Variations of Volcanic Aerosols Observed in Fukuoka —A Comparison of Mt. El Chichón and Mt. Pinatubo Events—

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Variations of volcanic aerosol layers originated from eruptions of Mt. El Chichón and Mt. Pinatubo observed in Fukuoka are analyzed.

The arrival of the bulk of the El Chichón aerosol layer at Japan was sooner after the eruption, about two weeks after the major eruption, than the arrival of Pinatubo volcanic aerosols which was about three months after the major eruption. The difference is mainly because of the difference in the seasons of the major eruptions between the two events.

Although the altitude of the layer of aerosols formed in the case of El Chichón was higher than that of Pinatubo, the speeds of the downward motions were comparable in both cases. It is suggesting that mean radius of the El Chichón aerosols was smaller than that of the Pinatubo aerosols.

1. Introduction

Large amount of stratospheric aerosols produced from the sulfur containing gases injected by violent eruptions of volcano are considered to be possible cause of global climate change. The sulfuric acid aerosols transported to the polar region, on the other hand, may act as nuclei of Polar Stratospheric Cloud, which subsequently play important roles in the destruction of ozone in the polar stratosphere (Hofmann and Solmon, 1989; Arnold *et al.*, 1990; Hofmann and Oltmans, 1993; Xue and Brassene, 1994). The serious eruption of Mt. El Chichón in Mexico (17.3°N, 93.0°W) on 4 April in 1982 injected large amount of volcanic gases into the stratosphere and the increase of aerosol loading in the global stratosphere was regarded as one of the largest atmospheric perturbations in this century (Shibata *et al.*, 1984; Hofmann, 1987). Effects of the volcanic aerosols on the global climate have been discussed by a lot of researchers since then (Parker and Branscombe, 1983; Hansen *et al.*, 1992; Labitzke and McCormik, 1992; Angell, 1993). Angell (1993) examined the effects of three volcanic events, Mt. Agung, Mt. El Chichón, and Mt. Pinatubo, on stratospheric warming, and reported that warming in the tropical stratosphere following the three eruptions were greatest at 20 km.

About 9 years after the eruption of Mt. El Chichón, Mt. Pinatubo in Philippine (15.1°N, 120.4°E) erupted violently. The major eruption of Mt. Pinatubo occurred on 15 June in 1991 and the amount of sulfur containing gases injected into the atmosphere has been reported to be larger than that injected by the eruption of Mt. El Chichón. And the amounts of sulfuric acid aerosols produced from the volcanic gases were expected to have been the greatest one in this century (EOS, 1991; Bluth *et al.*, 1992; McCormick and Veiga, 1992; DeFoor *et al.*, 1992; Jäger, 1992; Gobbi *et al.*, 1992; Hayashida and Sasano, 1993; McPeters, 1993; Uchino *et al.*, 1993). The sulfuric acid aerosols formed in the stratosphere, which spread

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all over the globe, are expected to be more serious than the El Chichón event in their effect on the global climate, as well as on the destruction of polar stratospheric ozone.

We have conducted the observation of stratospheric aerosols by Nd-YAG lidars in Fukuoka (33°N, 135°E) for about 15 years before 1989 at Kyushu University, and at Fukuoka University after that. In this paper, a comparison of both volcanic events especially in the initial stages of the events is made.

2. Lidar Systems and Observations

The observations of El Chichón event were made with a Nd-YAG lidar using both the fundamental and second harmonic wavelengths at Kyushu University. The results of observation by the fundamental wavelength were discussed elsewhere (Shibata *et al.*, 1984). The second harmonic data obtained in 1982 and 1983 are analyzed in this paper. The Pinatubo event was observed by the second harmonic of Nd-YAG laser at Fukuoka University. Characteristics of the lidar systems at two of the stations are shown in Tables 1(a) and 1(b). In spite of the difference in the power of laser and the diameter of receiving telescope for the two lidar systems as well as the difference in the number of laser sounding at every observations, which led the different accuracies of data, all the data are averaged vertically to the same height resolution of 750 m. From the measured profile of intensity of the backscattering light, the backscattering coefficient of aerosols, β , and the scattering ratio, R , are calculated with the normalization height around 30 km using an algorithm described by Fernald (1984). The backscattering coefficient is the backscattering cross sections in a unit volume and roughly proportional to the number density of the aerosols. The scattering ratio is defined as

$$R = \frac{\beta_a + \beta_m}{\beta_m}$$

where, β_a and β_m are the backscattering coefficient of aerosols and that of atmospheric molecules respectively.

