained from NASA. The Meteorological data were obtained from GANAL data (Global objective ANALysis data made by Japan Meteorological Agency). The ozone observations at Wakkanai were conducted from 15th to 24th February 2001. In addition, TOMS data showed low total ozone values less than 250 DU (the minimum value is 219 DU) on 13th and 14th February 2001 over Europe. This phenomenon was related to the polar vortex that covered Wakkanai on 19th February 2001. For these reasons, the period of analysis was chosen from 13th to 24th February 2001. We calculated the ozone mixing ratio and potential vorticity on ten (300 K, 330 K, 350 K, 400 K, 450 K, 500 K, 550 K, 600 K, 650 K, 700 K) isentropic surfaces at each ozonesonde observation. The data set used in this paper is only for the northern hemisphere. The ozonesonde data are normalized to the total ozone amounts obtained at almost the same time with ground based instruments except for Wakkanai. For Wakkanai TOMS data were used for normalization of ozonesonde data (Chubachi *et al.,* 2002). Names and locations of the ozonesonde stations used in this paper are listed in Table 1.

Table 1. Names and locations of the ozonesonde stations.

No.	Station	Latitude (°N)	Longitude (°E)	Nation
1	Naha	26.2	127.7	Japan
2	Kagoshima	31.6	130.6	Japan
3	Tateno (Tsukuba)	36.1	140.1	Japan
4	Sapporo	43.1	141.3	Japan
5	Wakkanai	45.4	141.7	Japan
6	Payerne	46.5	6.7	Switzerland
7	Hohenpeissenberg	47.8	11.0	Germany
8	Plaha	50.0	14.7	Czech Republic
9	Lindenberg	52.2	14.1	Germany
10	Legionowo	52.4	21.0	Poland
11	Goose Bay	53.3	−60.3	Canada

3. Ozone mixing ratio on isentropic surfaces at Wakkanai

3.1. Ozone mixing ratio over 700 K isentropic surface (~20 hPa) at Wakkanai

Figure 1 shows the cross section of ozone mixing ratio at Wakkanai. The horizontal axis shows the date and the vertical axis shows the potential temperature. The ozone mixing ratio decreased on the 400 K isentropic surface during 21st and 23rd February. The ozone mixing ratio decreased on the 600 K, 650 K and 700 K isentropic surfaces on 19th February. However, significant changes of ozone mixing ratio are not seen on isentropic surfaces lower than 350 K. Because the ozone mixing ratio is thought to be a conservative quantity on a given isentropic surface, we can trace its origin.

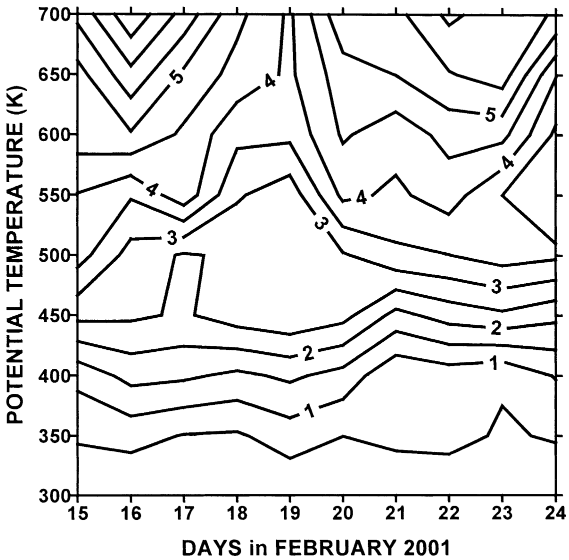

Fig. 1. Time-height cross section of ozone mixing ratio (ppmv) at Wakkanai during 15th to 24th February 2001. The horizontal axis shows days in February 2001 and the vertical axis shows potential temperature.

Figure 2 shows the ozone mixing ratios on the 700 K isentropic surface at Wakkanai during the period from 15th to 24th February 2001. The ozone mixing ratios except on the 18th and 19th were between 5 ppmv and 7 ppmv. On the 18th and 19th February 2001, they were below 5 ppmv. Figure 3 shows the potential vorticity at Wakkanai on the 700 K isentropic surface from 13th to 24th February 2001. The potential vorticity increased on the 19th (Fig. 3) on the same day as the decrease of ozone mixing ratio on the 700 K isentropic surface was observed (Fig. 2).

