Geof. Int. Vol. 23-2, 1984, pp. 277-288

LIDAR MEASUREMENTS OF STRATOSPHERIC AEROSOL CONTENT AND DEPOLARIZATION RATIOS AFTER THE ERUPTION OF EL CHICHÓN VOLCANO: MEASUREMENTS AT NAGOYA, JAPAN

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RESUMEN

Después de la erupción de "El Chichón", se observó un enorme aumento en la dispersión de fondo de la luz desde la capa de aerosol estratosférico, utilizando un lidar de rubí en Nagoya, Japón (35°N, 137°W). En la parte inferior de la capa principal de aerosol se observó también un aumento aparente en la tasa de despolarización. El aumento en la tasa de despolarización indica la existencia de partículas no esféricas, tales como las de silicatos. La tasa de despolarización disminuyó a solo un porcentaje bajo, lo que sugiere que casi todas las partículas eran esféricas, después de fines de septiembre.

Aún varios meses después de la erupción, los aerosoles en la región de los vientos orientales por encima de los 20 km de altitud estaban todavía distribuidos heterogéneamente. Después del cambio del sistema de vientos al de tipo invernal, la capa de aerosol mostraba solamente un ancho pico y parece que los aerosoles estaban distribuidos por zonas, de manera homogénea. Con base en los datos obtenidos después de septiembre, se calculó un coeficiente efectivo de difusión vertical, y el resultado fue de alrededor de $3 \times 10^3 \, cm^2/s$.

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ABSTRACT

An enormous increase in backscattered light from the stratospheric aerosol layer was observed after the El Chichón eruption by using a ruby lidar in Nagoya, Japan (35°N, 137°W). An apparent increase in depolarization ratio was also observed in the lower part of the main aerosol layer for several months after the eruption. The increase in depolarization ratio indicates the existence of non-spherical particles such as silicate particles. The depolarization ratio decreased to only a few percent, which suggests that almost all particles were spherical, after the end of September.

Even several months after the eruption, aerosols in the easterly wind region above 20 km were still distributed inhomogeneously. After the wind system changed into the winter system, the aerosol layer showed only one broad peak and it seems that aerosols were distributed zonally homogeneously. An effective vertical diffusion coefficient was estimated on the basis of the data obtained after September and the value of about $3 \times 10^3 cm^2/s$ was obtained.

INTRODUCTION

Stratospheric aerosol content has been monitored by using a ruby lidar in the Water Research Institute, Nagoya University in Nagoya, Japan, since 1977. A sudden increase in backscattered light from the stratospheric aerosol layer was observed by the lidar immediately after the eruption of El Chichón (March 29 and April 4, 1983, Mexico) (Iwasaka *et al.*, 1983; Hayashida and Iwasaka, 1983). The increase observed after the El Chichón eruption is the biggest we have observed in the past several years, though we found also an increase in stratospheric aerosol content after the eruption of Mt. St. Helens (Iwasaka and Hayashida, 1981) and that of Mt. Alaid. Data presented here will help to interpret vertical and meridional diffusion processes of materials injected into the stratosphere.

We measure not only the intensity of backscattered light but also its polarization characteristics. The backscattered light from air molecules and spherical particles has polarization properties similar to those of the transmitted laser beam, while backscattered light from non-spherical particles has a significant depolarized component. The depolarization ratio gives useful information about the shape of particles and hence suggests chemical components or phase state of particles. Nevertheless, only a few studies have been done on the depolarization ratio of stratospheric aerosols so far (Reiter *et al.*, 1979; Iwasaka and Hayashida, 1981; Goad, 1982). Here we will report the temporal increase in depolarization ratios around 20 km altitude immediately after the eruption of El Chichón and the decay of the depolarization ratio. Our results suggest the existence of nonspherical particles such as silicate particles in the volcanic aerosol cloud immediately after the eruption.

LIDAR SYSTEM AND MEASUREMENTS

The lidar system used here consists of a Q-switched ruby laser at $\lambda = 0.6943\ \mu m$, which produces a pulse every five seconds with an output energy of 0.1 - 1.0 joule per pulse. Specifications of the lidar are described by Iwasaka *et al.* (1976).

