Seasonal/latitudinal variations in the satellite observed aerosol properties in the stratosphere and upper troposphere during the eruption of Alaid and Pagan

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Aerosol extinction data at two wavelengths from SAGE satellite measurements made during the period January to November 1981 has been used to study seasonal/latitudinal variations of aerosol size distributions in the stratosphere and upper troposphere. As the volcanic eruptions from Alaid (50.8° N, 155.5° E) on 27 Apr. 1981 and from Pagan (18.1° N, 145.8° E) on 15 May 1981 occurred during the observational period, the effects of volcanic injection of material have been investigated in particular. The latitudinal variation of aerosol optical depth shows a broad maximum in the tropical region and again larger values in the high latitudes with midlatitude minima around 25°-30° in both the hemispheres. At the equatorial latitudes, mode radius, computed from extinction data at two wavelengths, is large in the upper troposphere and decreases rapidly with increasing altitude. An interesting latitudinal variation is seen in the mode radius which is almost the same in all the three seasons of spring, summer and fall. At altitudes below 22 km, mode radius shows an equatorial maximum with smaller values at middle and higher latitudes in both the hemispheres. But at altitudes above 22 km, a reverse latitudinal variation is seen. During northern summer, smaller-sized particles are more prevalent in the northern high latitude stratosphere and relatively bigger aerosol particles are obtained at the southern high latitudes. The effect of volcanic injection of particulate material into the stratosphere can be seen as an increase in mode radius immediately and an increase in aerosol number density for several months after the eruption. Plausible explanations about the variations of stratospheric aerosol properties are given.

1 Introduction
Accurate measurements of atmospheric aerosols are of considerable importance to our understanding of the physics of the atmosphere, including the possible effects of aerosols on climatic processes. Stratospheric aerosols usually have smaller optical depths compared to tropospheric aerosols, but in the aftermath of a volcanic eruption their number is greatly enhanced in the stratosphere as well as in the upper troposphere. The atmospheric aerosols directly influence the heat budget of the atmosphere by absorbing, scattering and emitting radiation depending on their optical properties. Temperature increases in the stratosphere due to perturbations in stratospheric aerosols have also been reported (e.g. Labitke et al.). These aerosols may also indirectly influence the concentration of minor constituents in atmosphere by changing the intensity of radiation available for production or destruction of ozone and other minor chemical species. The introduction of large amounts of gases and aerosols into the stratosphere by volcanic eruptions and the diffusion of chemical species into the stratosphere due to mankind's increasing activities will certainly affect the properties of the stratospheric aerosols and ultimately cause climatic perturbations. In the past both in situ and remote sensing methods were used to obtain information about the optical and chemical properties of aerosol particles and their spatial-temporal variations. Remote sensing methods include solar aureole almuncantar, lidar measurements and satellite. To monitor stratospheric aerosols on a global and near-continuous basis, Stratospheric Aerosol Measurement (SAM II) and Stratospheric Aerosol and Gas Experiment (SAGE I and II) satellite missions were launched. The SAGE sensor is a sunphotometer designed to measure the
intensity of solar radiation traversing the earth's limb at four different wavelengths (0.38, 0.45, 0.60, and 1.00 \textmu m). The SAGE-I instruments have successfully collected data from February 1979 to November 1981 and the measured data were inverted to obtain profiles of aerosol volume extinction (km\(^{-1}\)) at 0.45 and 1.00 \textmu m (Ref. 6). An overview paper by McCormick describes the early results from SAGE observations. In the present paper, published aerosol extinction data at the two wavelengths, 0.45 and 1.00 \textmu m, from SAGE-I measurements during the period 1 Jan. 1981 to 18 Nov. 1981, have been used to study some aspects of seasonal/latitudinal variations in the aerosol distributions in the stratosphere and upper troposphere. Also, as the volcanic eruptions from Alaid (50.8° N, 155.5° E) on 27 Apr. 1981 and from Pagan (18.1° N, 145.8° E) on 15 May 1981 occurred during the above observational period, the data have been utilized to investigate the influence of volcanic material on the stratospheric and upper tropospheric aerosol size distributions. Since the two volcanic eruptions occurred during the above SAGE-I data period, most of the variations reported here, especially the latitudinal variations, may not be representative of the typical quite time variations.