Figure 4 shows the scatter diagram of the potential vorticity and ozone mixing ratio on the 700 K isentropic surface constructed using the ozonesonde data obtained from the stations listed in Table 1 from 13th to 24th February. Ozonesonde data at Wakkanai are available only for the period from 15th to 24th February. The ozone

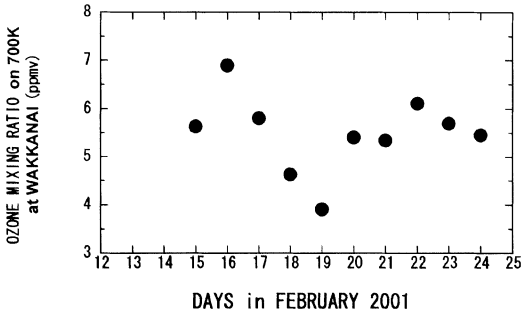

Fig. 2. *Ozone mixing ratio on the 700 K isentropic surface at Wakkanai during 15th to 24th February 2001.*

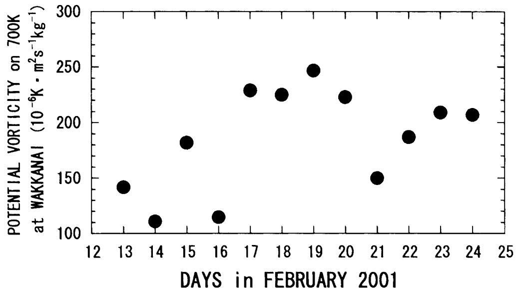

Fig. 3. *Potential vorticity on the 700 K isentropic surface at Wakkanai during 13th to 24th February 2001.*

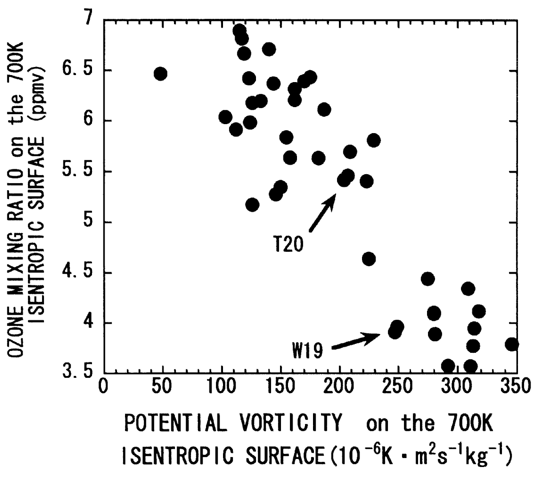

Fig. 4. *Scatter diagram of ozone mixing ratio and potential vorticity on the 700 K isentropic surface. The label W19 indicates the data point corresponding to 19th February 2001 at Wakkanai, T20 indicates the data point corresponding to 20th February 2001 at Tsukuba.*

mixing ratio tends to decrease with potential vorticity when the potential vorticity is smaller than 220 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) and it shows a sharp decrease at potential vorticity between 220 and 240 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$). It shows an almost constant value around 4 ppmv when the potential vorticity is larger than 240 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$).

Based on Fig. 4, the area where potential vorticity is larger than or equal to 240 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) is "in the polar vortex" on the 700 K isentropic surface and the area where potential vorticity is between 220 and 240 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) is "on the boundary". The area of potential vorticity smaller than or equal to 220 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) is "out of the polar vortex" on the 700 K isentropic surface. Data at the point marked "W19" were obtained at Wakkanai on 19th February on the 700 K isentropic surface. We can see that Wakkanai was covered with air "in the polar vortex" on the 700 K isentropic surface on 19th February.

The small ozone mixing ratio with potential vorticity larger than or equal to 240 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) in Fig. 4 can be due to a less active ozone forming chemical reaction in the polar night region on the 700 K isentropic surface over high latitudes. The intensity of sunlight is very weak and hours of sunlight are short in winter at high latitudes. The polar vortex where potential vorticity is larger than or equal to 240 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) was located in higher latitudes until just before the analysis period discussed in this paper.