A profile of backscattering coefficient or scattering ratio is obtained from the averaged value of the return signal of a few hundred laser pulse firings. The return signal is counted by a photon counter and its vertical resolution is adjusted to 1.5 km. The profile is normalized at the upper or lower level of the main aerosol layer and the backscattering coefficient from a molecular atmosphere is calculated from a U. S. Standard Atmosphere (1976). The attenuation of the laser power in the stratosphere due to extinction was included in the data analizing procedure because the aerosol cloud was so highly concentrated that the effect of the extinction was not negligible.

Iwasaka and Hayashida (1981) describe the detailed procedure in which the depolarization ratio is derived. Depolarization ratio δ is given by the ratio of intensity of backscattered light polarized perpendicularly to the plane of polarization of the transmitted laser pulse to that polarized parallel, that is

$$\delta(z) = \frac{P_{r\perp}(z)}{P_{r/\!/}(z)} \qquad (1)$$

where z indicates the altitude. $P_{r/\!/}(z)$ and $P_{r\perp}(z)$ are the parallel and orthogonal components of received power, respectively. These two components of backscattered light are measured alternately and normalized by using the monitored output energy.

RESULTS

In Fig. 1 the profiles of scattering ratio from April 1982 to January 1983 are shown. As pointed out by Hayashida and Iwasaka (1983) a two layer structure is continuously observed from the end of April to the beginning of July 1982. The lower layer exists in the westerly wind region and the upper one exists in the easterly wind region. After September the aerosol layer shows only one broad peak and the shape of the profile doesn't change largely. Shadowed regions in Fig. 1 show the layers of high depolarization ratio. Large values of depolarization ratio were observed at about 20 km immediately after the eruption.