2 Data and analysis

Between January and November 1981, over 2500 SAGE sunset measurements were made, and monthly average extinction profiles (extinction as a function of height from 10 to 40 km) at 1-km intervals at the two wavelengths, 0.45 and 1.00 \textmu m, have been used here. The data available are in zonally averaged 10-deg latitude bands. Seasonally averaged extinction data for the three seasons of 1981, namely, spring (March, April, May), summer (June, July, August) and fall (September, October, November) have been considered for some investigations. The corresponding temperature profiles and information on tropopause height have also been used. The optical depths were obtained by evaluating the integral of each aerosol extinction profile 2 km above the tropopause up to 40 km. The data source for this study is a NASA Research Report by McCormick. While considering the altitude profiles, interpretation of the results above 30 km is made with caution because of the fact that there are greater uncertainties in the aerosol extinction at 0.45 \textmu m at these altitudes. Results of the investigations undertaken are presented and discussed in this paper.

2.1 Aerosol size distribution

Aerosol size distribution data can be represented by suitable analytical models and Russell et al. have used nine different analytical types of size distributions for stratospheric aerosols in their optical models. Among these models, the lognormal size distribution expression is accepted and widely used one for stratospheric aerosol studies (e.g. Yue and Deepak, Yue et al., Jager and Hofmann).

Assuming that stratospheric aerosols consist of aqueous sulphuric acid with 75% H\(_2\)SO\(_4\) by mass, the lognormal size distribution function is given by

\[
n(r) = \frac{N_0}{\sqrt{2\pi} \ln \sigma} \frac{1}{r} \exp \left(\frac{\ln^2(r / r_g)}{2 \ln^2 \sigma}\right)
\]

where \(n(r)\) is the number of particles per cm\(^3\) for particles whose radii are between \(r\) and \(r+dr\), \(N_0\) the total number concentration (cm\(^{-3}\)), \(\sigma\) the width of the lognormal curve, and \(r_g\) the mode radius.

Information about the relative size of particles may be obtained from the ratio of the aerosol extinction at 0.45 \textmu m to the aerosol extinction at 1.00 \textmu m; larger values of this ratio indicate presence of more smaller-sized particles and smaller values of the ratio indicate the prevalence of larger-sized particles in that altitude region. It has been shown that this ratio of aerosol extinction at the two wavelengths is a monotonic function of the variable parameter (for example, \(r_g\) in the lognormal size distribution function) governing the size distribution of stratospheric aerosols for nine analytical aerosol models used by Russell et al. This ratio is not very sensitive to either the composition or the radii limits of stratospheric aerosols under consideration, but is quite sensitive to the size parameter. The quadratic relationship

\[
\ln R = 2.846 - 28.07 r_g + 88.59 r_g^2
\]

given by Yue and Deepak has been made use of in this study to retrieve mode radius \(r_g\) from actual SAGE-I data of ratio of aerosol extinction, \(R\), at two wavelengths (i.e., \(R = \beta_{0.45}/\beta_{1.00}\)). Use of this second-order polynomial needs only to solve a second-order equation in order to determine the mode radius for each pair of SAGE-I aerosol ex-
tinctions. Wang et al.\textsuperscript{14} have used SAGE-II multi-wavelength aerosol extinctions to retrieve aerosol size distributions. Thus SAGE-I data are limited by the availability of extinction at two wavelengths only, and hence the mode radius has been evaluated. The height variations in this mode radius, especially in the pre- and post-volcanic eruption periods, and its latitudinal-seasonal variations at different heights have been studied.

