A-1.2.1 Variability of ozone layer over Eastern Siberia and Japan from ground-based and balloon observation

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Abstract

Temperature lower than PSCs threshold was observed in the Arctic polar vortices in three winter seasons since 1995. In order to clarify the effects of the ozone depletion in the Arctic polar vortex on the mid-latitude region, we carried out following observation and analyses: Ozone sonde measurements at Yakutsk in Eastern Siberia in Russia and at Moshiri in Hokkaido Island in Japan, visible spectrometer measurements at Moshiri and Rikubetsu in Hokkaido Island, FTIR measurements at Moshiri and Rikubetsu, millimeter radiometer measurements of ozone at Rikubetsu and Tsukuba, lidar measurements at Rikubetsu. The observed data are analyzed together with meteorological data such as ECMWF. Intensive observations were carried out based on the Arctic vortex information or "MATCH" information based on the ECMWF data in the framework of European Ozone Projects such as SESAME and THESEO. Especially, in the case of April 1996 campaign in Hokkaido, we predicted the polar vortex events over Hokkaido and carried out intensive ozone sonde and FTIR measurements. The estimated ozone depletion in the vortex air was approximately 60 % comparing with the similar case observed in 1972. The FTIR data also gave evidences of the effects of the heterogeneous process on PSCs in the Arctic polar vortex. These results were consistent with the estimation given by the MATCH result. Such phenomena were also observed in May 1997. The degree of ozone depletion was consistent with the MATCH results, the ozone depletion estimated based on the Yakutsk ozone sonde and the ILAS MATCH. As this result indicates the importance of more frequent and more comprehensive measurements of parameters and species in the stratosphere, we developed a millimeter radiometer and temperature laser radar to be installed at Rikubetsu.

Key Words Ozone depletion in the northern high- and mid-latitude, polar vortex, PSCs, vorticity analysis, FTIR, millimeter radiometer, laser radar, ozone sonde

1. Introduction

In most of the year in 1990's, the Arctic polar vortices were extremely strong and the temperature inside them was low enough to generate considerable amount of the polar stratospheric clouds (PSCs). As a result, ozone depletion with almost same mechanism in the 'Antarctic Ozone Hole' was observed in the Arctic polar vortices. The purpose of this sub-theme is to investigate how the Arctic ozone depletion affects the ozone depletion in the mid-latitude region based on observations carried out in the Siberia region and Japan. For this,
(1) the magnitude of the Arctic ozone depletion,

(2) the frequency of the vortex events,
(3) the effects of the vortex events on the ozone and other species in the mid-latitude region, should be clarified. We have been analyzing the data obtained in this study together with existing data, and have been developing systems to observe stratospheric species and parameters more frequently and for longer period. We will describe the behaviors of the recent Arctic polar vortices and the frequency of the vortex events in section 2, the ozone depletion shown in the ozone sonde observations in Yakutsk and Hokkaido in section 3, the FTIR and visible spectrometer observations in Hokkaido and their results in section 4, and the developments of the observing systems in section 5.

2. Behaviors of the recent Arctic polar vortices

(1) Visualization of the polar vortices

The polar vortex is characterized by the strong circumpolar westerly wind named 'polar night jet'. Though maps of the wind vectors on isentropic surfaces could be used to visualize the polar vortex, maps of the potential vorticity are more suitable and popular to examine the details of the polar vortex. Figure 1 is a typical potential vorticity map in winter in the Northern Hemisphere. The contours of the polar vortex are dense at the boundary of the polar vortex where the polar night jet exists and the gradient of it is large when the polar night jet is strong. The polar air stays inside of the polar night jet (or the boundary region) and is difficult to be transported across the polar night jet. This 'transport barrier' is strong when the gradient of the potential vorticity is large. Therefore, the gradient of the potential vorticity, which is visualized as the density of the contours of it, is a measure of the intensity of the polar vortex and also a measure of the strength of the transport. The shape of the Arctic polar vortex visualized by the boundary of the polar vortex is not circular and the center of it is usually far from the North Pole because of the effects of the planetary waves. Therefore, the latitudinal mean quantities are not so useful when we discuss on the phenomena related to the polar vortex. To solve this problem, we can describe the structures and behaviors of the polar vortex using the equivalent latitude [Nash et al., 1996]. And Bodeker first made the time-equivalent latitude cross section of the gradient of the potential vorticity during the period from the generation through breaking of the polar vortex to show the behaviors of the polar vortex in 1996/1997. We modified the methods developed by Nash et al. and Bodeker by normalizing the gradient of the potential vorticity by potential vorticity and obtained clearer figures.

