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Scientific Paper

POLAR VORTEX MEANDERING AND STRATOSPHERIC AEROSOL DISTRIBUTION: LIDAR MEASUREMENTS AT FAIRBANKS, ALASKA

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Abstract: Lidar measurements at Fairbanks, Alaska (64°49′N, 147°52′E) and Ny-Ålesund, Svalbard (78°54′N, 11°53′E) in December 1991 and January 1994, respectively, were made to monitor the distribution of stratospheric aerosols. The location of the Fairbanks lidar site is advantageous to observe the effect of the polar vortex margin to stratospheric aerosol density distributions, since the lidar was sometimes located inside and sometimes outside of the polar vortex due to its meandering motion. The lidar site at Ny-Ålesund is usually inside the polar vortex in winter. The comparison of measurements at Fairbanks and Ny-Ålesund has shown that polar vortex dynamics controls profiles of stratospheric aerosol content.

Above about 20 km there was little aerosol content when the lidar station was inside the polar vortex. The aerosol load on the local tropopause showed large changes, which would be associated with aerosols descending from the stratosphere to the troposphere near the margin of the polar vortex. At the end of February 1994, the aerosol content of layer peak at Fairbanks was apparently smaller than that at Ny-Ålesund even though both lidar stations were inside the polar vortex.

1. Introduction

Diabatic subsidence of air-masses in the polar vortex has significant effects directly on distribution of stratospheric constituents and indirectly on the global budget and transport of stratospheric constituents to the troposphere. Observations of N_2O made in the Arctic polar winter (LOEWENSTEIN *et al.*, 1990; SCHMIDT *et al.*, 1991; BAUER *et al.*, 1994) have shown mixing ratios that are much lower than those observed in mid-latitudes, possibly due to the subsidence of the polar stratospheric air-mass inside of the polar vortex.

KENT *et al.*(1985) reported that there was a large difference in the aerosol vertical distribution above about 25 km between inside and outside of the polar vortex on the basis of SAGE satellite measurements. Additionally, they estimated descent rates of the air mass on the order of 8×10^{-4} m/s at 20 km altitude near the center of the vortex between September and December; below 14 km altitude near the base of the polar vortex horizontal movements occurred. Airborne lidar measurements crossing the polar vortex margin (MCCORMICK *et al.*, 1983) showed that the stratospheric aerosol distribution has a very strong gradient across the polar night jet stream.

Those measurements show that the behavior of the polar vortex is an important factor affecting global diffusion of stratospheric constituents -transport from the stratosphere to the troposphere in the polar winter, transport from the mid-latitudes to the polar region, and other processes.

The previous measurements by KENT *et al.* (1985) covered an extended latitudinal range over the Arctic region, but they were limited by weekly averaged profiles. Therefore detailed vertical and temporal changes in aerosol density have not been clarified yet. The airborne lidar measurements made by MCCORMICK *et al.* (1983) also covered an extended latitudinal range, but the observational period was extremely limited, and temporal changes of aerosol distribution were disturbed by polar vortex dynamics.

At high latitudes, the distribution of stratospheric particulate matter seems to be strongly associated with polar vortex dynamics in winter, since 1) the polar vortex isolates the polar region from mid- and low-latitudes, and transportation of aerosols between high and mid-latitudes strongly depends on the formation and movement of the polar vortex, and 2) inside the polar vortex stratospheric temperature frequently decreases to the frost point of PSCs (Polar Stratospheric Clouds) and thus controls the spatial and temporal distribution of PSCs.

Lidar measurements of atmospheric aerosols made in 1991 at Poker Flat near Fairbanks, Alaska (64°49′N, 147°52′W) will present useful information in order to discuss the change in aerosol distribution associated with meandering or distortion of the north polar-night vortex.

2. Lidar Measurements at Fairbanks, Alaska

Lidar measurements on stratospheric aerosols were made in mid-December 1991 at Poker Flat near Fairbanks, Alaska. In January 1993 the lidar system was moved to Sheep Creek near Fairbanks. The system used here, as summarized in Table 1, is composed of a Nd-YAG laser and a 35 cmϕ cassegrain receiving telescope. The matching point for accepting an aerosol-free atmosphere was chosen above 30 km.

Observations were made on clear days to avoid noise from haze and clouds. About 6000 lidar return shots were integrated in order to obtain a density profile of stratospheric aerosols. The error range is 10% or less at 25 km. About 20 profiles per day were observed as routine measurements, and averaged profiles were taken as the representative profile of that day.

The scattering ratio, *SR*, is defined by

$$SR(z) = [\ \beta 1(z) + \beta 2(z)\ ]\ /\ \beta 1(z), \quad (1)$$

$$= 1 + \beta 2(z)\ /\ \beta 1(z), \quad (2)$$

where $\beta 1$ and $\beta 2$ are the backscatter coefficients of air molecules and atmospheric particulate matter at altitude of z, respectively.

The parameter $[\ SR(z) - 1\ ]$ can be regarded as the mixing ratio of atmospheric aerosols.