3 Results and discussion

3.1 Latitudinal-seasonal variations of aerosol optical depth

To investigate the latitudinal-seasonal variations in the stratospheric aerosol optical depth, the average values at different latitude bands (75° S to 75° N) for the three seasons of spring, summer and fall have been taken separately for the two wavelengths and plotted and shown in Fig. 1. A very interesting latitudinal variation in aerosol optical depth can be seen which is almost identical at both the wavelengths. There is an equatorial (tropical region) peak in aerosol optical depth in all the three seasons and at both wavelengths. Large values of optical depth are also obtained at high latitudes (>40°) in both northern and southern hemispheres. Largest values of aerosol optical depth are observed at high northern latitudes in the summer season. Larger optical depths in northern summer could be due to volcanic effect. Optical depths are also slightly higher in the southern high latitudes in the months of June-September. But this period happens to be winter and post-winter in the southern hemisphere and optical depth (extinction) is higher as a possible consequence of increase of particle size due to cold temperature in winter.\textsuperscript{15} Evidence for such an increase in mode radii during summer and fall (northern) at 55°S and 65°S can be seen in a later figure (Fig. 3). Interestingly there are low mid-latitudinal minima around 25°S and 25-35°N in all the seasons. Similar latitudinal variation in optical depth at 1.00 μm has been reported by Brogniez and Lenoble\textsuperscript{15}. However, these latitudinal variations cannot be generalized and may not be typical because of the occurrence of volcanic eruptions during the period.

In addition to the above latitudinal variations, an examination of the available data shows that the volcanic eruptions from Alaid on 27 Apr. 1981 and from Pagan on 15 May 1981 have added volcanic material into the stratosphere and upper troposphere. During the spring season (March-May), aerosol optical depths at almost all the latitudes are the smallest. During summer and fall, which happens to be in the post-volcanic period, aerosol optical depths are larger especially in the northern latitudes. This is expected because both the above eruptions have occurred in the northern hemisphere and stratospheric effects due to them may be confined mostly to that hemisphere. Aerosol extinction values also showed that the peak values increased 2 to 4 times above typical near-background values of $1 \times 10^{-4}$ to $2 \times 10^{-4}$ km$^{-1}$ at 1.00 μm and $4 \times 10^{-4}$ to $8 \times 10^{-4}$ km$^{-1}$ at 0.45 μm observed during a period of low volcanic activity\textsuperscript{16}.

The latitudinal-seasonal variations of tropopause height and the corresponding tropopause temperature (K) have been plotted and shown in Fig. 2. Tropopause height is nearly constant between 25°S and 25°N and falls off steeply beyond 25° latitude in both the hemispheres. The tropopause heights are greater in summer beyond 25°N than those in the other two seasons. In the tropical latitudinal belt when the tropopause heights are the lowest in summer, aerosol optical depths are the largest. Further the low mid-latitude minima in aerosol optical depth (Fig. 1) in both the
hemi­
pheres coincide very well with the latitude where tropopause heights start decreasing rapidly (for example, at 35°N in summer, 25°N in fall, and 25°S in all the three seasons). The tropopause temperatures are generally higher during summer and lower during spring season. The tropical region peak in aerosol optical depth seems to be related to the latitudinally coldest tropopause in all the seasons.