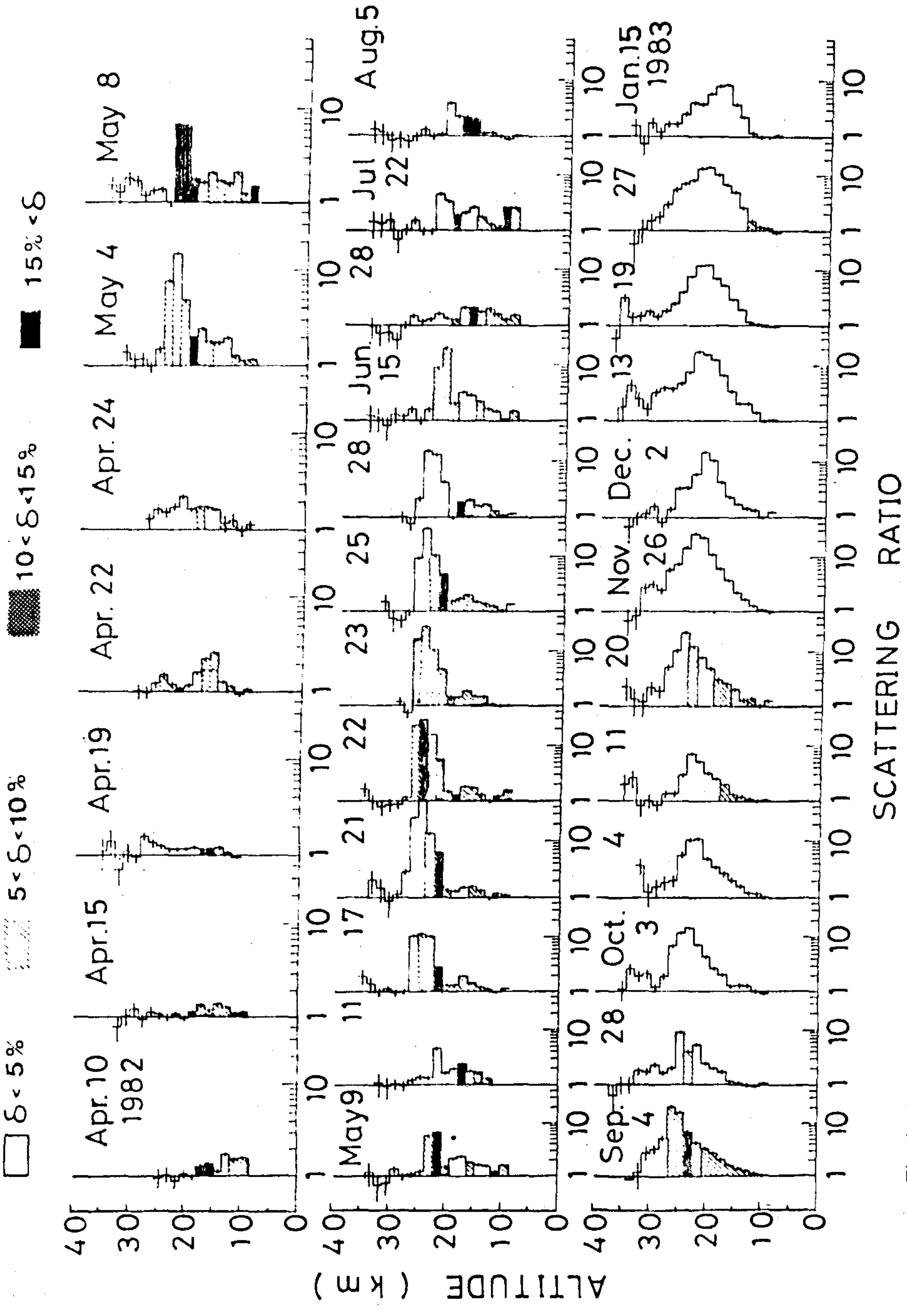

Fig. 1. Scattering ratio profiles and depolarization ratio observed from April 10, 1982 to January 15, 1983. Shadowed regions show layers of high depolarization ratios.

δ < 5 %, 5 δ < 10 %, 10 < δ < 15 %, and 15 % < δ.

Figures 2 (a) and 2 (b) present the profiles of depolarization ratio of background stratospheric aerosols. Fig. 2 (c) is a typical profile of a cirrus cloud. A cirrus cloud consists of ice crystals and gives a depolarization ratio of several tens of percent or sometimes even more. The depolarization ratio observed in May 1983 (Fig. 3(a)) shows a value larger than 10% and it reaches more than 20%. These high ratios were observed at around 20 km for about 4 months. Non-spherical particles seem to have existed at around 20 km. They would be possibly volcanic ash such as silicate particles. Woods and Chuan (1983) found volcanic ash at about 20 km by aircraft sampling.