Table 1. Characteristics of the lidar used at Kyushu University (a) and at Fukuoka University (b).

(a)	
(1) Transmitting system	
laser	Nd-YAG laser
wave length	532 nm
power	140 mJ/pulse
repetition	10 Hz
(2) Detecting system	
telescope	50 cm (Newton type)
photo multiplier	EMI9558QB
(b)	
(1) Transmitting system	
laser	Nd-YAG laser
wave length	532 nm
power	100 mJ/pulse
repetition	10 Hz
(2) Detecting system	
telescope	30 cm (Cassegrain type)
photo multiplier	EMI9558QB

3. Results of Observations

3.1 *El Chichón*

Traces of volcanic scattering layer superposed on the background aerosols appeared over Fukuoka 2 weeks after the major eruption of Mt. El Chichón at altitudes around 15 km and 25 km, which were followed by the appearance of extraordinary strong scattering especially in the upper altitude. Figure 1(a) is the time-height cross section of the scattering ratio R for the observations of about 20 months after the major eruption. The main layer with large values of the scattering ratio persisted at altitudes around 25 km for about five months and then descended down to an altitude of about 20 km during the next 5 months.

To see the rate of descent motion of the aerosol layer, we defined the center of gravity of the backscattering coefficient in the stratosphere as following equation.

$$C = \frac{\int_{\text{Tropopause}}^{30 \text{ km}} z \cdot \beta_a(z) dz}{\int_{\text{Tropopause}}^{30 \text{ km}} \beta_a(z) dz}$$

Fig. 1. Time-height cross section of the scattering ratio observed in the event of Mt. El Chichón (a) and Mt. Pinatubo (b).

Fig. 2. Variability of the peak value of the scattering ratio observed in the event of Mt. El Chichón (a) and Mt. Pinatubo (b).

where, C , $\beta_a(z)$, and z are center of gravity, backscattering coefficient of the aerosol, and altitude respectively. Time variability of the center of gravity is shown in Fig. 3(a). The center of gravity which lay around 23 km in the first summer moved down to the altitudes around 20 km in the second summer. The speed of the downward motion of the center of gravity averaged over one year from the first summer to the second summer was about 8 m/day.

Fig. 3. Variability of the center of gravity of the back scattering coefficient, β , in the event of Mt. El Chichón (a) and Mt. Pinatubo (b).

Time variability of the peak value of R is shown in Fig. 2(a). Peak value attained its maximum, $R = 48$ at 25 km, about one month after the major eruption. After having taken its maximum in May 1982, peak scattering ratio decreased quickly, almost exponentially with time.

The variation of integrated backscattering coefficient (I.B.C.) which, roughly speaking, is the

quantity proportional to the column content of the aerosols above the tropopause, is shown in Fig. 4(a). Heights of the tropopause are also plotted in the lower part of the figure. The figure shows that the bulk of the volcanic cloud arrived in Fukuoka very fast, about a month after the eruption. The figure also shows remarkable seasonal variation, increase in winter and decrease in summer, being superposed on the

Fig. 4. Variability of the integrated backscattering coefficient, I.B.C., in the event of Mt. El Chichón (a) and Mt. Pinatubo (b).

monotonical decrease. Values of I.B.C. were quite large, around $4 \times 10^{-3} \text{ Sr}^{-1}$, in the first and second winter, but decreased to the values around $1\sim 2 \times 10^{-3} \text{ Sr}^{-1}$ in the third year.

3.2 Pinatubo

The scattering layer originated from Mt. Pinatubo was first observed just above the local tropopause over Fukuoka in early July 1991, about three weeks after the major eruption of Mt. Pinatubo. An intense but very thin scattering layer appeared around 21 km a month after the eruption. During the first three months after the eruption, volcanic layers appeared intermittently over Fukuoka.

Time-height cross section of the scattering ratio and time variability of peak values of the scattering ratio observed in Fukuoka are shown in Figs. 1(b) and 2(b) respectively. From September 1991, three months after the eruption, the volcanic layer could be observed steadily at about 21 km. The intense scattering layers, $R > 9.5$, appeared periodically with a period of about a month in the first year, and the largest value, $R = 17$, was observed about 130 days after the eruption.