(2) Behaviors of the Arctic polar vortices in recent five years

By applying the above method to show the behavior of the polar vortex in each year and by plotting the minimum temperature at 50 hPa, we can grasp the characteristics of the recent polar vortices at 475 K, which approximately correspond to 19 km in altitude and 60 hPa in pressure coordinate (Fig. 2). 1n 1994/1995 winter, the polar vortex was made in November and became strong in December and strongest in the middle of January. Temperature descended below the threshold of the PSC type I (195 K) in early December and reached the threshold of the PSC type II (188 K) at the middle of January. However, a strong minor warming occurred at the beginning of February 1995. During this minor warming the intensity of the polar vortex became weaker and the vortex size decreased, which should have resulted in transport of the polar air to the outside of the polar vortex through the weakened vortex barrier. The polar vortex became strong again at the beginning of March and the PSC type I temperature returned which was the cause of the considerable spring ozone depletion in 1995 [Rex et al., 1999]. The final warming and the breaking of the polar vortex occurred at the beginning of April. A small part of the vortex broken came close to Japan on April 12 this year.

In 1995/1996 winter, though the formation of the polar vortex was later than the previous year, the PSC type I temperature came out in the middle of December and it continued for three months. The PSC type II temperature occurred frequently and it may have resulted in the strongest denitrification in the Arctic polar vortex in the recent five years and in the prolonged ozone depletion [Rex et al., 1996]. After the minor warming at the beginning of March, the minimum temperature increased up to 200 K. However, the polar vortex was maintained and the final warming occurred in the middle of April. The head of the stretched vortex reached Hokkaido in Japan on April 14 and the part of the broken vortex came over Hokkaido on April 23.

In 1996/1997 winter, the polar vortex was formed at the end of December or the beginning of January, and became strong in February. However, it was strong and extraordinary stable up to the middle of April and the final warming occurred in May. A part of the vortex broken covered the Hokkaido on May 12.

However, in 1997/1998 winter, minor warming frequently occurred and the minimum temperature decreased only intermittently to the PSC type I threshold. In 1998/1999 winter, the polar vortex was extremely weak and even the minimum temperature did not reach the PSC type I threshold.

3. Arctic ozone depletion observed at Yakutsk in Eastern Siberia and Moshiri in Hokkaido

(1) Frequency of the vortex events at Yakutsk and Moshiri

In this study, ozone sonde observations were carried out at Yakutsk (62°N, 130°E) and Moshiri (43 °N, 144 °E). We calculated the position of the boundary of the polar vortex in each year in terms of potential vorticity using the similar method with the Nash et al., [1996]. Reflecting the latitude of the two stations, Yakutsk was in the boundary region of the polar vortices in average and Moshiri was outside of the vortex boundary. Yakutsk located inside of the polar vortices when it became weak in Fig. 2. In other word, Yakutsk located inside the polar vortices during minor warming phenomena. It should reflect the location of the Aleutian High. The location of the Arctic polar vortex tends to shift to the European side because of the Aleutian High. When the planetary wave activities are enhanced and the Aleutian high goes toward Europe, the polar vortex moves toward Siberia. The potential vorticities over Moshiri had peaks five to ten days after the high vorticity events at Yakutsk. At the potential temperature of 475 K, Moshiri was inside of the Arctic polar vortex only when it was broken. However, Moshiri was more frequently inside of the Arctic polar vortex below 400 K.

(2) Ozone depletion in the Arctic polar vortex observed at Yakutsk in winter 1996/1997

We carried out ozone sonde measurements at Yakutsk for the MATCH project and for detection of ozone depletion. Here, we examined the intra-seasonal changes of the ozone mixing ratio in the Arctic polar vortex on various potential temperature. Ozone depletion was clearly observed at all the potential temperature levels. As the descending in the polar vortex was neglected, the rate of the ozone depletion should be underestimated. However, as the descending motion was small in late winter and spring. The maximum rate of ozone depletion was 21 ppbv/day at 475 K, which is consistent with the estimation by the results of the ozone sonde MATCH [Shultz et al., 1999] and the ILAS MATCH [Sasano et al.,1999].