The Depolarization ratio is defined by

$$DR(z) = [\ \beta(z)\ ]\perp / [\ \beta(z)\ ]\ //, \qquad (3)$$

$$= [\ \beta1(z) + \beta2(z)\ ]\perp / [\ \beta1(z) + \beta2(z)\ ]\ //, \qquad (4)$$

where // and ⊥ mean parallel and cross components of backscattered light with respect to the polarization plane of emitted laser light. The polarization properties of backscattered light do not change when spherical particles are scattering light. Therefore, the parameter *DR* can be considered as the value indicating nonsphericity of particles (IWASAKA, 1985, 1986a).

Altitudes of the local tropopause over Fairbanks were determined on the basis of meteorological sonde measurements performed at the airport of Fairbanks and weather map provided by Japan Meteorological Agency. The tropopause heights over Ny-Ålesund were obtained from meteorological balloon soundings made near the lidar site.

3. Density Profiles of Stratospheric Aerosols Observed by Lidar

The scattering ratios measured at Alaska in the winter of 1991/1992 (Fig. 1) were extremely enhanced in comparison with values observed in mid-latitudes during calm stratospheric periods without volcanic disturbance (stratospheric aerosol mixing ratios of 0.1–0.05 at laser wave length=0.6943 μm were frequently observed in calm periods (*e.g.*, IWASAKA *et al.*, 1983; HIRONO and SHIBATA, 1983; HAYASHIDA and IWASAKA, 1985)). Typical examples of aerosol density profiles are shown for the winters of 1992/1993 and

Table 1. Main characteristics of lidar.

Laser:	Nd-YAG	
	Wavelength	0.53 μm
	Power	0.5 J/pulse (maximum)
	Repetion rate	10 Hz (maximum)
Recieving mirror		Cassegrain type 35 cm diameter

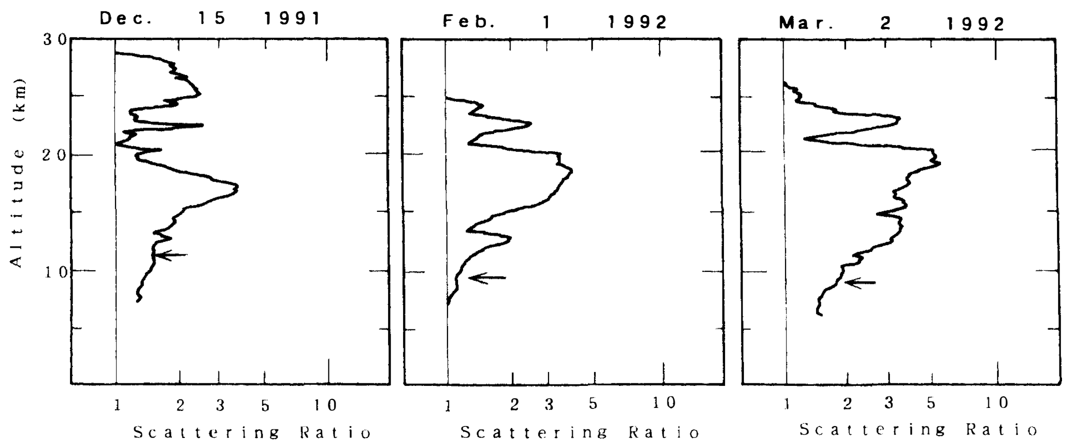

Fig. 1. Profiles of scattering ratio measured at Poker Flat near Fairbanks, Alaska in winter of 1991/92. Local tropopause height is shown by arrows.

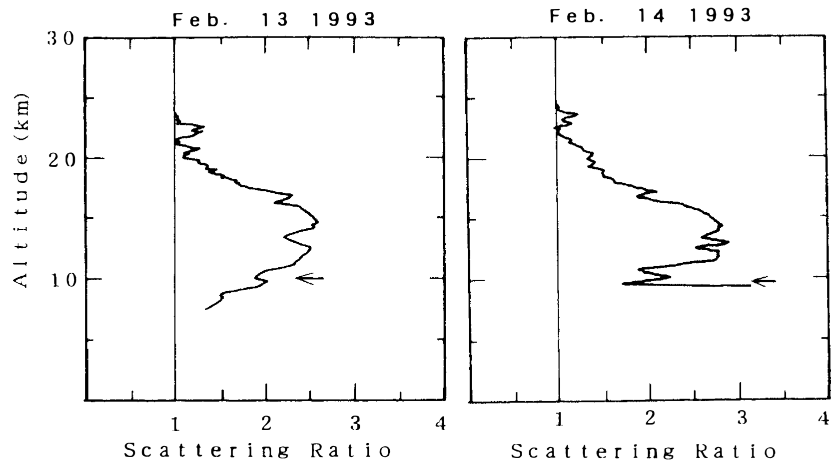

Fig. 2. Profiles of scattering ratio measured at Sheep Creek near Fairbanks, Alaska in winter of 1992/93. Local tropopause height is shown by arrows.

