Study of lidar and satellite data on stratospheric aerosols formed due to Mt. Pinatubo volcanic eruption

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Lidar aerosol backscatter data of a few stations published in Bulletin of Global Volcanism Network (USA) (Vol. 16, Nos 5-12, 1991) have been used to investigate various transport/dynamical processes and also aerosol loading in the stratosphere due to the 15 June 1991 Pinatubo volcanic eruption. Some recently reported satellite observations have also been used to support the results obtained. Satellite data showed that in the zone extending 10°N from equator, Pinatubo aerosols circled the globe in 21 days, implying a mean easterly speed of 20-22 m/s. Ground-based lidar observations showed that aerosol cloud spread northward faster in low mid-latitudes and slowly in higher mid-latitudes. The stratospheric aerosol loading due to Pinatubo was about 30 times the pre-eruption value at a low latitude station (Mauna Loa) and about 4 times at a higher mid-latitude station (Obninsk). The analysis further showed that the aerosol cloud due to Pinatubo was nearly 1.5 times that produced due to the 1982 El Chichon volcanic eruption. The presence and morphology of the multiple stratospheric aerosol layers that appeared over Mauna Loa in the aftermath of Pinatubo are discussed.

1 Introduction

The physical origin of stratospheric aerosols is nearly well understood, being mainly due to condensation of sulphuric acid produced by the solar photodissociation of carbonyl sulphide and sulphur dioxide by UV light, injected into the stratosphere during volcanic eruptions. The stratospheric aerosol layer was one of the first atmospheric constituents to be measured by the lidar technique. Since then, lidar measurements have contributed a substantial portion of the existing data set on stratospheric aerosol behaviour. These measurements have documented the response of the stratospheric aerosol layer to several major volcanic injections, and have also helped to study the dynamics by determining the vertical and latitudinal structure of the quiescent or background layer.

Stratospheric aerosols are not normally a significant component of the earth’s climate system because their optical depth is usually quite small. However, after an explosive volcanic eruption, the number of stratospheric aerosols is greatly enhanced and their optical depth can then be as large as that of tropospheric aerosols. Thus volcanic aerosols can alter the climate by upsetting the balance between sunlight entering the atmosphere and infrared light leaving the atmosphere. It is widely believed that volcanic eruptions that inject large quantities of sulphur dioxide into the stratosphere are responsible for increasing stratospheric temperatures by several degrees and for cooling tropospheric temperatures by several tenths of a degree for a year or two after the eruption. The extent to which volcanic eruptions influence surface temperature has been a matter of controversy for decades. While some workers have shown evidence of volcanic influence on surface temperature, there are others who question the efficacy of volcanoes in producing surface cooling. In view of the fact that many historical climate changes are believed to have been caused by volcanic eruptions, it is important to make detailed measurements/studies of stratospheric aerosol layers that are formed in the aftermath of a volcanic eruption.

As the lidar measurements of the stratospheric layer are being well documented in recent years, attention is now being focussed on the behaviour and effects of the layer on atmospheric chemistry, radiative transfer and ultimately on the climate of the earth. The perturbation to stratospheric aerosols caused by the massive eruption of the El Chichon volcano (17.33°N, 93.2°W) in Mexico on 4 Apr. 1982 has been very well documented and has been studied by many workers around the
globe using the lidar technique (Refs. 11-14). The June 1991 eruption of Mt. Pinatubo, Philippines, is reported to have introduced large quantities of aerosols into the stratosphere and many lidar stations all over the globe have made measurements of aerosol backscattering. Some papers describing the early characterization of the stratospheric impacts of Pinatubo eruption have appeared in one of the recent issues of *Geophys Res Lett* (USA) (Ref. 15). Lidar data collected at five stations for the period 1 July to 4 Dec. 1991 have been used in the present study to investigate various transport/dynamical processes in the stratosphere and aerosol loading due to the Pinatubo volcanic eruption. Some of the recently reported satellite observations have also been used to supplement the results.