(3) Ozone depletion at Moshiri observed by ozone sondes during the polar vortex events

We carried out campaign measurements using ozone sondes in winter/spring in 1996 and 1997 at the Moshiri Observatory of the Solar Terrestrial Environment Laboratory of

Nagoya University (43 °N, 144 °E) in Hokkaido, the northern Island in Japan. We determine the timing of launches based on the ECMWF potential vorticity maps sent by NILU data center for European Ozone Projects and based on the MATCH alerts. As the first clear vortex events was predicted over Hokkaido on April 14, 1996, we decided to carry out intensive observation at Moshiri (by ozone sondes) and Rikubetsu (by the FTIR and visible spectrometer). The FTIR results will be shown later. The Arctic polar vortex covered Hokkaido Island also on April 23, 1996 and May 12, 1997. The vertical profiles of ozone partial pressure and temperature on these three days and the potential vorticity map at 475 K are shown in Fig. 3. As a reference, we plot the vertical profiles of ozone partial pressure and temperature observed on April 13, 1972 at Sapporo Meteorological Observatory by Japan Meteorological Agency (JMA) with broken lines. Ozone deficits are clearly found for all three days; from 100 hPa to 60 hPa for April 14, 1996, from 100 hPa to 30 hPa on April 23, 1996 and from 100 hPa to 30 hPa on May 12, 1997. The altitude and potential temperature corresponding to 100 hPa are 16 km and 410 K. Those for 70 hPa, 50hPa and 30 hPa are 18 km and 460 K, 20 km and 520 K, and 24 km and 620 K, respectively. More detailed analysis by plotting the mixing ratio of ozone to the potential temperature shows approximately 60 % ozone deficit at 475 K (19 km) on April 23, 1996 when we use the ozone mixing ratio on April 13, 1972 at Sapporo as the reference. As the ozone depletion in the Arctic polar vortex in the spring 1996 and 1997 was almost 60 %, ozone deficit should have been preserved throughout the process of breaking of the polar vortex.

4. Effects of the Arctic atmospheric chemical processes on the chlorine partitioning and ozone

Transport of air from the Arctic region can cause an ozone decrease at northern midlatitude. However, the degree of the effect from the Arctic chemistry on midlatitude ozone trend is poorly understood. When air mass is transported from the Arctic to midlatitude, active chlorine should be sequestered to relatively unreactive reservoir species, mostly $ClONO_2$ and HCl. Since the reaction to HCl is slower than that to $ClONO_2$, a ratio of $ClONO_2$ to HCl in an air mass affected by the heterogeneous reactions is expected to be higher as compared to that at midlatitude when the air mass is transported to midlatitude. Consequently, the relative abundance of $ClONO_2$ and HCl can be used as an indicator of the process of the Arctic chemistry.

HF, HCl, $ClONO_2$, HNO_3, and O_3 were measured by the Solar Terrestrial Laboratory of Nagoya University using the Ground-based FTIR instrument at Rikubetsu (44 °N, 144 °E) in Hokkaido in Japan during the winter and early spring of 1996. A measurement of O_3 was also made using the visible spectrometer at the Moshiri Observatory (43 °N, 144 °E). In this study, column amounts of these species were used to investigate the effect of heterogeneous chemistry on the partitioning of chlorine at midlatitude.

(1) Observational Method

The IR solar absorption spectra were obtained on clear days at Rikubetsu by a Bruker IFS 120M Fourier Transform infrared (FTIR) spectrometer with a spectral resolution of 0.0035 cm^{-1}. More detailed descriptions on the FTIR observation system are given in Nakajima et al. [1997]. The micro-window regions of the solar IR spectra used to derive the vertical column amounts of HF, HCl, $ClONO_2$, HNO_3, and O_3.

In addition to the FTIR observations, daily total O3 column amounts were measured by a visible spectrometer at Moshiri. Stratospheric O_3 slant column amounts were measured at sunrise and sunset by observing scattered sunlight in the visible region from the zenith sky [Koike et al., 1993]. The derived O_3 vertical column amounts have been demonstrated to agree with the Dobson measurements at Sapporo within 4-6 % [Koike et al., 1999].

(2) Results and discussion

1) Seasonal variation

Temporal variations of column amounts of HF, HCl, and $ClONO_2$, HNO_3, and O_3 were obtained using the FTIR from May 1995 to December 1997. All these species show marked seasonal variations. Namely the column amounts are minimum in July-September and reach maximum values in February-April. All these species are produced through photolysis of long lived trace species. The increases of the abundance of these species from fall to spring are basically due to poleward transport by planetary waves. In addition to the general increase of the column abundances in winter and spring, the variability is larger in these seasons. In this paper, we will focus on the variability of these species during the winter and early spring in 1996.