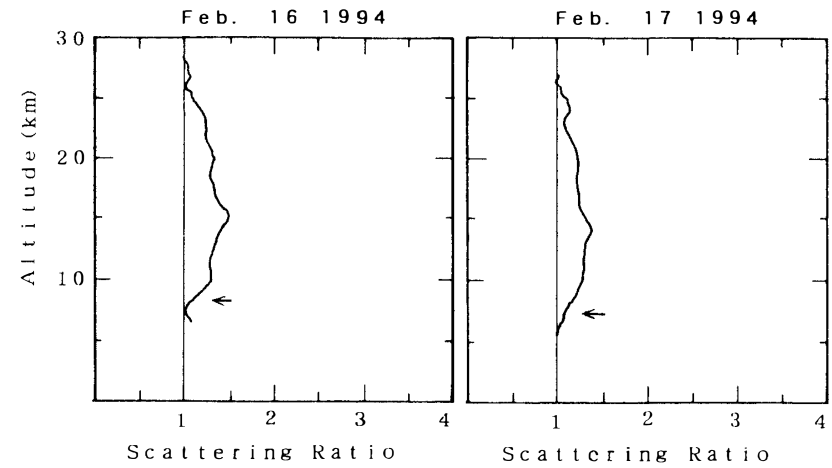

Fig. 3. Profiles of scattering ratio measured at Sheep Creek near Fairbanks, Alaska in winter of 1993/94. Local tropopause height is shown by arrows.

1993/1994 in Figs. 2 and 3, respectively.

The mixing ratio of the layer peak was 1–3 in the winter of 1991/1992 and decreased to the value of about 0.2–0.4 until winter 1993/1994.

According to lidar, balloon, and satellite observations (*e.g.*, BLUTH *et al.*, 1992; MCCORMICK and VEIGA, 1992; UCHINO *et al.*, 1993; PUESCHEL *et al.*, 1994) large enhancement of stratospheric aerosol loading followed the Pinatubo eruption in June 1991, Philippines, suggesting the global diffusion of volcanic aerosols which were formed from SO_2 and other substances injected into the stratosphere through the eruption. The highly enhanced aerosol layer shown in Fig. 1 is possibly due to the volcanic disturbance of the Mt. Pinatubo eruption of 1991.

The stratospheric aerosol density over the Fairbanks lidar site can be noticeably controlled by the dynamics of lower stratosphere in addition to such a volcanic eruption. In Figs. 4a and 4c two typical cases of measurements at Fairbanks, Alaska show the change in the density profile of aerosols possibly caused by the dynamics of polar vor-

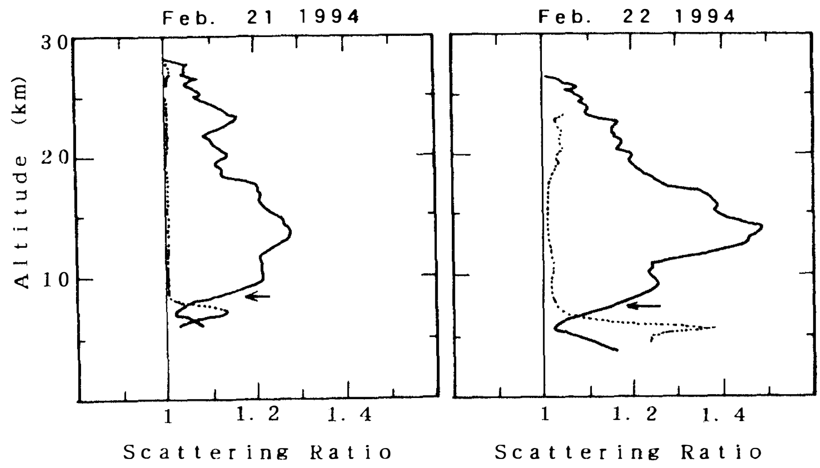

Fig. 4a. Vertical profile of scattering ratio (full line) and depolarization ratio (dotted line) measured at Sheep Creek near Fairbanks, Alaska.