2. Volcanic eruptions of Mt. Pinatubo

Mt. Pinatubo (15.14°N, 120.35°E, summit elevation 1745 m), Luzon Islands, Philippines, is reported to have last erupted some 635 years ago16. In the eruption of 1991, renewed volcanic activity was first observed in April-May 1991 which later intensified by early June. SO2 flux rose up to 5000 metric tonnes per day (t/d) on 28 May. Initial strong explosions were reported on 12 June and a tephra column rose to about 20 km on that day. An explosion at 0555 hrs LT on 15 June fed a 20-22 km ash column marking the onset of strong sustained activity that included the climactic explosions and lasted until early hours of 16 June. Satellite data suggested that more than 95% of the aerosol cloud was produced during this 12 h phase17. This stratospheric cloud expanded rapidly west-south-west, and by 1300 hrs LT on 16 June, its leading edge had reached the Bangkok area, more than 2000 km away. This travel time implies a mean easterly wind speed of 26.5 m/s. Preliminary Nimbus-7 satellite data showed a very high concentration of SO2 over a broad area covering Indochina and south China sea, with a total mass that appeared to be approximately double that of the 1982 injection from El Chichon. Light ash falls were reported in the southern Vietnam, Northern Borneo and Singapore about 20 h after the onset of strongest activity.

3 Results and Discussion

3.1 Zonal and meridional transport of aerosols

Reflected solar radiation measurements from the advanced very high resolution radiometer (AVHRR) on NOAA-11 polar orbiting satellite showed the aerosol cloud's dispersal as it moved generally west along the equator17. In the zone extending 10°N from the equator, aerosols reached the longitude of Pinatubo (120°E) on 6 July, 21 days after the paroxysmal eruption. This travel time implies a mean easterly wind velocity of 20-22 m/s during the three weeks following the eruption. This speed is consistent with the stratospheric winds at about 30 mb level (about 24 km altitude). The 1982 El Chichon eruption cloud (source latitude 17.33°N, about 2°N of Pinatubo) travelled around the globe in about 22 days.

The earliest reported detection of this stratospheric aerosol cloud due to Pinatubo by ground-based lidar was at Mauna Loa (19.5°N, 130.35°W), Hawai, on 1 July 1991. Later on, several lidar stations in the low-middle and high latitudes have detected the arrival of enhanced stratospheric aerosols over their locations from backscatter information. Table 1 lists the details of 19 stations (mostly lidar) along with the dates of first detection of significant increase in stratospheric aerosol backscatter due to the Pinatubo cloud. A few observations of visual effects, especially from the southern hemisphere, are also included in the table to infer the meridional transport of aerosols. The dates of first detection at some northern latitude stations (indicated with an asterisk mark in the table) are plotted against their latitudes in Fig. 1. It is seen that the stratospheric aerosol cloud seemed to have spread northwards at faster rate initially in low mid-latitudes (at a rate of about 57 km/day) and later slowly to high mid-latitudes (at a rate of about 44 km/day). This can be inferred from the two best-fit lines having slightly different slopes shown in Fig. 1.

From SAGE-II atmospheric extinction measurements during June-August 1991, it was reported that Pinatubo aerosols were confined to tropics (15°S to 25°N) up to about 40 days after the 16 June eruption15,17. Reflecting solar radiation data from NOAA-11 satellite also showed no significant migration into mid-latitude regions till the week ending 1 August.

Ground-based measurements of stratospheric aerosols made at several stations, covering a wide range of latitudes, have also been reported (as shown in Table 1) and they yield spatial distribution of aerosol cloud in the aftermath of Pinatubo eruption. Thus the ground-based lidar data along with satellite observations provide an insight into the zonal and meridional transport of aerosol cloud in the stratosphere after volcanic injection.

3.2 Stratospheric aerosol loading

Lidar-derived integrated aerosol backscattering (total backscatter, expressed in steradians−1) data
Table 1 – Details of some ground-based observing stations that reported the signatures of the Pinatubo aerosol cloud