3.2. Ozone mixing ratio on the 450 K isentropic surface (~70 hPa)

3.2.1. Case at Wakkanai

In this section, we conduct a similar discussion for the 450 K isentropic surface to the one described in the previous section. In Fig. 5, the ozone mixing ratio at Wakkanai, Japan on the 450 K isentropic surface from the 15th to 24th is shown. Figure 5 shows that the ozone mixing ratio from the 15th to 20th is larger than that on the 21st to 24th. Figure 6 shows the potential vorticity at Wakkanai, Japan on the 450 K isentropic surface from the 13th to 24th. In Fig. 6, it is shown that the potential vorticity is large on the 15th, 16th, 17th, 18th, 19th, 20th and 24th of February 2001 and be small on the 21st and 23rd. Figure 7 shows the scatter diagram of the potential vorticity and ozone mixing ratio on the 450 K isentropic surface based on ozonesonde

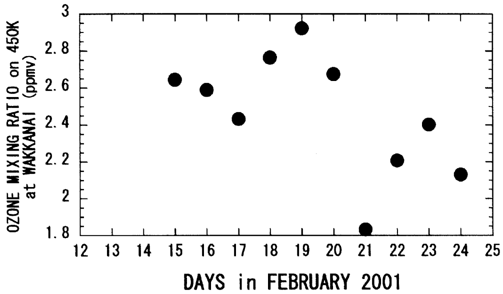

Fig. 5. Ozone mixing ratio on the 450 K isentropic surface at Wakkanai during 15th to 24th February 2001.

data from the stations listed in Table 1 from 13th to 24th February. Ozonesonde data at Wakkanai are available from 15th to 24th February. In Fig. 7, it is shown that the ozone mixing ratio shows a low value around 1 ppmv when the potential vorticity is less than or equal to 15 (10^{-6}K・$m^2s^{-1}kg^{-1}$). The ozone mixing ratio shows a sharp increase for potential vorticity between 15 and 22 (10^{-6}K・$m^2s^{-1}kg^{-1}$). Ozone mixing ratio shows a higher and almost constant value around 2.5 to 3 ppmv when the potential vorticity is larger than or equal to 22 (10^{-6}K・$m^2s^{-1}kg^{-1}$). Based on Fig. 7, the area with potential vorticity larger than or equal to 22 (10^{-6}K・$m^2s^{-1}kg^{-1}$) is "in the polar vortex" on the 450 K isentropic surface, and the area with potential vorticity between 15 and 22 (10^{-6}K・$m^2s^{-1}kg^{-1}$) is "on the boundary". The area with potential vorticity less than or equal to 15 (10^{-6}K・$m^2s^{-1}kg^{-1}$) is "out of the polar vortex". The thick broken line in Fig. 6 shows potential vorticity equal to 22 (10^{-6}K・$m^2s^{-1}kg^{-1}$). Wakkanai is covered with air of potential vorticity larger than or equal to 22 (10^{-6}K・$m^2s^{-1}kg^{-1}$), in the polar vortex on the 15th, 16th, 17th, 18th, 19th 20th and

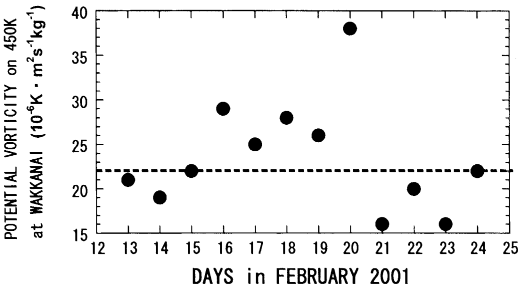

Fig. 6. Potential vorticity on the 450 K isentropic surface at Wakkanai during 13th to 24th February 2001.

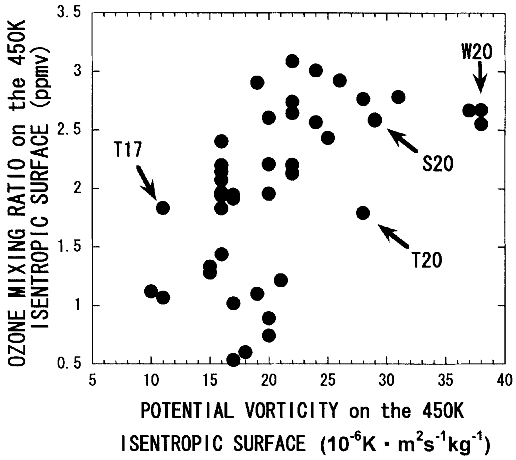

Fig. 7. Scatter diagram of ozone mixing ratio and potential vorticity on the 450 K isentropic surface. Labels S20, T17, T20, and W20 indicate data points observed on the 20th February 2001 at Sapporo, on the 17th and 20th at Tsukuba and on the 20th at Wakkanai.