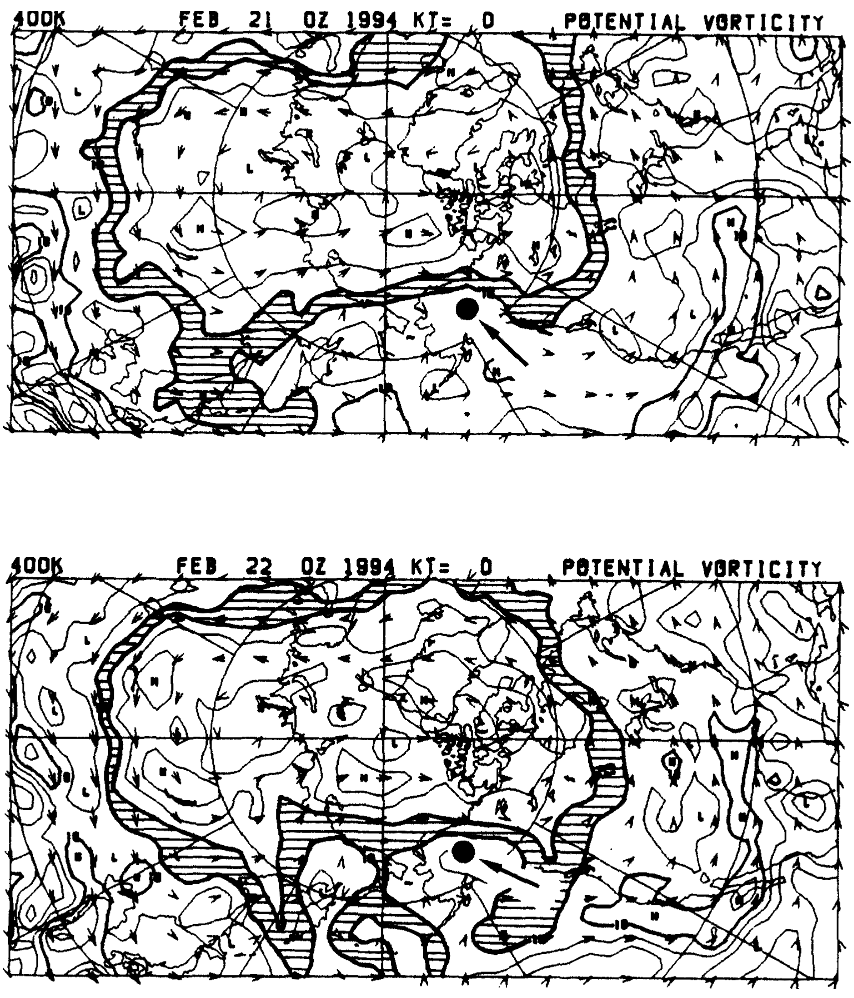

Fig. 4b. Potential vorticity distribution on the isentropic surface of 400 K (unit: $m^2Kkg^{-1}s^{-1}$). The counter interval is $2\times10^{-6}m^2Kkg^{-1}s^{-1}$. Shaded area is $10–12\times10^{-6}$ $m^2Kkg^{-1}s^{-1}$.
● indicates the location of Fairbanks lidar site.

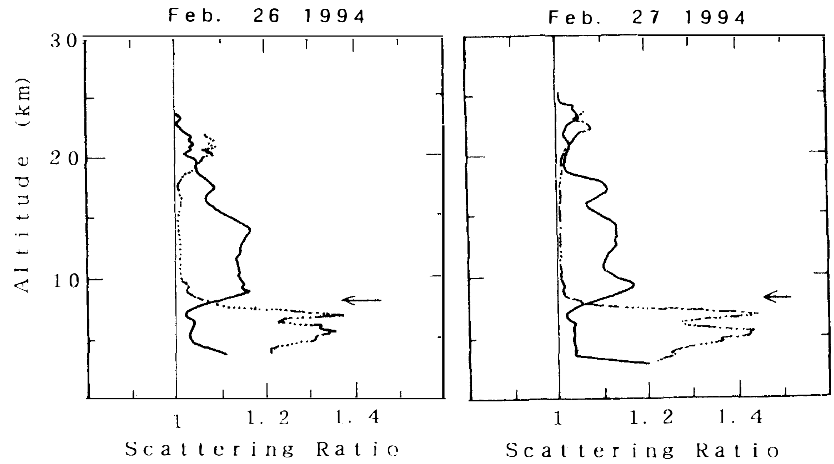

Fig. 4c. Same as Fig. 4a.

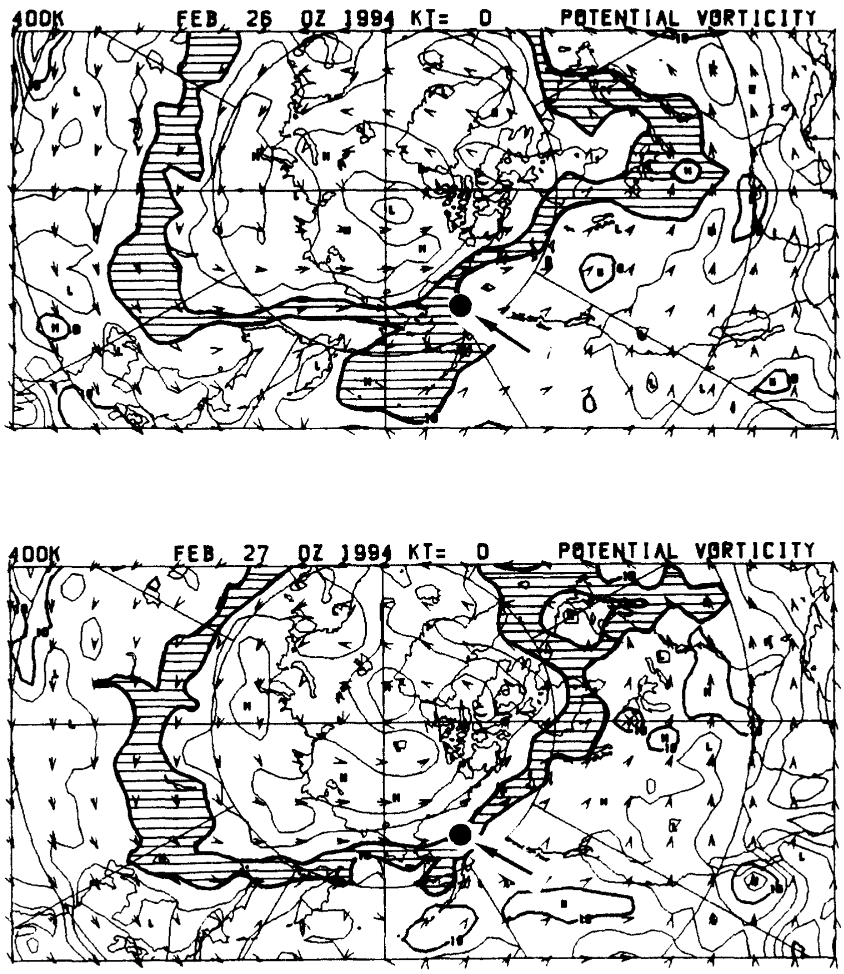

Fig. 4d. Same as Fig. 4b.