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Station</th>
<th>Geographic location</th>
<th>Date of first detection</th>
<th>Observational technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mauna Loa*</td>
<td>19.5°N 130.4°W</td>
<td>01.07.91</td>
<td>Ruby lidar</td>
</tr>
<tr>
<td>2</td>
<td>Fukuoka*</td>
<td>33.7°N 155.6°E</td>
<td>07.07.91</td>
<td>Nd-YAG lidar</td>
</tr>
<tr>
<td>3</td>
<td>Tsukuba*</td>
<td>36.2°N 140.1°E</td>
<td>15.07.91</td>
<td>Nd-YAG lidar</td>
</tr>
<tr>
<td>4</td>
<td>Hampton*</td>
<td>37.1°N 76.3°W</td>
<td>03.08.91</td>
<td>Ruby lidar</td>
</tr>
<tr>
<td>5</td>
<td>Coal Creek Canyon</td>
<td>39.9°N 105.4°W</td>
<td>28.08.91</td>
<td>Visual effects</td>
</tr>
<tr>
<td>6</td>
<td>Boulder*</td>
<td>40.0°N 105.3°W</td>
<td>27.07.91</td>
<td>Lidar</td>
</tr>
<tr>
<td>7</td>
<td>Salt Lake City*</td>
<td>40.8°N 111.8°W</td>
<td>28.07.91</td>
<td>Ruby lidar</td>
</tr>
<tr>
<td>8</td>
<td>Teplochuchenka*</td>
<td>41.0°N 78.0°E</td>
<td>13.07.91</td>
<td>Nd-YAG lidar</td>
</tr>
<tr>
<td>9</td>
<td>Laramie*</td>
<td>41.0°N 105.8°W</td>
<td>30.07.91</td>
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</tr>
<tr>
<td>10</td>
<td>Garmisch Partenkirchen*</td>
<td>47.5°N 11.8°E</td>
<td>Early August</td>
<td>Nd-YAG lidar</td>
</tr>
<tr>
<td>11</td>
<td>Saskatoon*</td>
<td>52.0°N 106.5°W</td>
<td>18.08.91</td>
<td>Backscatter sonde</td>
</tr>
<tr>
<td>12</td>
<td>Obninsk*</td>
<td>55.0°N 38.0°E</td>
<td>14.08.91</td>
<td>Nd-YAG lidar</td>
</tr>
<tr>
<td>13</td>
<td>Andoya Rocket Range*</td>
<td>69.3°N 16.0°E</td>
<td>18.09.91</td>
<td>Nd-YAG lidar</td>
</tr>
<tr>
<td>14</td>
<td>Resolute*</td>
<td>74.7°N 95.0°W</td>
<td>09.10.91</td>
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</tr>
<tr>
<td>15</td>
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<td>82.5°N 62.5°W</td>
<td>02.12.91</td>
<td>Backscatter sonde</td>
</tr>
<tr>
<td>16</td>
<td>Irene</td>
<td>25.9°S 28.2°E</td>
<td>Early August</td>
<td>Visual effects</td>
</tr>
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<td>17</td>
<td>Canberra</td>
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<td>Early August</td>
<td>Visual effects</td>
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<tr>
<td>18</td>
<td>Melbourne</td>
<td>38.0°W 145.0°E</td>
<td>19.07.91</td>
<td>Visual effects</td>
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<tr>
<td>19</td>
<td>Antarctica</td>
<td>66.7°W 140.0°E</td>
<td>20.07.91</td>
<td>Lidar</td>
</tr>
</tbody>
</table>

*The dates of first detection of enhanced stratospheric aerosols at these stations have been plotted against their latitudes in Fig. 1.

Fig. 1 – The dates of first detection of Pinatubo cloud by ground-based lidar systems at different northern latitudes.

Valero and Pilewskie. However, the backscattering data used here could not be corrected for the wavelength dependence as such correction factors, varying from day to day, were not available. Data for the months of April and May (pre-Pinatubo eruption period) is available only for Mauna Loa. It can be seen from the figure that in the post-eruption period up to December 1991, Mauna Loa showed the highest stratospheric loading and the other four mid-latitude stations showed more or less the same values. To examine the increase in stratospheric aerosol content, the integrated backscattering values for the period 16 June-4 December have been averaged at each station to represent the value for post-volcanic eruption period. The pre-eruption data of integrated backscatter at each station are taken according to the availability of the data and the same is shown in Table 2. The periods considered to obtain the average pre-eruption value are given in parentheses for each station. From the table it can be seen that the pre-eruption values represent fairly the background integrated backscatter uncontaminated by volcanic aerosols. The stratospheric aerosol loading in the 5 to 6 months' period following the Pinatubo eruption decreased with increasing latitude. The ratios of post-eruption to pre-eruption backscatter also confirm that the effective...
enhancement in the stratosphere due to the volcanic injection decreased away from the equator in the first few months after the eruption. It is further seen that at Mauna Loa which is latitudinally close to Pinatubo, the stratospheric aerosol loading was increased by as much as 30 times the background value. Monthly mean integrated optical depth data for Mauna Loa for pre-El Chichon eruption period (April 1981 to March 1982) and post-eruption period (April 1982 to March 1983) are taken and the ratios are obtained as explained above. It is found that the increase in aerosol loading was about 21 times during 1982 El Chichon eruption. Thus the preliminary results suggest that the aerosol cloud due to Pinatubo was massive and larger (approximately 1.5 times) than that due to El Chichon. Stowe et al. have used the mean tropical Pacific AOT (atmospheric optical thickness) values derived from NOAA satellite and have shown that post-Pinatubo AOT values are 1.6 to 1.8 times than those of the 1982 El Chichon. Monthly mean AOT values measured over Pacific Ocean (30°N-20°S) from June to December 1991 have been taken and plotted (inset...
in Fig. 2). It is observed that the mean tropical Pacific AOT reached a maximum in August.