24th.

In Fig. 7 we can see that the ozone mixing ratio in the polar vortex is larger than that out of the vortex on the 450 K isentropic surface. This is because the downward motion in the northern hemisphere polar vortex carries ozone rich air downward from higher altitudes of the stratosphere. Kanzawa *et al.* (2000) reported slow downward motion of the stratospheric air mass with a rate of 0.6–0.8 km per month in the northern hemisphere winter polar vortex using the ILAS (Improved Limb Atmospheric Spectrometer) data.

3.2.2. Case at Tsukuba

In Fig. 8, ozone mixing ratios at Tsukuba, Japan on the 450 K isentropic surface from the 13th to 24th are shown. The ozonesonde data are available only for 7 days (14th, 15th, 17th, 18th, 19th, 20th and 21st). Increases of ozone mixing ratios on 17th and 20th February 2001 are shown in Fig. 8. Figure 9 shows the potential vorticity at Tsukuba, Japan on the 450 K isentropic surface from the 13th to 24th. In Fig. 9, the thick broken line shows the potential vorticity equal to 22 (10^{-6}K・$m^2s^{-1}kg^{-1}$). We can see that the potential vorticity is larger or equal to 22 (10^{-6}K・$m^2s^{-1}kg^{-1}$) for the 16th, 20th and 22nd February 2001.

"T20" in Fig. 7 shows the value at Tsukuba on 20th February, the day when increases of ozone mixing ratio and potential vorticity were observed at Tsukuba.

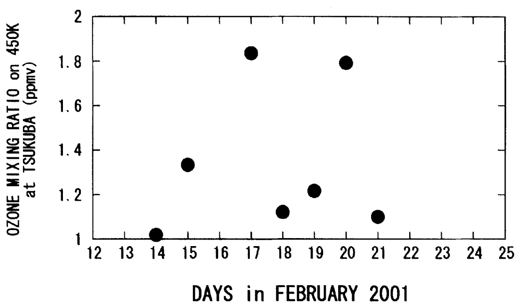

Fig. 8. Ozone mixing ratio on the 450 K isentropic surface at Tsukuba during 13th to 24th February 2001.

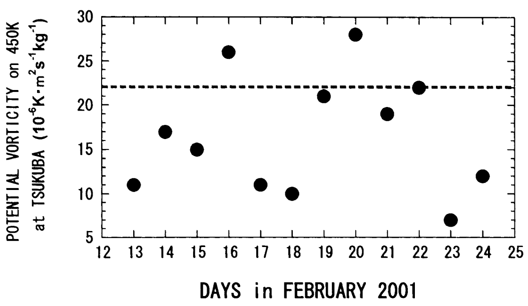

Fig. 9. Potential vorticity on the 450 K isentropic surface at Tsukuba during 13th to 24th February 2001.

Based on Fig. 7, it is seen that Tsukuba was covered with air "in the polar vortex" on the 450 K isentropic surface on 20th February 2001. On 17th February, the point marked "T17" (Tsukuba 17th February) in Fig. 7 was out of the vortex, though an increase of ozone mixing ratio is also shown in Fig. 8. The polar vortex passed over Tsukuba on the 450 K isentropic surface on 20th February 2001 though Tsukuba was out of the vortex (*cf.* marked as "T20" in Fig. 4) on the 700 K isentropic surface.

An increase of potential vorticity was seen on 20th February at Tsukuba on the 500 K, 550 K, 600 K and 650 K isentropic surfaces. On the 500 K and 550 K isentropic surfaces, Tsukuba would be in the polar vortex, though the boundary was not clear on the scatter diagrams similar to Fig. 4 and Fig. 7. On the 600 K isentropic surface, we could not conclude that Tsukuba is in the polar vortex on these surfaces because the boundary was not clear on the scatter diagrams similar to Fig. 4 and Fig. 7. On the 650 K isentropic surface Tsukuba would be on the border of the vortex.