tex. Above 20 km altitude the mixing ratio [$SR(z) - 1$] was about 0.2 on February 21 and 22, 1994 while it was extremely low on February 26 and 27, 1994.

4. Discussion

The diffusion of volcanic materials in the stratosphere is a matter of great concern from the view point of volcanic effects on global climate and environment. The eruption of Mt. Pinatubo in June 1991 injected considerable amount of volcanic materials and highly enhanced stratospheric aerosols (*e.g.*, BLUTH *et al.*, 1992; McCORMICK and VEIGA, 1992; UCHINO *et al.*, 1993; PUESCHEL *et al.*, 1994). The extremely enhanced aerosol layer in the winter of 1991/1992 in Alaska is possibly due to diffusion of volcanic aerosols into high latitudes from low and mid latitudes (IWASAKA *et al.*, 1995).

Usually such a volcanic disturbance in the stratospheric aerosols gradually decreases to the historical trend with the characteristic decay time of about 11 months (TURCO *et al.*, 1982). In the case of the Pinatubo eruption of 1991, the disturbance of stratospheric aerosols had been observed until the winter of 1993/1994 over Fairbanks from the comparison of lidar return from the stratospheric aerosols measured at Tyokawa (34°50′N, 137°22′E), and Fairbanks, Alaska (Fig. 5).

Fairbanks, Alaska was near the polar vortex in winter season, and thus sometimes inside of the polar vortex, and frequently outside the polar vortex. The movement of the polar vortex possibly causes large variation of stratospheric aerosol density profiles over Fairbanks in winter.

According to the distribution of potential vorticities on the 400 K potential temperature surface shown in Figs. 4b and 4d, Fairbanks lidar site was outside of the vortex on February 21 and 22, and inside on February 26 and 27. The values of $10–12\times10^{-6}$ $m^2Kkg^{-1}s^{-1}$ are chosen as the values indicating the vortex boundary on the 400 K surface in the figures.

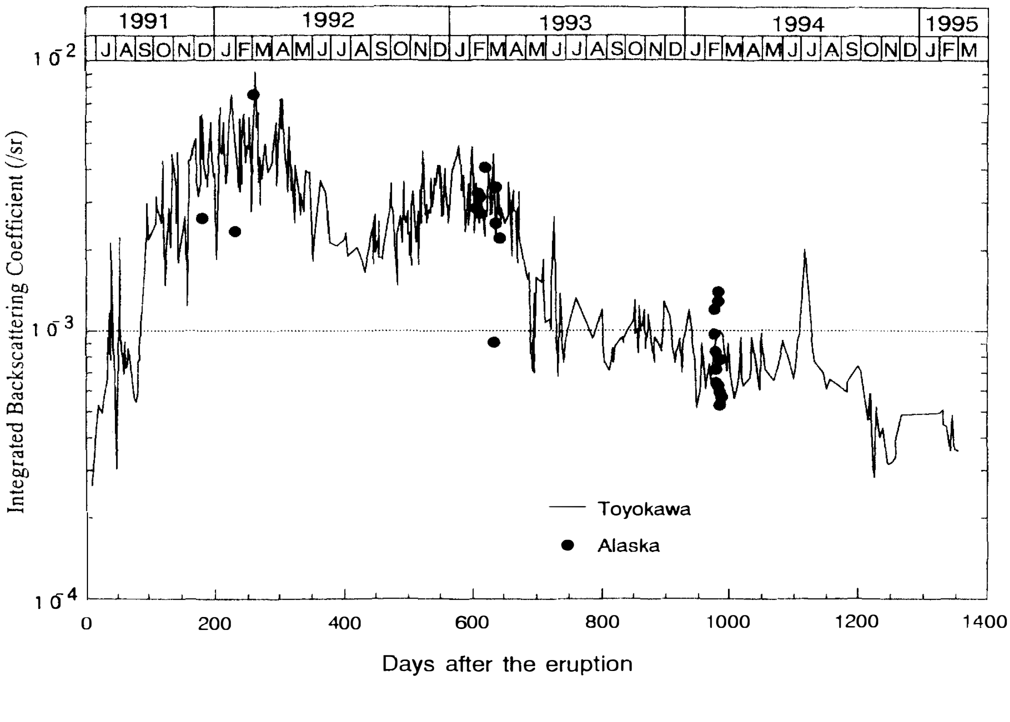

Fig. 5. Integrated backscattering coefficient of stratospheric aerosols measured at Toyokawa, Japan (full line) and Fairbanks, Alaska (dot) after the eruption of Mt. Pinatubo of June 1991.