2) Meteorological Conditions

On February 27 and March 19, the asymmetric polar vortex stretched in the direction of 100-160°E and the eroded vortical air was transported to down to 44°N. On April 15, the polar vortex had broken more thoroughly and the remaining vortex extended longitudinally at 0-180°E. The eastern part of the vortical air reached to midlatitude and Rikubetsu was located inside the vortex.

4) Variation of HCl and $ClONO_2$ in winter and spring

The HCl + $ClONO_2$ column amount is linearly correlated with the HF column amount when the data obtained at Rikubetsu between January and April were used. HCl + $ClONO_2$ has a tighter correlation with HF than each component species, HCl or $ClONO_2$. These results indicate that HCl and $ClONO_2$ are dominant species for the column amount of Cl_y .In addition, HF column amount is a good parameter which represents the HCl + $ClONO_2$ column amount. Therefore the ratios of HCl/HF and $ClONO_2$/HF should reflect the change of partitioning between HCl and $ClONO_2$.

The temporal variations of HCl, HF and the potential vorticity at 475 K show that when the Arctic air mass reached over Rikubetsu, the HF amount increased. This was consistent with the fact that the HF column amount is higher at higher latitudes. On the other hand, the HCl value decreased and increased on February 27 and April 15, respectively, when the Arctic air mass arrived, suggesting that chemistry as well as the transport process caused to change the HCl level. When the Arctic air arrived over Rikubetsu, the HCl/HF ratio was observed to decrease. This is consistent with the fact that these air masses were perturbed by the Arctic chemistry, because the most of reactive chlorine species were considered to be converted into $ClONO_2$, as described above.

5. Development of observing systems of ozone and related species and parameters

At the National Institute for Environmental Studies in Tsukuba, monitoring of ozone profiles from 10 km to 75 km using an ozone laser radar and a millimeter radiometer. Temperature profiles in the stratosphere and mesosphere are also observed by laser radars. During the period of this project, NIES and Nagoya University installed a millimeter radiometer to measure ozone profiles from 20 km to 60 km every 5 minutes continuously, and NIES installed a temperature lidar in a room at the astronomical observatory named 'Ginganomori Tenmondai' constructed by Rikubetsu Town. NIES and Tohoku University carried out FTIR and IR laser heterodyne measurements.

6. Conclusion

The effects of the ozone depletion in the Arctic polar vortex were observed and analyzed based on the ozone sonde measurements at Yakutsk and Moshiri, and FTIR measurements at Rikubetsu. Approximately up to 60 % ozone deficit was estimated in a vortex event and the corresponding change of chlorine partitioning was confirmed. The systems for longer and more frequent measurements and the data analysis systems are developed for further studies.

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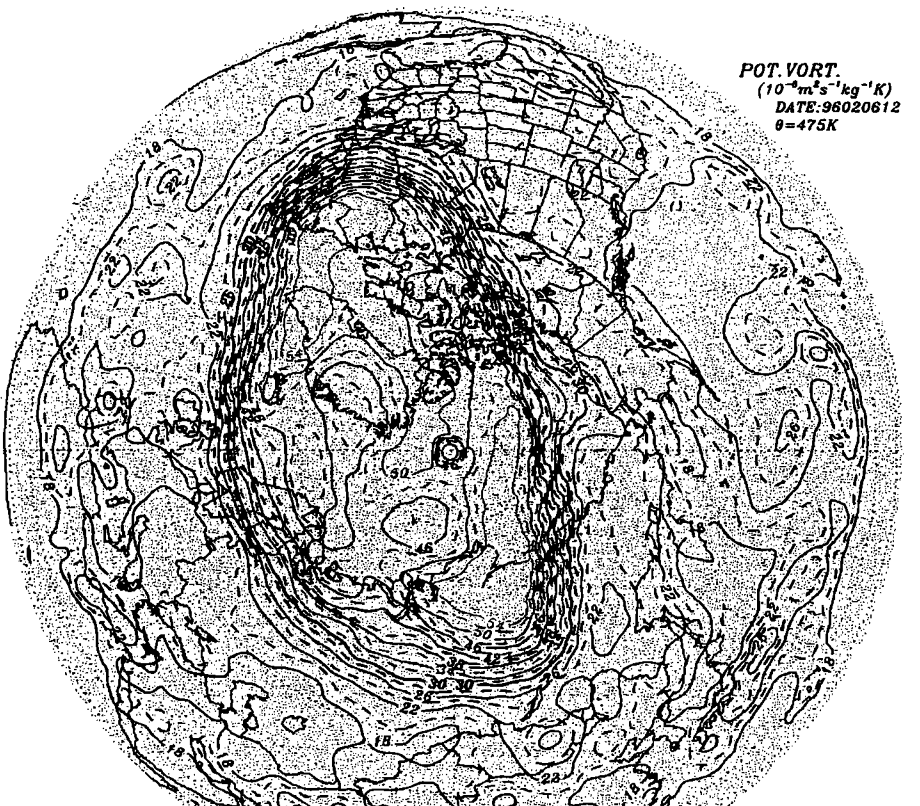