The center of gravity of the backscattering coefficients, which were around 20 km in the first winter, descended gradually with time to about 17 km in the second winter (Fig. 3(b)). Average speed of the downward motion is calculated to be about 8 m/day, which is comparable to that in the case of El Chichón event.

Time variability of the I.B.C. is shown in Fig. 4(b). Although very strong scattering appeared a month after the eruption, the remarkable enhancement of the I.B.C. was observed in September of the first year. It took about three months for the bulk of the volcanic aerosols to arrive in Fukuoka in this case. The variation also shows the seasonal variation similar to the case of Mt. El Chichón event, large in winter and small in summer. Maximum value of the I.B.C., around $4 \times 10^{-3} \text{ Sr}^{-1}$, was observed in the first winter. After attaining the maximum, I.B.C. decreased monotonically with time.

4. Discussion

4.1 Characteristics of the transport of the volcanic aerosols, and the altitudes where the volcanic aerosol layers were formed in the initial stages

At the initial stages, the height of the main layer of volcanic aerosols and the time of arrival in Fukuoka are quite different between the two of the events. The differences inferred from the differences of the heights where the ejecta were injected to and the time of a year when the injection occurred. Comparing the features of the volcanic clouds of El Chichón and Pinatubo, it proved that the height of the main layer and the time of arrival of the aerosols were quite different.

In the case of El Chichón, the upper layer of volcanic aerosols which was observed around a height of 25 km initially two weeks after the major eruption increased quickly and attained the maximum, $R_{\text{max}} = 48$, only in about a month. While, the bulk of Pinatubo volcanic aerosol layer arrived about three months after the major eruption. The altitudes of the layer were around 22 km and the maximum scattering ratio was $R_{\text{max}} = 17$ at about 130 days after the eruption. DeFoor *et al.* (1992) also reported that the height of the El Chichón cloud was higher than that of Pinatubo cloud. They observed the Pinatubo volcanic cloud by lidar at Mauna Loa observatory in Hawaii (19.53°N , 155.58°W), and reported that the Pinatubo volcanic plume reached up to the altitude range of 27 to 28 km, while height of the El Chichón volcanic plume was higher than 30 km. Although it is difficult to make a direct comparison between the initial stages of the El Chichón cloud and the Pinatubo cloud, because of the difference in the seasons of the eruptions, it is probable that the Mt. El Chichón injected the ejecta up to higher altitude than Mt. Pinatubo.

The difference in the time of arrival of the bulk of the volcanic aerosols is considered to be resulted from the difference in the seasons when the major eruption occurred. The features of transport in the lower stratosphere varies with season accompanying with the variation of the background wind field and accordingly the planetary waves. In winter, when the westerly wind prevails, the planetary waves can be transmitted to the stratosphere, and the latitudinal transport is activated by the meandering of the stream lines. In the case of Mt. El Chichón event, the volcanic aerosols were transported to the higher latitudes

as Fukuoka very quickly. In summer, when the wind in the lower stratosphere was easterly and the latitudinal transport was weak, the supply of the volcanic aerosols to the higher latitudes decreased, and the I.B.C. was small. The aerosols began to increase again in September when the wind in the lower stratosphere began to change to westerly, and I.B.C. attained its maximum in December, about eight months after the eruption of Mt. El Chichón. In the case of Pinatubo event, the arrival of the bulk of the aerosol layer was about three months after the eruption, in September, as the major eruption of Mt. Pinatubo was in summer when the wind in the lower stratosphere was easterly and the latitudinal transport was weak. The maximum of I.B.C. was observed in the first winter, about six months after the eruption.

To examine the day to day variation of the transport of the volcanic aerosols around Japan in winter when the planetary wave was active, heights of isobars at 30 hPa and scattering ratios observed on the same days are shown in Figs. 5(a) and 5(b) and Figs. 6(a) and 6(b), respectively. These synoptic charts are showing typical patterns observed often in winter season. On 19 October 1991, when the scattering ratio

Fig. 5. Distributions of heights of isobar at 30 hPa around Japan, which were extracted from synoptic charts drawn at Berlin University. (a) On October 19 1991, the high pressure regions in the east of Japan did not developed enough, and the stream lines over Japan were not systematic. (b) On October 21, the high pressure region developed, and a systematic structure of the stream lines was formed over Japan. Arrows are showing the wind directions.