The differential position with regard to the polar vortex can be seen in the temporal changes in wind and temperature at Fairbanks, Alaska, summarized on the basis of the Japan Meteorological Agency data set in Fig. 6. A cold air-mass appeared in the stratosphere (about 100 hPa) and wind direction changed from westerly to north-westerly on February 11–12, and atmospheric temperature increased to –50°C on around February 20 but wind had a north-west component. The cold air-mass appeared again and wind direction recovered to westerly at the end of February. These changes correspond well to the distortion of the polar vortex shown in Figs. 4b and 4d.

The polar stratosphere was suggested to be an important sink of stratospheric water vapor through active condensation of water vapor on background aerosols and descending motion of those particles (STANFORD, 1977; IWASAKA, 1986b, 1986c). Recently, formation of PSCs particles has been thought to dehydrate and denitrify the polar stratosphere since PSCs particles growing to super-micron size can easily descend from the stratosphere to the troposphere (TOON *et al.*, 1989). Descending motion of cold air-mass inside of the polar vortex, in addition to the descent of individual particles having large size, has been believed to be an important process transporting stratospheric constituents including aerosol particles to the troposphere.

Concerning the observational fact of low concentration of aerosols above about 20 km inside the polar vortex (KENT *et al.*, 1985; MCCORMICK *et al.*, 1983), descent of polar cold air-mass is suggested as the process causing descent of the aerosol layer during winter. This feature is also found in lidar measurements above 20 km altitudes at Fairbanks, Alaska when the lidar station was inside the polar vortex (Fig. 4c).

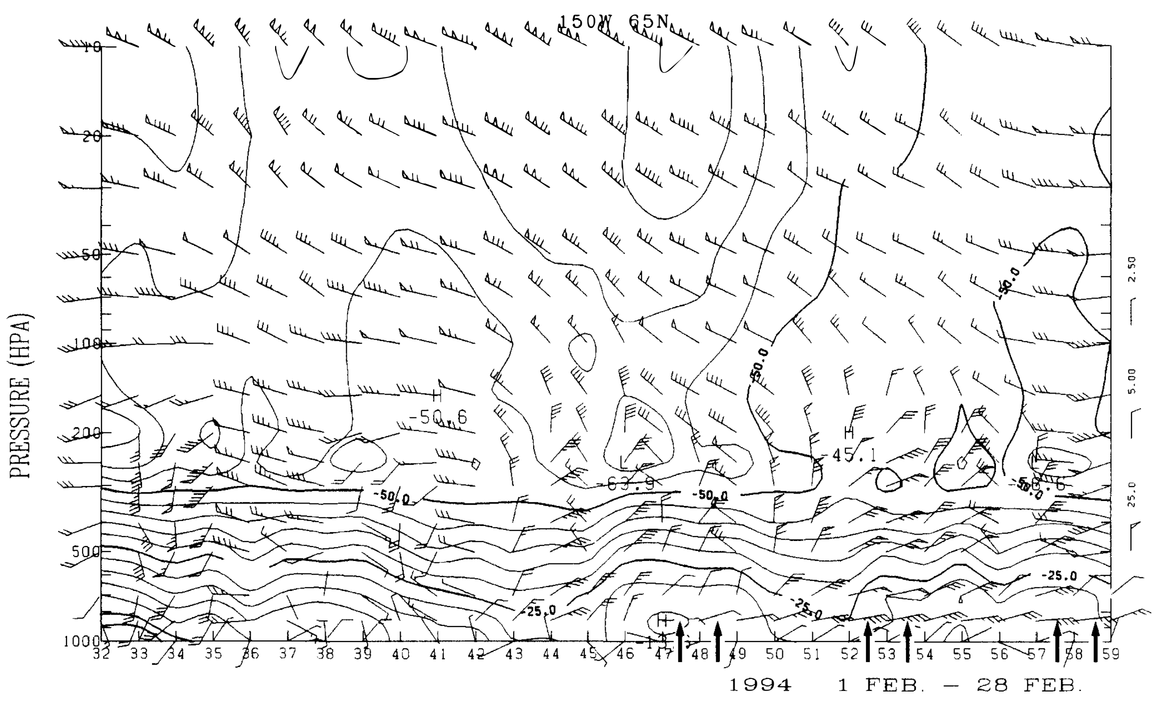

Fig. 6. Pattern of the vertical distributions of atmospheric temperature and wind at Fairbanks, Alaska for February 1994 based on the analysis of Japan Meteorological Agency data set. Days of lidar measurements made are indicated by arrows (Figs. 3, 4a and 4c).