Integrated backscatter data at Mauna Loa from 16 June (as can be seen in Fig. 2) showed an apparent oscillatory pattern till the middle of September. To investigate this in more detail, the data between 1 July and 30 September were taken and the linear trend was removed using a straight line fit. The detrended curve showed more clearly the presence of a 15-18 day period wave pattern in the lidar-derived integrated backscatter data at Mauna Loa in the post-Pinatubo period. It is reported that the optical depth data between 28 June and 28 July 1991 revealed such a wave pattern that propagated coherently westward. Satellite data have also shown a series of bands of aerosol layers moving westward with a frequency of 16-18 days and this was suggested to be due to the non-uniform longitudinal mixing of inhomogeneities in the aerosol cloud which were being transported around the globe. These bands of aerosol layers may have resulted in the observed wave pattern in the lidar backscatter data at Mauna Loa.

3.3 Eruption-induced aerosol layers

The lidar data from Mauna Loa for the period 1 July to 25 Sep. 1991 suggested the presence of multiple layers in the stratosphere which started appearing/forming on different days and continued to persist for several days. As many as six distinct layers, sometimes with 2 to 3 layers appearing simultaneously for few days, could be seen in the above period. The altitude of each layer peak was picked up and plotted for different days and is shown in Fig. 3 to examine the vertical redistribution of the layers. These curves have been numbered from 1 to 6 in the figure for identification. It is observed that the stratospheric layer that appeared from 3 to 10 July (No. 2) was narrow (about 1 km thick) but the subsequent layers (Nos 3, 4, 5 and 6) were 1-4 km thick on formation. However, the peak scattering ratios of all the layers on formation were nearly of the same order. The layers which were narrow on formation subsequently widened (vertically) on descent, may be due to diffusion and sedimentation. McCormick et al. from ground-based lidar observations at Hampton in the aftermath of El Chichon have also found that the altitude of the peak of stratospheric layers initially centred around 25 km, moved downward to 15-20 km and the layers broadened in width as the material aged. In this study all the layers appeared initially in the 22-25 km altitude range and then descended down to altitudes between 17 and 20 km up to the period reported here. The layer thickness was on an average 2 km (ranging from 0.6 to

![Fig. 3—Time-height variation of stratospheric aerosol layers as observed by Mauna Loa lidar during 1 July-25 Sep. 1991](image-url)
3.9 km) on formation and thickened to about 5 km (ranging from 0.9 to 12.9 km) as they propagated downwards.

It is also seen from Fig. 3 that the descent of the layers appears to be exponential, initially with faster descent rates (as large as 0.86 km/day). The average descent rates of the layers corresponding to the curves numbered 1 to 6 are, respectively, 0.44, 0.53, 0.43, 0.17, 0.16 and 0.14 km/day. Thus the first three layers which formed around 1-2 July had higher descent rates compared to the layers that formed later. This suggests that the larger sized aerosol particles might have descended down quickly due to sedimentation. By superposing the initial dates of all the six curves shown in Fig. 3, it is found that the aerosol layers which formed generally around 25 km altitude took nearly 30 days to reach a stable state (descent rate = 0). This corresponds to a mean descent rate of 0.14 km/day. Thus the lidar aerosol backscatter data provide an insight into the formation, dissipation and descent of stratospheric aerosol layers in the post-volcanic eruption period.

As the stratospheric lidar data for several stations and also satellite optical depth data in the post-Pinatubo period continue to come, further detailed studies are planned to understand the various dynamical processes taking place in the stratosphere. Using global climate model to make a preliminary estimate of Mt. Pinatubo’s climate impact, Hansen et al. assume the aerosol optical depth due to Pinatubo eruption to be nearly twice as great as due to the El Chichon eruption, and forecast a dramatic but temporary break in recent global warming trends. Their simulations indicate intense aerosol cooling late in 1992. Thus the preliminary results reported in this paper emphasize the fact that such a unique set of measurements help for a better assessment of the short- and long-term impacts of the volcanic eruption induced stratospheric aerosols on the earth’s radiation budget.

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