3.2 Altitude variation of mode radius

Using the seasonal mean profiles of ratio of aerosol extinction ($R$) computed from the SAGE-I aerosol extinction data at the two wavelengths, 0.45 and 1.00 μm, for different latitude bands, the mode radius ($r_g$) has been evaluated from the quadratic expression given in the previous section. Firstly the vertical structure of mode radius in the equatorial latitude band (5°N) and high latitudes (65°N and 65°S) during spring, summer and fall seasons of 1981 are examined. During summer, data at 55°S are used due to the non-availability of data at 65°S. Figure 3 shows the height variation (10-30 km) of mode radius at the three latitudes and in the three seasons. At the equatorial latitude, mode radius is large in the upper troposphere (as large as 0.14 μm at 11 km) and decreases rapidly with increasing altitude, especially during spring and summer. In the altitude range 11-18 km, mode radii are large at equatorial latitude compared to the high latitudes in both spring and fall and up to about 15 km it is large in summer also. Above 22 km, mode radii are smaller at equator compared to the values found at high latitudes. Aerosol particles grow as they move upward and they grow through heteromolecular condensation processes. As they move northward or southward from equatorial latitudes, they grow larger. As a result above about 22 km, the mode radii of these aerosol particles at high northern and southern latitudes are observed to be larger than those at the equator. Such an indication of larger mode radii at high latitudes (65°S and 65°N) above 19-20 km can be seen in all the seasons in Fig. 3.

Mode radii in the high latitudes in both the hemispheres are nearly equal in magnitude in
spring and fall. But during northern summer, mode radius in the 65°N latitudinal belt is smaller (<0.06 μm) at all heights than that at 5°N and 55°S. That is, during northern summer, smaller-sized particles are more prevalent in the northern high latitude stratosphere. At the same time relatively larger aerosol particles are dominant in number at southern high latitudes in the stratosphere.

Monthly mean altitude distributions of ratio of aerosol extinction (R) are taken to compute monthly mean altitude distribution of mode radius and are used to examine the nature of changes in size distribution of aerosols in the stratosphere and upper troposphere in the aftermath of volcanic eruptions. In particular, the altitude distribution of mode radius at 15°N (close to the Pagan volcanic eruption on 15 May 1981) for the months of February, May and November, and that at 55°N (close to the Alaid volcanic eruption on 27 Apr. 1981) for the months of February, May and September have been considered and the same are shown in Fig. 4. At 15°N during the month of February, the mode radii are small and varied between 0.09 and 0.05 μm between 11 and 30 km. Immediately after the volcanic eruption of Pagan relatively larger-sized aerosol particles are observed in this latitude belt during the month of May at all the altitudes. The mode radii ranged from 0.12 μm at 11 km to 0.06 μm at 30 km during post-eruption period. Larger-sized aerosol particles can still be seen in the upper troposphere even during the month of November, some 6 months after the volcanic injection. At 55°N also there is an indication of the presence of larger-sized particles in the month of May. However, above about 20 km, at this latitude, the mode radius is larger in the month of February compared to that in the months of May and September. This could again be explained on the basis of increase in particle size due to cold temperatures at those altitudes in winter months. Thus the results show that the effect of volcanic eruptions can be seen not only in the integrated aerosol extinction but also in the size distribution of aerosols and such effects are discernible because of the availability of satellite aerosol extinction information at more than one wavelength.

3.3 Aerosol number density

Aerosol number concentrations have been derived from SAGE extinction data following the method described by Yue and Deepak10 to see their altitude distribution and also to examine the effects of volcanic eruption on stratospheric aerosol number densities. Assuming the stratospheric aerosol to follow lognormal size distribution of the type given by Eq. (1), mode radii are first determined as described in the previous section. Then the expected extinction coefficient, \( \beta_{1.0} \) at \( N_0=1 \) is determined from the computed mode radius using the curve, i.e. Fig. 1(a) of Yue and Deepak10. The ratio between the measured value of extinction coefficient (from SAGE data) and the expected extinction coefficient derived above gives the value of \( N_0 \), the aerosol number concentration (particles/cm³) at each altitude.