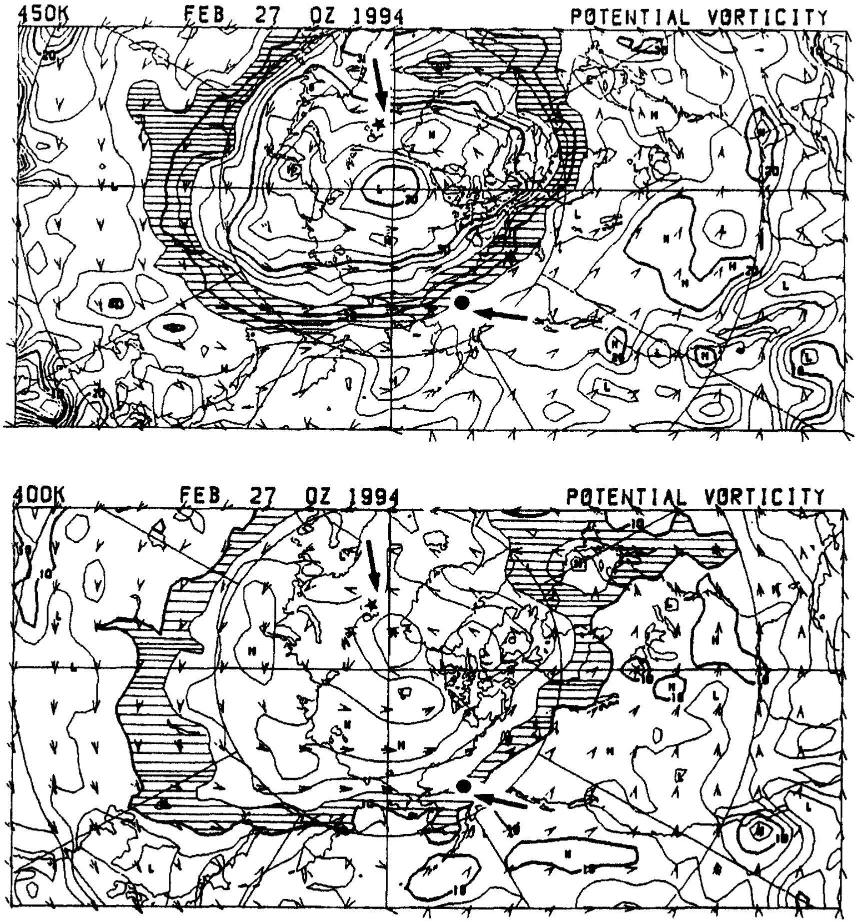

Fig. 7. Potential vorticity distribution on the isentropic surfaces of 450 K (upper panel) and 400 K (lower panel) on February 27, 1994. Shaded areas are 18–26×10^{-6} *m*^{2}*Kkg*$^{-1}$*s*$^{-1}$ *(upper panel) and 10–12×10*$^{-6}$ *m*^{2}*Kkg*$^{-1}$*s*$^{-1}$ *(lower panel).* ● *and* ★ *indicate the location of the Fairbanks and Ny-Ålesund lidar sites, respectively.*

It is interesting to compare the profiles obtained at Fairbanks to those at Ny-Ålesund, which is mostly located inside the polar vortex during winter since in winter of 1993/1994 both lidar sites performed cooperative measurements. A sample of potential vorticity distributions on the 400 and 450 K isentropic surfaces on February 27, 1994 are shown in Fig. 7 in order to confirm that the lidar sites of Fairbanks, Alaska and Ny-Ålesund, Svalbard, Norway (78°54′N, 11°53′E) were inside the polar vortex. Here, 10–12×10^{-6} and 18–26×10^{-6} m^{2}Kkg^{-1}s^{-1} are chosen as the values indicating the vortex boundary on the 400 and 450 K surfaces, respectively. Those maps suggest that the lidar station at Fairbanks was inside the vortex on the 400 K surface but outside the edge of the vortex at 450 K on February 27. The scattering ratio profiles measured at Ny-Ålesund on February 26 and 27 are shown in Fig. 8.

Two observational features are found when the Fairbanks lidar station is inside of the polar vortex: low aerosol density above 20 km altitude, and relatively low altitude of the layer center (Fig. 4c).

The largely enhanced layer at about 20 km altitude on February 26, 1994 above Ny-Ålesund (Fig. 8) shows a large depolarization ratio, suggesting a layer of non-spherical

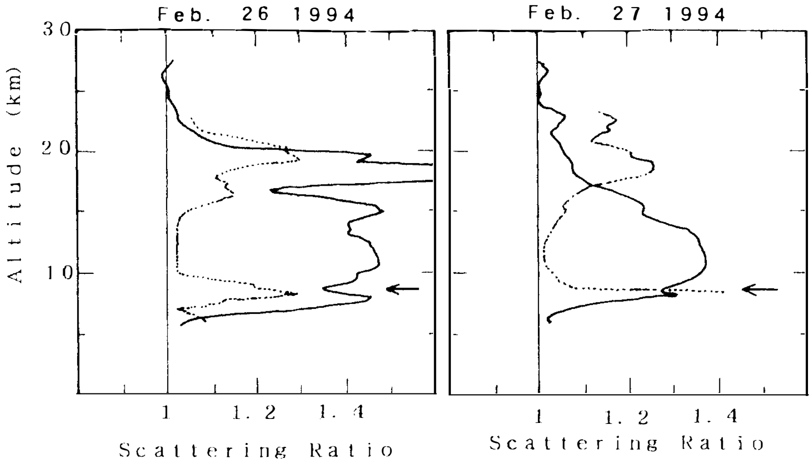

Fig. 8. Vertical profiles of scattering ratio (full line) and depolarization ratio (dotted line) measured at Ny-Ålesund, Svalbard, Norway. Local tropopause height is shown by arrows.

particles. According to studies on polar stratospheric cloud particles (CARSLAW *et al.*, 1994; TABAZADEH *et al.*, 1994; HANSON and RAVISHANKARA, 1994), there are particles which might be crystallized containing nitric acid trihydrates and/or water ice, and thus the layer with large depolarization ratio is considered to be PSCs particles.