Potential vorticity was greater than or equal to 22 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) on 16th, 20th and 22nd February on the 450 K isentropic surface over Tsukuba. It appears that Tsukuba was covered with the polar vortex on the 450 K isentropic surface on these days. However, ozonesonde data are not available for Tsukuba on the 16th and 22nd, hence it is not possible to discuss the relation between the ozone mixing ratio and potential vorticity for these days at Tsukuba.

4. Discussion

4.1. Movement of the polar vortex on the 700 K isentropic surface

The shaded area in Fig. 10a shows the area where potential vorticity (calculated from GANAL data) is larger than or equal to 240 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) on the 700 K isentropic surface and is thought to have been in the polar vortex on 14th February

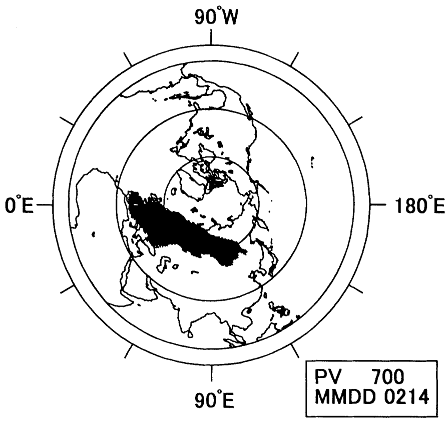

Fig. 10a. Shaded area shows potential vorticity larger than or equal to 240 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) on the 700 K isentropic surface on 14th February 2001.

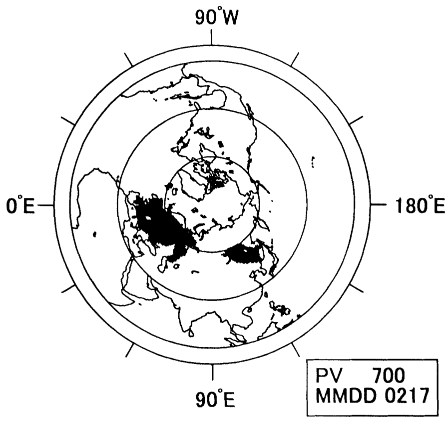

Fig. 10b. Same as Fig. 10a but for 17th February 2001.

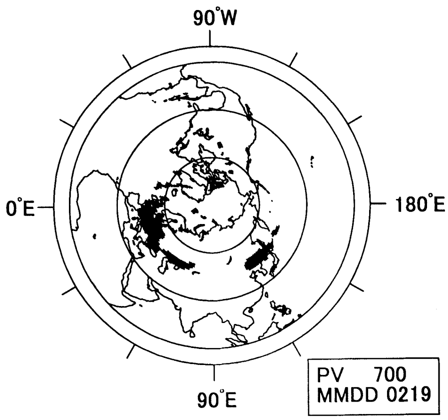

Fig. 10c. Same as Fig. 10a but for 19th February 2001.

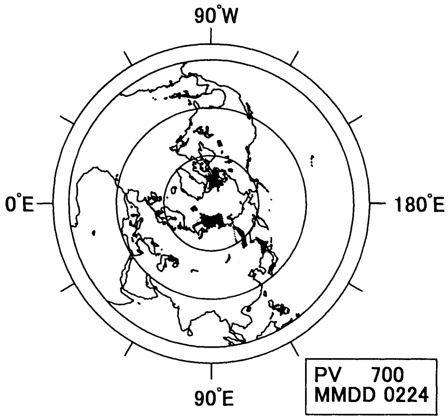

Fig. 10d. Same as Fig. 10a but for 24th February 2001.

2001. The extent of the area is wide and its latitude is north of 35°N, covering Europe through Siberia. However, it did not cover Japan yet. Figure 10b shows that the area separated into two on 17th February 2001. Figure 10c shows that one of the two areas arrived at Wakkanai on 19th February 2001 when the decrease of ozone mixing ratio at 700 K over Wakkanai was observed. The area of this domain became very small on 24th February 2001 (Fig. 10d).