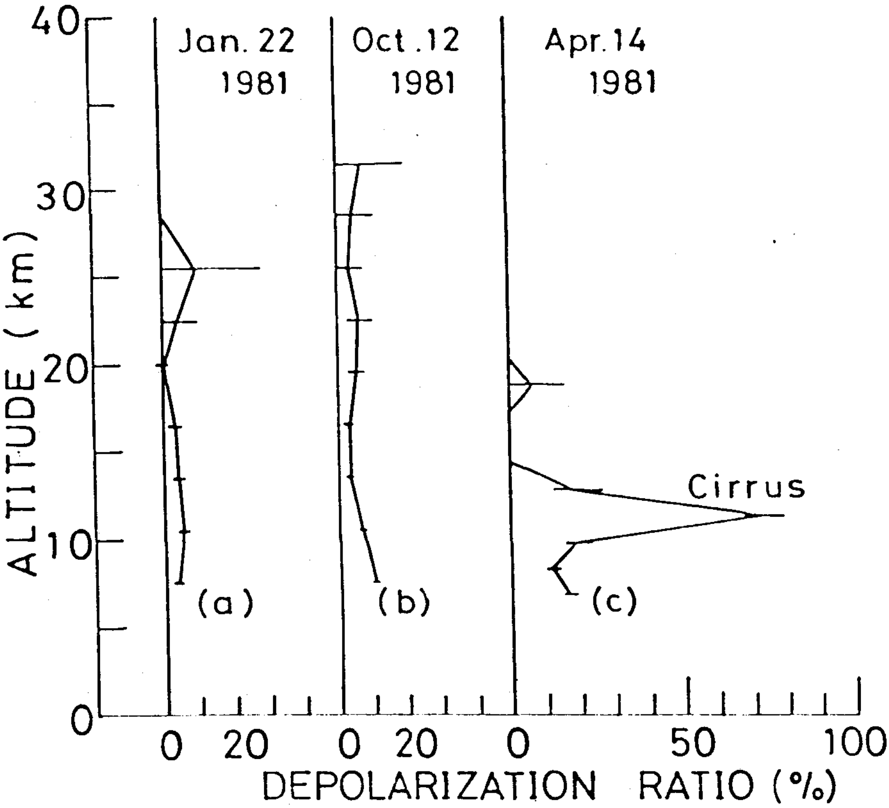

Fig. 2. (a), (b) Depolarization ratio of backscattered aerosols.
(c), Depolarization ratio of a cirrus cloud.

As shown in Fig. 3 (b), the depolarization ratio was as low as 2 or 3 percent after the end of September probably because silicate particles were covered with sulfuric acid or removed from the stratosphere by sedimentation. It will be discussed in the following section.

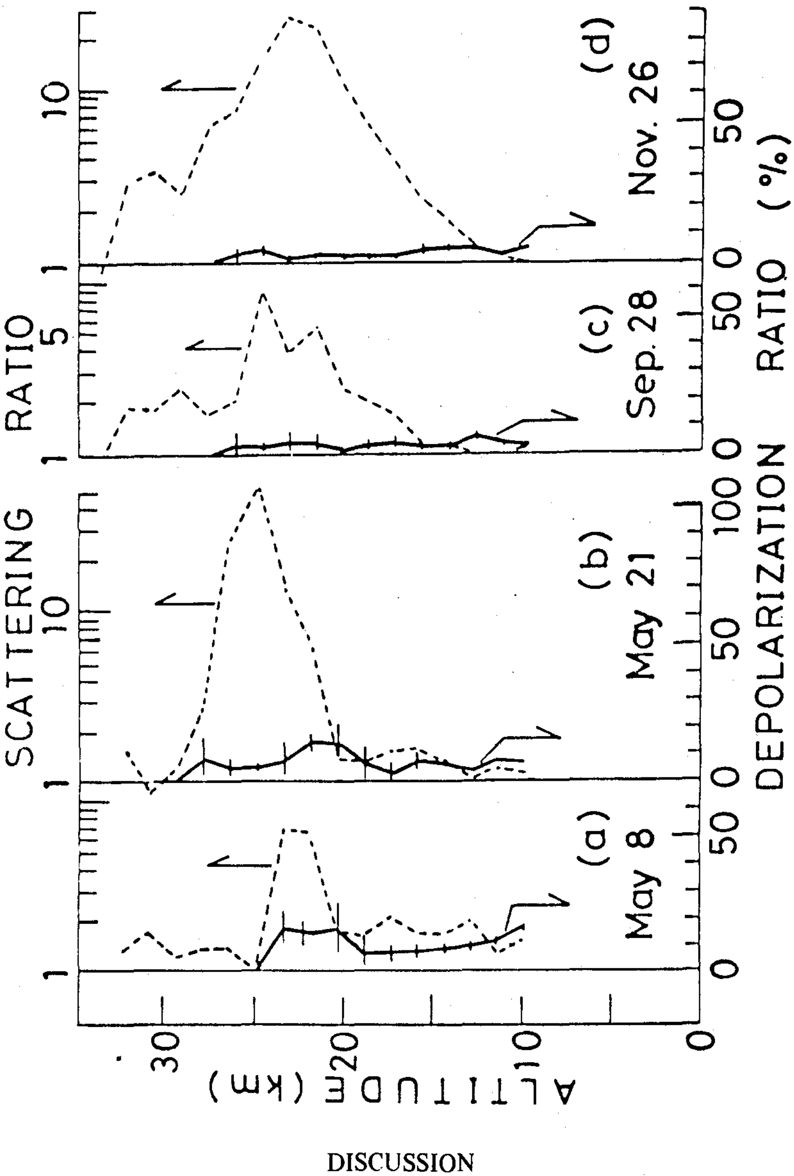

Fig. 3. (a), (b) The increase in depolarization ratio immediately after the eruption of El Chichón. (c), (d) The decay of depolarization ratio after September.