The low aerosol density above about 20 km was also found in the measurements at Ny-Ålesund when PSCs were not observed, and showed good correspondence to the previous measurements by McCORMICK *et al.* (1983) and KENT *et al.* (1985).

However, there is a large difference in aerosol load at 10–15 km between at Fairbanks and at Ny-Ålesund, connected with the measurements on February 26 and 27, 1994, even though both lidar stations were inside of the polar vortex. The value of $[SR(z) - 1]$ at Ny-Ålesund is about 0.5 at the layer peak and about 2.5 times the measurements at Fairbanks. One possible process causing such a large difference is that the descending speed is not always unity inside the polar vortex. Additionally, complicated unknown dynamical effects on aerosol load can be expected near the vortex wall (BAUER *et al.*, 1994) which causes the decrease of aerosol content. According to BAUER *et al.* (1994) the stratospheric N_2O mixing ratio changed due to diabatic cooling inside of the polar vortex and dynamic wave activity at the edge of the vortex led to significant lateral erosion in the lower stratosphere in winter. Thus, aerosol distribution near the polar vortex also may be disturbed by such atmospheric wave motion.

Microphysical processes of aerosol particles and dynamics including meandering of the polar vortex can make a large contribution to the global budget of stratospheric particulate matter and various gases relating to aerosols. However measurements have been highly limited. It is desired to make more intensive measurements near the edge of the polar vortex in order to understand the relation between aerosol density profile and polar vortex meandering.

5. Summary

Lidar measurements of stratospheric aerosols at Fairbanks, Alaska show that mean-

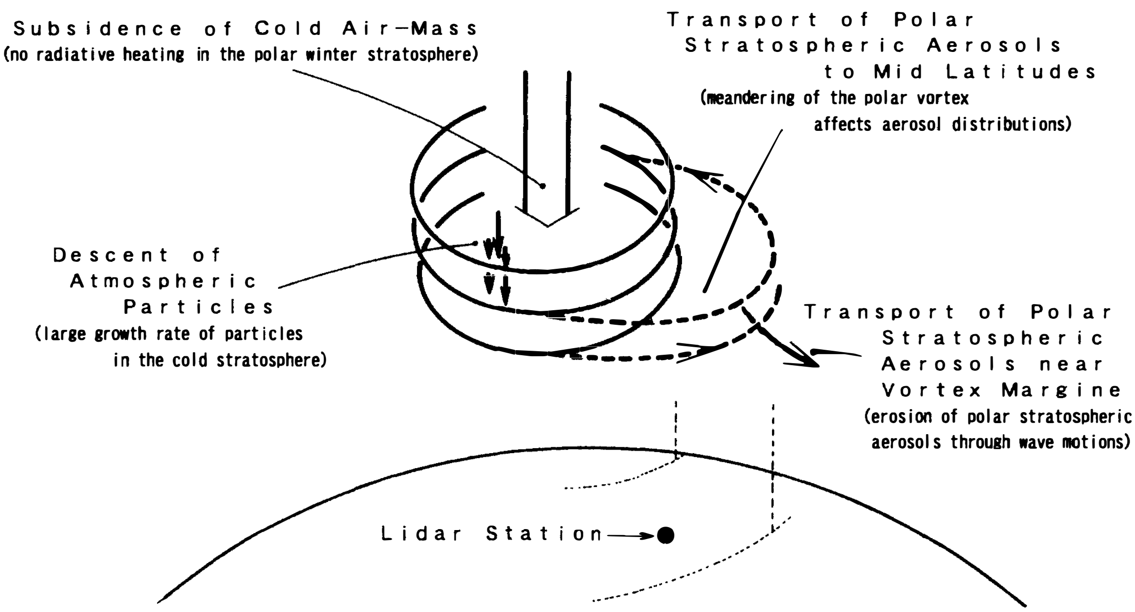

Fig. 9. A schematic picture of the dynamics near the vortex margin.

dering of the polar vortex controls the distribution of stratospheric aerosols. Descending of stratospheric particulate matter to the troposphere, which is active inside of the polar vortex occur in the mid-latitudes when the mid-latitudes region becomes under the polar vortex through its meandering, distortion, or traveling. However, a large difference of aerosol load of 10–15 km between at Ny-Ålesund and at Fairbanks shows the possibility that the atmosphere near the wall of the polar vortex is disturbed by an unknown complicated process. Meandering motion of the polar vortex may form very complicated chemical conditions near the boundary of the vortex because the polar air-mass formed under the winter night can absorb solar radiation during the air-mass travel in the mid-latitude stratosphere.

More observations should be made to understand the effect of meandering motion of the polar vortex on aerosol loading, transport of particulate matter, and chemical disturbance including aerosols (Fig. 9).

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