4.2. Movement of the polar vortex on the 450 K isentropic surface

The shaded area in Fig. 11a shows the area where potential vorticity is larger than

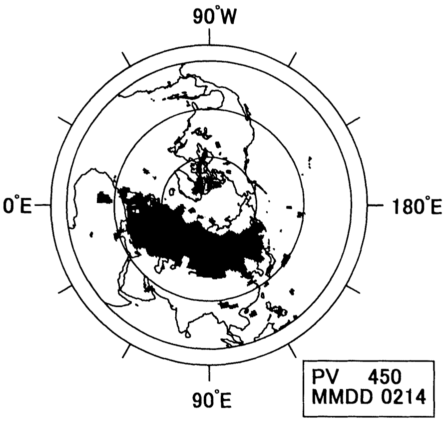

Fig. 11a. Shaded area shows potential vorticity larger than or equal to 22 (10^{-6} K · $m^2 s^{-1} kg^{-1}$) on the 450 K isentropic surface on 14th February 2001.

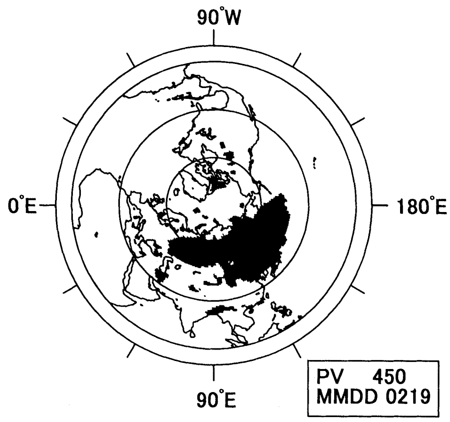

Fig. 11b. Same as Fig. 11a but for 19th February 2001.

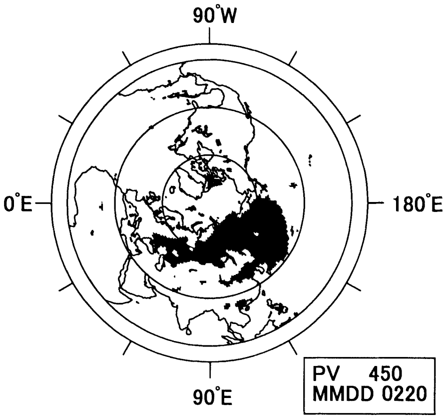

Fig. 11c. Same as Fig. 11a but for 20th February 2001.

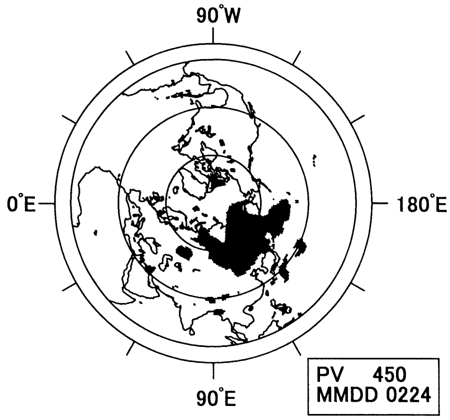

Fig. 11d. Same as Fig. 11a but for 24th February 2001.

or equal to 22 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$) on the 450 K isentropic surface and is thought to have been in the polar vortex on 14th February 2001. The polar vortex covered a large area at latitudes north of 30°N over Europe through Siberia and Sakhalin. Figure 11b shows that the polar vortex moved east and Wakkanai was covered by the polar vortex, whereas Tsukuba was not covered by the polar vortex region on 19th February 2001. Figure 11c shows that the polar vortex covered most of Japan on 20th February 2001, when increase of ozone mixing ratio on the 450 K isentropic surface and decrease of the HCl ratio at Tsukuba were also observed (*cf.* Fig. 14). The polar vortex moved northward and Tsukuba was outside of the polar vortex on the 24th (*cf.* Fig. 11d).

4.3. The possibility of ozone destruction in the polar vortex on the 450 K isentropic surface

Figure 12 shows the ozone mixing ratios in the polar vortex where potential

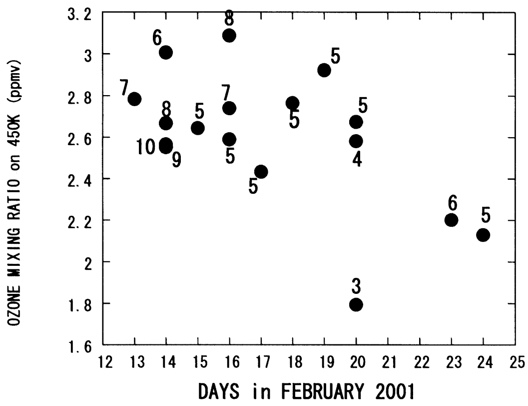

Fig. 12. Ozone mixing ratios on the 450 K isentropic surface when the potential vorticity on the 450 K isentropic surface is larger than or equal to 22 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$), which is in the polar vortex. The mark "3" on 20th Feb. 2001 indicates data from Tsukuba.