Fig. 6. Scattering ratios observed on October 19 1991 (a) and October 22 1991 (b).

was not so large, there were two high pressure regions in the east of Japan. The effects of the existence of the high pressure regions on the stream line over Japan were small on that day, as they were not developed well. After a few days, on 21 October (Fig. 5(b)), the two high pressure regions merged into one and well developed, and a systematic structure of the stream line was formed in the west of Japan. A stream which came from far western longitudes along the zonal circle and another stream which was swirling around the high pressure region converged just by the west coast of Japan. When the systematic convergence of the stream lines occurred, dense aerosol layer was transported from the southern latitudes by the circulation around the high pressure region, and the density of the aerosols in the zonally circulating parcel around Japan was enhanced by the convergence (Fig. 6(b)). This result suggests the existence of a large latitudinal density gradient in the southern latitudes. Trepte *et al.* (1993) reported the existence of the large latitudinal gradient of the aerosols. They analyzed the data of the distribution of the Pinatubo volcanic aerosols obtained by SAGE II satellite during 10 months after the eruption. According to their report, large portion of the volcanic aerosols were confined within the tropical belt bounded by a large density gradient at subtropical belt, and the transport of the aerosols to higher latitudes in the winter hemisphere was caused by synoptic scale events which correspond to the planetary wave activities around the altitudes of 30 hPa. Such a day to day variation which caused fine structures of the seasonal variation occurred frequently under the atmospheric condition of large latitudinal density gradient in the southern latitudes and was greatly affected by the location and intensity of the high pressure region in the east of Japan.

4.2 Comparison of two of the events with corresponding seasons

As explained in the previous section, the characteristics of the transport of the volcanic aerosols to Fukuoka highly depend on the seasons. That is why, it is needed to make the comparison with corresponding seasons to discuss properly about the differences in the long term variations between two of the events.

Comparing the two of the events with corresponding seasons, they are showing similar seasonal variations except for the initial periods. The variability of El Chichón volcanic aerosols after the first winter is showing similar seasonal variations to that of Pinatubo volcanic aerosols observed after the first winter. The values of I.B.C. observed after the first winters in the two of the events were comparable.

In spite of the difference in the altitudes of the main layer, the one year average speeds of the downward motion of the center of gravity were about 8 m/day in both cases. The density of atmospheric molecules at 25 km, where the layer of El Chichón was formed, was smaller than that at 22 km where the

Pinatubo layer was formed. If the size distribution of the both events were comparable, the center of gravity of El Chichón layer should have descended faster than that of Pinatubo layer, but the speeds were almost the same value. From those facts, it is supposed that the aerosols of the El Chichón event have been smaller than those of Pinatubo event.

5. Conclusion

The volcanic aerosol layers formed from the ejecta injected by the eruptions of Mt. El Chichón and Mt. Pinatubo observed by lidar in Fukuoka were compared.

The difference in the times of the arrival of the bulk layer between the two events were caused by the difference in the seasons of their eruption. Mt. El Chichón erupted in spring (on April 4 1982) when the latitudinal transport in the lower stratosphere accompanying the planetary wave was still active, and the main layer of the volcanic aerosols were transported to Japan soon, about two weeks after the eruption. While, in the case of Mt. Pinatubo, it was about three months after the eruption that the main layer of the volcanic aerosols arrived at Japan, as the major eruption was occurred in summer (on June 15 1991) when the latitudinal transport was not active.

Although the volcanic aerosol layer formed in the event of Mt. El Chichón was a few km higher than that formed in the case of Mt. Pinatubo, the speeds of the downward motion of the center of gravity were comparable, about 8 m/day in both cases. It is supposed that the mean radius of the aerosols formed in the El Chichón event was smaller than that of the aerosols originated by Mt. Pinatubo.