DISCUSSION

(a) Time variation of depolarization ratio

A molecular atmosphere yields a depolarization ratio of about 2.5%. A large value of depolarization ratio would indicate the existence of non-spherical particles. It is possible to conjecture the chemical and physical state of particles from the depolarization ratio. Reiter *et al.* (1979) suggested the possibility of the existence of frozen particles in the lower stratosphere from their measurements. Iwasaka and Hayashida (1981) discussed a possibility of the existence of ammonium sulfate particles. On the other hand, Goad (1982) found a depolarization ratio of about 18% immediately after the eruption of Mt. St. Helens and suggested the existence of non-spherical particles.

We have measured the depolarization ratio since June, 1980. As shown in Figs. 2 (a) and 2(b), the depolarization ratio is usually less than 5% for background aerosols observed before the eruption of El Chichón, though sometimes high depolarization ratios were observed temporarily. From May to September 1982, values larger than 10% were observed for about 4 months at around 20 km continuously as shown in Fig. 1. This fact shows that some non-spherical particles existed at around 20 km.

In Fig. 1 the peak altitude of the depolarization ratio is lower by several kilometers than that of the scattering ratio. Non-spherical particles (primary particles) were possibly separated from spherical particles (secondary particles) due to larger settling velocity because non-spherical particles were probably larger in size and specific gravity.

In Fig. 4, time series of the maximum depolarization ratio are shown. Since the end of September the maximum depolarization ratio decreased drastically (to less than 5%). Woods and Chuan (1983) found naked irregular particles at about 20 km during the period when we observed high depolarization ratios, but they found that those particles were coated with liquid after September. Similar results were obtained by Mossop (1964) after the eruption of Mt. Agung, Bali, 1963. From simple estimation of particle growth, it takes several months for a particle of 1.0 μm radius to get covered with sulfuric acid of 1 μm thickness if the vapor pressure of sulfuric acid is assumed to be $2 - 3 \times 10^7$ molecule/cm^3 which is estimated by Hofmann and Rosen (1983). The condensation growth was calculated after the manner of Hamill *et al.* (1977) and the sticking coefficient of sulfuric acid vapor to substrate was assumed to be unity. The effect of coagulation is negligible compared with the condensation growth. On the other hand, a particle of 1.0 μm radius falls from 25 km to 20 km in 4 months due to sedimentation. Therefore, a decrease in depolarization ratio can be interpreted by the effects of condensation growth and sedimentation.

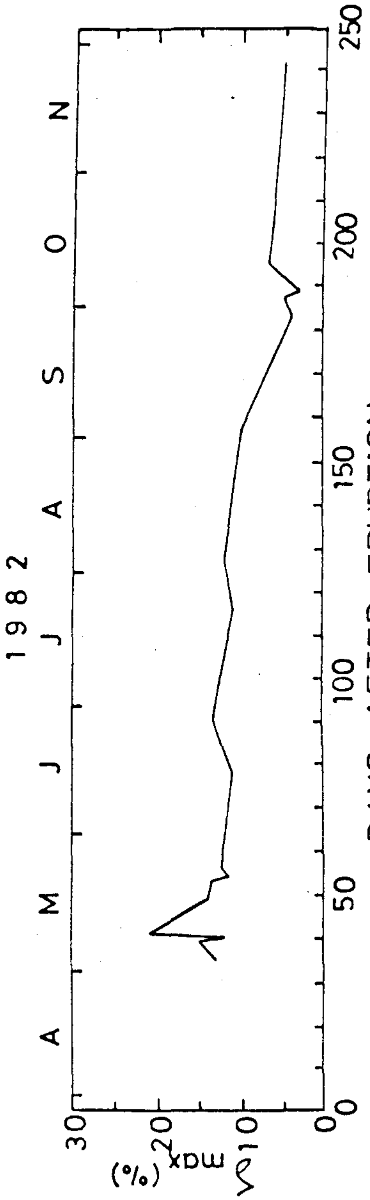

Fig. 4. Time series of maximum value of depolarization ratio (δ max).