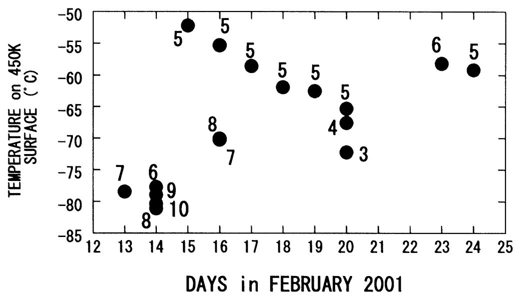

Fig. 13. Temperature on the 450 K isentropic surface obtained from ozonesonde data during 13th to 24th February 2001 when potential vorticity was larger than or equal to 22 ($10^{-6}K \cdot m^2s^{-1}kg^{-1}$).

vorticity was larger than or equal to 22 (10^{-6}K · $m^2s^{-1}kg^{-1}$) on the 450 K isentropic surface obtained from ozonesonde observations from 13th to 24th February 2001. The number attached to the data point indicates the station number in Table 1. A decreasing tendency of ozone mixing ratio during the period 17th to 24th is seen and can be associated with the destruction of ozone molecules on the 450 K isentropic surface. The temperature obtained from ozonesonde observations from 13th to 24th February 2001 on the 450 K isentropic surface, shown in Fig. 13, were as low as minus 80°C on 13th and 14th February 2001. At this temperature the formation of PSCs (Polar Stratosphere Clouds) is possible. If PSCs formed, chlorine molecules can be released by the following chemical reactions on the PSCs (Solomon *et al.,* 1986).

$$ClONO_2 + HCl \rightarrow Cl_2 + HNO_3, \quad (a)$$

$$H_2O + ClONO_2 \rightarrow HNO_3 + HOCl. \quad (b)$$

Figure 14 shows the ratios of column density of observed HCl to HCl estimated from HF data under the condition of no heterogeneous reaction from infrared

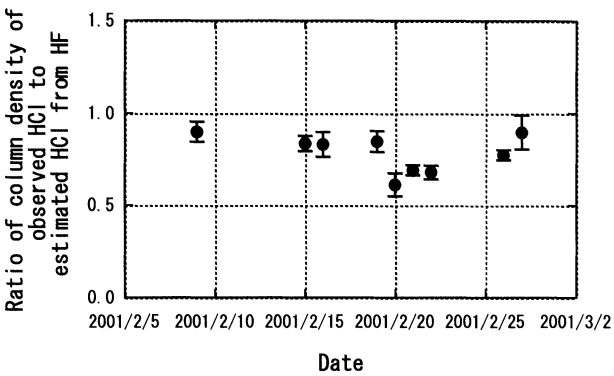

Fig. 14. Ratio of column density of observed HCl to HCl estimated from HF data under the condition of no heterogeneous chemical reaction from infrared spectroscopic measurements during 5th February–2nd March 2001.

spectroscopic measurements at the Meteorological Research Institute in Tsukuba, Japan. In Fig. 14, it is seen that the ratio decreased rapidly on 20th February 2001.

The decrease of HCl by reaction (a) actually observed at Tsukuba when Tsukuba was covered by air in the polar vortex on the 450 K isentropic surface. Hence ozone destruction was possible during transpotation from upwind region. Here we address why the ozone decrease was not so severe in Sapporo and in Wakkanai. These stations were also covered by the polar vortex on the 450 K isentropic surface on 20th February (see S20; 20th at Sapporo and W20; 20th at Wakkanai in Fig. 7) as well as Tsukuba. Tsukuba is 7 degrees south of Sapporo and 9 degrees south of Wakkanai. Hence, the incident solar radiation at Tsukuba is more intense than at the other two stations. Stronger solar radiation and more sunlit hours at Tsukuba would promote the ozone destructive chemical reactions. Terao *et al.* (2002) reported that ozone mixing ratio on the 475 K isentropic surface in the northern hemisphere polar vortex decreased by about 6 ppbv (0.006 ppmv) per sunlit hour based on the ILAS data for spring 1997. Moreover, ozone depletion on the 450 K isentropic surface in the polar vortex at the rate of 0.04 ppmv per day was observed at Eureka, Canada (80.0°N, 85.9°W) from February to March 2000 (Hirota *et al.,* 2003).