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REFERENCES

- Angell, J. K., Comparison of stratospheric warming following Agung, El Chichón, and Pinatubo Volcanic Eruptions, *Geophys. Res. Lett.*, **20**, 715–718, 1993.
- Arnold, F., Th. Buhrke, and, S. Qiu, Evidence for stratospheric ozone-depleting heterogeneous chemistry on volcanic aerosol from El Chichón, *Nature*, **348**, 49–50, 1990.
- Bluth, G. J. S., S. D. Doiron, C. C. Schnetzler, A. J. Krueger, and L. S. Walter, Global Tracking of the SO₂ Clouds from the June, 1991 Mount Pinatubo eruptions, *Geophys. Res. Lett.*, **19**, 151–154, 1992.
- DeFoor, T. E., E. Robinson, and S. Ryan, Early lidar observations of the June 1991 Pinatubo eruption plume at Mauna Loa Observatory, Hawaii, *Geophys. Res. Lett.*, **19**, 187–190, 1992.
- EOS, Pinatubo cloud measured, *Trans. Am. Geophys. Un.*, **72**, 305–306, 1991.
- Fernald, F. G., Analysis of atmospheric lidar observations: Some comments, *Appl. Opt.*, **23**, 652–653, 1984.
- Gobbi, G. P., F. Congeduti, and A. Adriani, Early stratospheric effects of the Pinatubo eruptions, *Geophys. Res. Lett.*, **19**, 997–1000, 1992.
- Hansen, J., A. Lacis, R. Ruedy, and M. Sato, Potential climate impact of Mount Pinatubo eruption, *Geophys. Res. Lett.*, **19**, 315–318, 1992.
- Hayashida, S. and Y. Sasano, Stratospheric aerosol change in the early stage of volcanic disturbance by the Pinatubo eruption observed over Tsukuba, Japan, *Geophys. Res. Lett.*, **20**, 575–578, 1993.
- Hofmann, D. J., Perturbations to the global atmosphere associated with the El Chichón volcanic eruption of 1982, *Rev. Geophys.*, **25**, 743–759, 1987.
- Hofmann, D. J. and S. J. Oltmans, Anomalous Antarctic ozone during 1992: Evidence for Pinatubo volcanic aerosol effects, *J. Geophys. Res.*, **98**, No. D10, 18555–18561, 1993.
- Hofmann, D. J. and S. Solomon, Ozone destruction through heterogeneous chemistry following the eruption of El Chichón, *J. Geophys. Res.*, **94**, 5029–5041, 1989.
- Jäger, H., The Pinatubo eruption cloud observed by lidar at Garmsch-Partenkirchen, *Geophys. Res. Lett.*, **19**, 191–194, 1992.

- Labitzke, K. and M. P. McCormick, Stratospheric temperature increases due to Pinatubo aerosols, *Geophys. Res. Lett.*, **19**, 207–210, 1992.
- McCormick, M. P. and R. E. Veiga, SAGE II measurements of early Pinatubo aerosols, *Geophys. Res. Lett.*, **19**, 155–158, 1992.
- McPeters, R. D., The atmospheric SO₂ budget for Pinatubo derived from NOSS 11 SBUV/2 spectral data, *Geophys. Res. Lett.*, **20**, 1971–1974, 1993.
- Parker, D. E. and J. L. Branscombe, Stratospheric warming following the El Chichón volcanic eruption, *Nature*, **301**, 406–408, 1983.
- Shibata, T., M. Fujiwara, and M. Hirono, The El Chichón volcanic cloud in the stratosphere: lidar observation at Fukuoka and numerical simulation, *J. Atmos. Terr. Phys.*, **46**, No. 12, 1121–1146, 1984.
- Trepte, C. R., R. E. Veiga, and M. P. McCormick, The poleward dispersal of Mount Pinatubo volcanic aerosol, *J. Geophys. Res.*, **98**, 18,563–18,573, 1993.
- Uchino, O., T. Nagai, T. Fujimoto, M. Fujiwara, H. Akiyoshi, S. Yasumatsu, S. Hayashida, Y. Sasano, H. Nakane, Y. Iwasaka, M. Nagatani, T. Shibata, T. Itabe, K. Asai, A. Nomura, Y. Saito, T. Kano, Y. Sai, K. Tamaki, R. Nomura, T. Sunagawa, C. Nagasawa, M. Abo, Y. Idesako, and K. Kai, Observation of Pinatubo volcanic cloud by lidar network in Japan, *J. Meteor. Soc. Japan*, **71**, 285–295, 1993.
- Xue Xi Tie, G. P. Brasseur, Bruce Briegleb and Claire, Two dimensional simulation of Pinatubo aerosol and its effect on stratospheric ozone, *J. Geophys. Res.*, **99**, 20545–20562, 1994.