(b) Vertical diffusion

In Fig. 5, the time series of backscattering coefficient integrated from 15 km to 30 km is shown. The stratospheric aerosol column mass was estimated from the results of lidar measurements on the basis of the relationships between backscattering coefficient and mass of aerosols (Pinnick *et al.*, 1980). We compared our estimated column mass with the balloon-borne measurements by Hofmann and Rosen (1983). Their results are plotted also in Fig. 5. The column mass decreased gradually at southern Texas (27 - 29°N) perhaps due to northwards transport and so at Laramie (41° N) the column mass increased gradually.

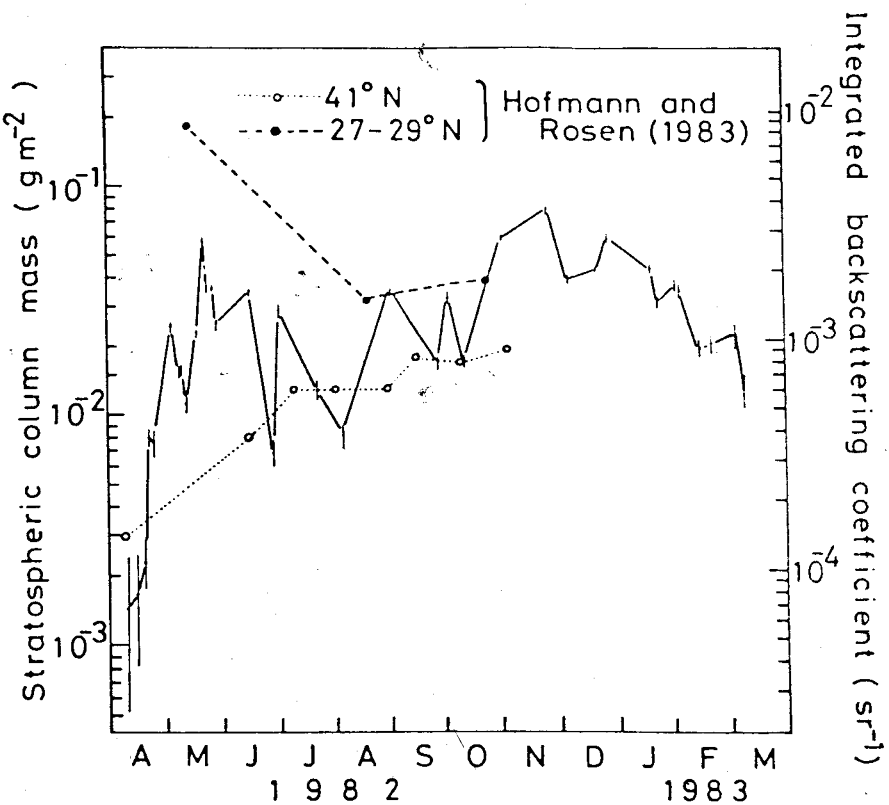

Fig. 5. Time series of backscattering coefficient integrated from 15 km to 30 km (solid line), which is compared with balloon-borne measurements by Hofmann and Rosen (1983). Dashed line shows the measurements in southern Texas and dotted line shows the measurements in Laramie.

The column mass of stratospheric aerosols estimated from lidar measurements at Nagoya lies between the two values obtained in Texas and Laramie and values at all three places are almost the same in autumn in 1982. In May 1982, the observed values in Nagoya is high and shows large fluctuations. As seen in Fig. 1 a huge aerosol cloud appeared at around 24 km in the easterly wind region in May 1982, but it disappeared in summer in 1982. Aerosols in the easterly wind region above 20 km would have been still distributed inhomogeneously even 5 months after the eruption (Hayashida and Iwasaka, 1983). As mentioned in Section 3 the profiles of scattering ratio show one broad peak and the maximum scattering ratio at the peak altitude doesn't fluctuate largely after September 1982. It can be presumed that aerosols were distributed almost homogeneously zonally after September.

The half-value thickness of the scattering ratio, ΔZ, increased gradually after September. The time series of $(\Delta Z)^2$ is shown in Fig. 6. Though the value of $(\Delta Z)^2$ shows a large fluctuation, it increases gradually.