5. Concluding remarks

In the present study, we analyzed the vertical distributions of ozone at Wakkanai using ozonesonde data taken from 15th to 24th February (Chubachi *et al.,* 2002). We found that on 19th February 2001, the 700 K isentropic surface over Wakkanai was covered with air in the polar vortex. From the 13th to 24th, the ozone mixing ratio on the 700 K isentropic surface decreased with potential vorticity less than or equal to 220 (10^{-6}K · $m^2s^{-1}kg^{-1}$), showed a sharp decrease at potential vorticity between 220 and 240 (10^{-6}K · $m^2s^{-1}kg^{-1}$) and showed an almost constant value with the potential vorticity larger than or equal to 240 (10^{-6}K · $m^2s^{-1}kg^{-1}$). On the other hand, the ozone mixing ratio on the 450 K isentropic surface is small (about 1 ppmv) with potential vorticity less than or equal to 15 (10^{-6}K · $m^2s^{-1}kg^{-1}$), increased to around 2.5 to 3 ppmv between 15 and 22 (10^{-6}K · $m^2s^{-1}kg^{-1}$) and showed an almost constant value (around 2.5 to 3 ppmv) with the potential vorticity larger than or equal to 22 (10^{-6} K · $m^2s^{-1}kg^{-1}$). On days when the polar vortex on the 450 K isentropic surface covered Wakkanai (15th, 16th, 17th, 18th, 19th, 20th and 24th), comparatively large ozone mixing ratios were observed on the 450 K isentropic surface. The polar vortex on the 450 K isentropic surface covered Tsukuba on 20th February 2001, when increase of ozone mixing ratio was observed. A decrease of the ratio of observed HCl amount to estimated HCl amount from observed HF amount was also found over Tsukuba on 20th February 2001. A decrease of HCl in the stratosphere would increase of Cl in the stratosphere and would further accelerate the ozone destructive chemical reactions. The ozone mixing ratio on the 450 K isentropic surface over Tsukuba was smaller compared to that at other stations of similar potential vorticity. The potential vorticity calculated from GANAL data (Global objective ANALysis data by Japan Meteorological Agency) showed the movement of polar vortices on the 700 K isentropic surface and on the 450 K isentropic surface well.

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References

Chubachi, S. (1984): Preliminary result of ozone observations at Syowa Station from February 1982 to January 1983. Mem. Natl Inst. Polar Res., Spec. Issue, **34**, 13–19.

Chubachi, S., Sawa, Y., Sekiyama, T., Makino, Y. and Miyagawa, K. (2002): Preliminary results of vertical ozone soundings at Wakkanai, Japan. Polar Meteorol. Glaciol., **16**, 149–162.

Farman, J.C., Gardiner, B.G. and Shanklin, J.D. (1985): Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interaction. Nature, **315**, 207–210.

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.

Kanzawa, H., Shiotani, M., Suzuki, M., Yokota, T. and Sasano, Y. (2000): Structure of the polar vortex of the Arctic winter of 1966/1997 as analyzed from long lived tracer data of ILAS and meteorological data. Proceedings of the Quadrennial Ozone Symposium, Sapporo, 253–254.

Komhyr, W.D. (1969): Electrochemical concentration cells for gas analysis. Ann. Geophys., **25**, 203–210.

Makino, Y., Fast, H., Mittermeier, R.L., Sasaki, T., Sawa, Y., Hirota, M. and Miyagawa, K. (2000): IR-spectroscopic measurements of stratospheric minor constituents over Tsukuba, Japan and Eureka, Canadian Arctic. Proceedings of the Quadrennial Ozone Symposium, Sapporo, 531–532.

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

Terao, Y., Sasano, Y., Nakajima, H., Tanaka, H.L. and Yasunari, T. (2002): Stratospheric ozone loss in the 1996/1997 Arctic winter (Evaluation based on multiple trajectory analysis for double-sounded air parcels by ILAS). J. Geophys. Res., **107** (D24), 8210, doi; 10.1029.2001JD000615.