From the altitude profiles of mode radius of the type depicted in Fig. 4 in the previous section, the corresponding profiles of aerosol number density have been obtained adopting the aforementioned method. Aerosol number densities obtained here are observed to be higher compared to those obtained by Wang et al.14 from SAGE-II multi-wavelength observations. Figure 5 shows these altitude profiles for the months of February, July and November 1981 at 15°N and for February, July and September 1981 at 55°N. The altitude profiles of aerosol number density for the month of May have also been computed and are available. But on observation it is seen that though the mode radii are largest in the month of May (as shown in Fig. 4), the number concentrations are high in the month of July. Therefore concentration profiles of
July have been shown in Fig. 5 instead of those for May to bring out the effect of volcanic injection. That is, the effect of volcanic injection of material is felt immediately in the size distribution, whereas its effect on number concentration can be seen in the months following. The presence of aerosol layers in the lower stratosphere at both 15° and 55°N is evident from the figure. It can also be seen clearly that aerosol concentrations, by and large, are greater in the month of July, which is the period after the Alaid and Pagan volcanic eruptions. At 15°N, at around 18 km altitude, the aerosol concentration has increased from February to July by about 2.5 times. Further, at this latitude, the effect of volcanic injection can be seen even in the month of November. Thus the increase in aerosol number density in the lower stratosphere can be seen for several months after a volcanic eruption.

3.4 Latitudinal variation of mode radius

The variation of mode radius with latitude from 75°S to 75°N at five different altitudes (14, 18, 22, 26, and 30 km) is examined here. Figures 6, 7, and 8 show respectively the latitudinal variation during the spring, summer and fall seasons of 1981. An interesting variation can be seen in almost all the seasons. At altitudes below 22 km, mode radius exhibits a tropical region peak with smaller-sized aerosols at middle and high latitudes in both hemic-
spheres. At altitudes above 22 km, this type of variation reverses completely. Small mode radii aerosols are observed in the equatorial and low latitudes and larger-sized particles are observed in high northern and southern latitudes. This is seen in all the seasons with varying degree of magnitude except in the northern high latitudes in summer where above 22 km mode radii do not show large values. For 14 km, the latitudinal variation in summer is similar to that in spring and fall. But at 18 km the tropical region peak in mode radius is shifted to 25°N in summer. This again may be connected to eruption of Pagan at 18°N on 15 May 1981. During fall at high southern latitudes, the size distributions show the maximum contrasting behaviour, with very small values of mode radii below 22 km and very large values above 22 km. However, the very large values of mode radii observed at 26 and 30 km beyond 55°S should be interpreted more cautiously due to the greater uncertainty in the measurement of aerosol extinction at altitudes around 30 km and above. It is also possible that the very cold temperatures at altitudes above 20 km in the high latitudes may be responsible for larger mode radii.

There is also a very distinct latitudinal minima in mode radius in the mid-latitudes (25°-35°) in both the hemispheres. These minima are very prominent in the upper troposphere and lower stratosphere. It is of interest to note that in the mid-latitudes where optical depths are minimum, the aerosol sizes are also relatively smaller. It has been recognized that the mean diabatic circulation in the lower stratosphere is characterized mainly by a two-cell pattern with an upward branch in the tropical regions and a downward branch at high latitudes in both hemispheres. The tropical lower stratosphere is a source region of particulate matter as is evident from the broad maximum in aerosol optical depth in the tropical latitude belt seen in Fig. 1. This maximum in optical depth is associated with coldest tropopause (latitudinally) as can be seen in Fig. 2. Krishna Murthy et al. from their lidar measurements at a tropical station have shown that stratospheric aerosol extinction has a strong negative correlation with tropopause temperature. The distribution of stratospheric particles is influenced not only by aerosol microphysics and vertical transport but also by dynamical processes involving meridional transport. Thus these low latitude aerosol particles are subsequently transported poleward and downward to higher latitude region by the above mentioned diabatic circulation. Yue and Deepak point out that some of the particles, while being transported towards higher latitudes from tropical region, subside in mid-latitudes. Here they may evaporate and become a source of water vapour in the stratosphere. Thus stratospheric aerosols can be used as tracers to study various microphysical and dynamical processes.

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References