Fig. 1 Potential vorticity map at the 475 K potential temperature surface on February 6,1996

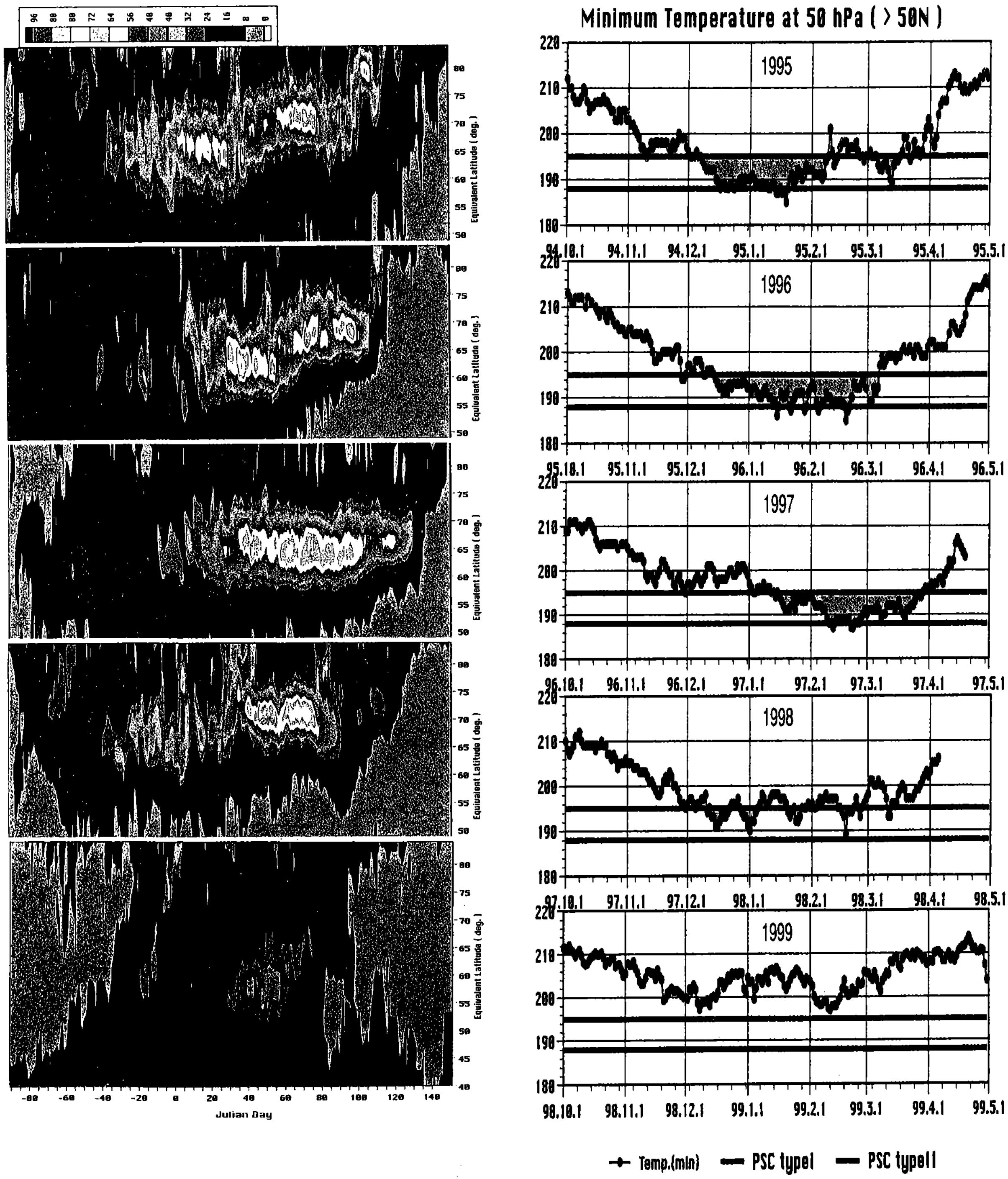

Fig. 2 Behaviors of the polar vortices (left) and the minimum temperature (right) in the winter/spring for five