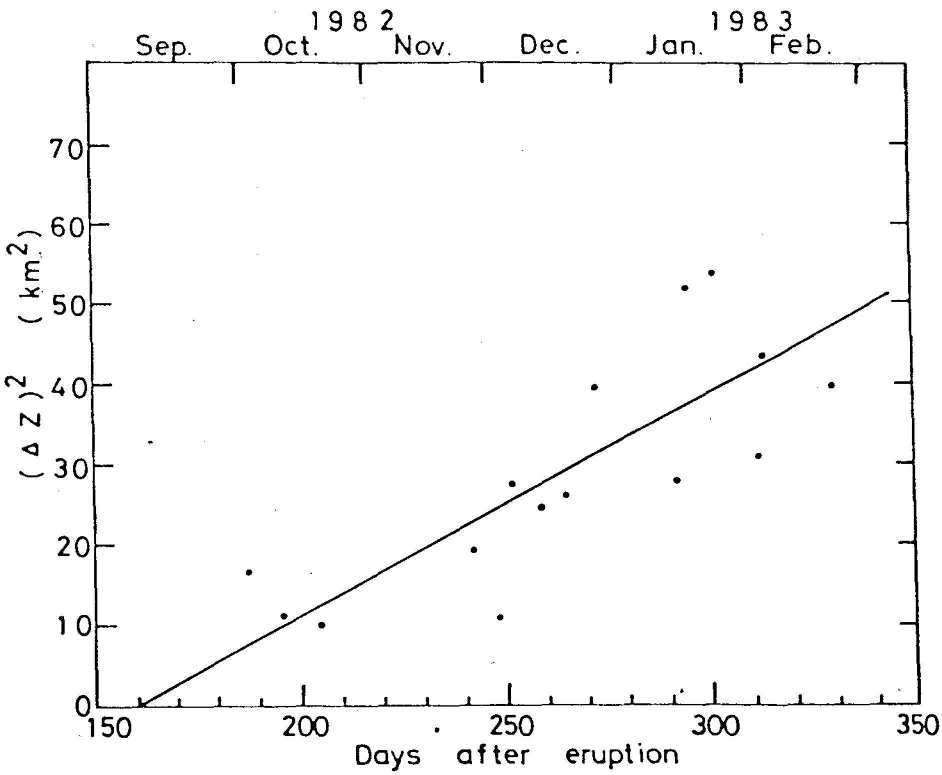

Fig. 6. Time series of $(\Delta Z)^2$. ΔZ is the vertical thickness of the layer at half-maximum in the scattering ratio profiles. Abscissa indicates days after the eruption on March 29, 1982.

Here we assume a zonally homogeneous line source function of aerosol mixing ratio (scattering ratio minus unity) and we will estimate the one dimensional vertical diffusion coefficient K_z based on the method of Remsberg (1980). The diffusion coefficient considered here includes the effect of atmospheric motions ranging from microscale turbulence to large scale disturbances and advections.

According to Remsberg (1980),

$$K_z = \frac{(\Delta z)^2}{11.1 \cdot t} \ , \tag{2}$$

where t is the time from t_0 when a line source is assumed. From eq. (2) K_z can be derived from the ratio of $(\Delta Z)^2$ to the time from t_0. In Fig. 6 an approximate linear function derived by the least squared method is shown. K_z estimated from Fig. 6 is about $3 \times 10^3 \, cm^2/s$ at altitudes of 15 to 25 km. This value is of the same order but somewhat smaller than values of K_z used in the one dimensional numerical model of many researchers (Oliver *et al.*, 1977).

The following assumptions were made in applying eq. (2) to the analysis: (1) the size distribution function is assumed to be constant with time and altitude, (2) the tensor of eddy diffusion is assumed symmetric, (3) the coefficients of eddy diffusion are assumed not to vary with latitude, altitude (between 15 - 25 km) and time, (4) sources and sinks of aerosols can be neglected.

The estimated value of the vertical eddy diffusion coefficient can be considered as a representative average in the lower stratosphere, but the effect of these assumptions on the estimated value should be examined in more detail.

ACKNOWLEDGMENT

The authors thank Prof. T. Takeda, Prof. A. Ono and Dr. H. Tanaka of Nagoya University for helpful discussions.

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