seasons from 1994/1995 to 1998/1999.

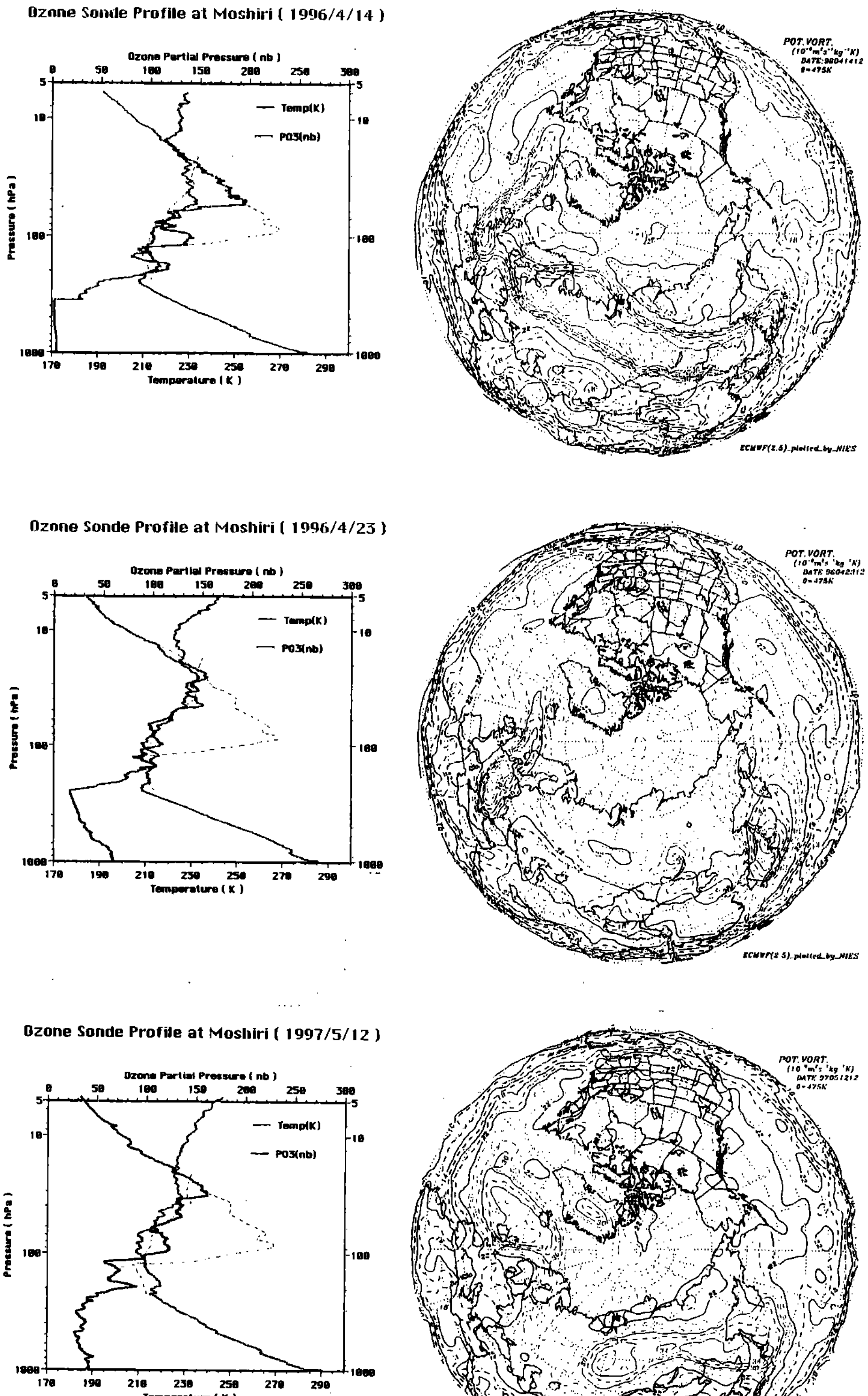

Fig. 3 Ozone depletion during the Arctic polar vortex events on Aril 14 and 15, 1996 and on May 12, 1997 (left) and the corresponding potential vorticity maps (right).

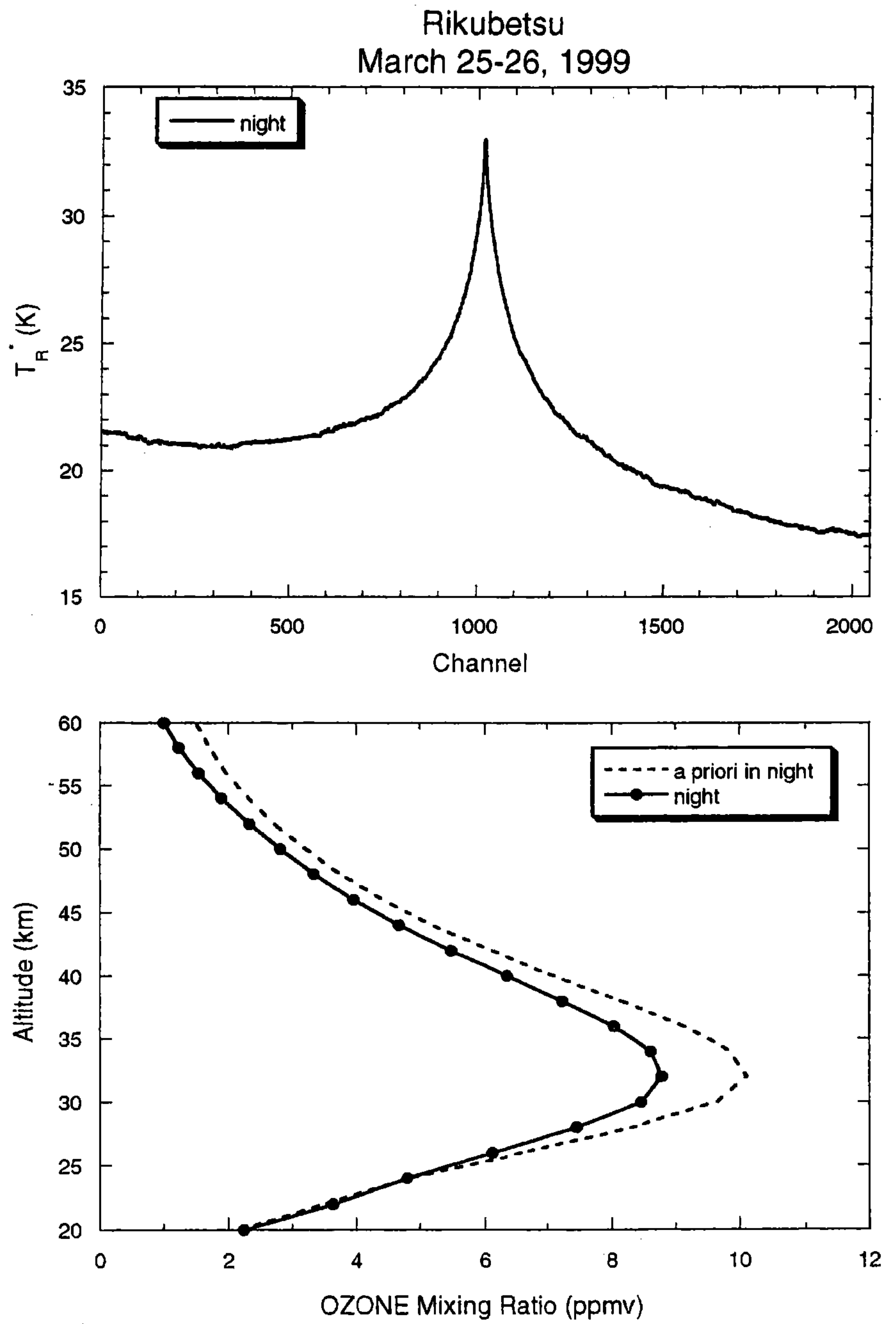

Fig. 4 The first spectrum of the millimeter radiometer installed at Rikubetsu and the retrieved vertical profile of ozone.