SAGE I AND SAM II MEASUREMENTS OF 1 μM AEROSOL EXTINCTION IN THE FREE TROPOSPHERE

by

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ABSTRACT

The SAGE I and SAM II satellite sensors were designed to measure, with global coverage, the 1 μm extinction produced by the stratospheric aerosol. In the absence of high altitude cloud, similar measurements may be made for the free tropospheric aerosol. Median extinction values in the northern hemisphere, for altitudes between 5 and 10 km, are found to be one-half to one order of magnitude greater than values at corresponding latitudes in the southern hemisphere. In addition, a seasonal increase by a factor of 1.5 → 2 is observed in both hemispheres in local spring and summer. Following major volcanic eruptions, a long-lived enhancement of the aerosol extinction is observed for altitudes above 5 km.

1. INTRODUCTION

Measurements of the properties of aerosols in the free troposphere at altitudes greater than a few kilometers are relatively scarce. At these altitudes, the aerosol, particularly over the ocean, may be derived from sources many thousands of kilometers distant and not be related to the underlying surface type. The majority of existing measurements have been made in the northern hemisphere over or close to continental areas, and our knowledge of the aerosol characteristics over remote regions, such as the oceans of the southern hemisphere rests on few in situ or remote measurements. Although the general latitudinal trends in aerosol concentration, composition and size distribution have been derived from the available measurements, little is known about the variability of these properties. Current interest in the development and deployment of a Global Wind Measurement Satellite System (WINDSAT) (NOAA 1981), has led to an awareness of our lack of knowledge of the global characteristics of the free tropospheric aerosol. WINDSAT, as presently proposed, would use CO_2 doppler shift lidar to measure wind velocity from the boundary layer to the lower stratosphere. It would rely on backscattering from the atmospheric aerosol for its signal and thus a knowledge of the global behavior of the aerosol concentration, size distribution and, in particular, the backscattering function at CO_2 laser wavelengths is required.

In this paper, we describe the use of data obtained by the SAGE I and SAM II satellite sensors to improve our knowledge of the global characteristics of the free tropospheric aerosol. These satellites are designed to measure stratospheric aerosol extinction at a wavelength of 1 μm. In the absence of high altitude cloud, tropospheric measurements are not only possible but are available from a significant fraction of the total number of measurement opportunities. A detailed study made of one year (March 1979 - February 1980) of satellite data is described. This has been used to derive the global variation of the 1 μm aerosol extinction for altitudes between approximately 5 km above the earth's surface and the tropopause. In addition to the anticipated dependance upon latitude and altitude, a seasonal cycle is also clearly evident in the aerosol extinction. The period following 1979 is significant for the number of volcanic eruptions that have injected material into the stratosphere. Analysis of upper tropospheric extinction data for 1980 and 1981 shows evidence of volcanic modification of aerosol loading and the results of a preliminary study of these changes are also presented.

2. SAGE I AND SAM II TROPOSPHERIC OBSERVATIONS

The SAGE I and SAM II satellite experiments contain sun photometers designed to measure the extinction produced by stratospheric aerosols (McCormick et al., 1979). SAM II, which was launched in October 1978, and which is still operational, consists of a single channel sun photometer centered at a wavelength of 1.0 μm. The orbit of SAM II is such that its observations, which are made at satellite sunrise and sunset, occur between latitudes of 64°S - 80°S and 65°N - 80°N, two measurements being made on each orbit. SAGE I commenced its observations in February 1979 and, owing to a faulty satellite power supply, these were terminated in November 1981. In contrast to SAM II, the SAGE I coverage is nearly global, the latitude of observation moving during a six-week period through about 120° of latitude, the latitude extremes being approximately 74°N & S. SAGE I has four channels which include an aerosol channel at a wavelength of 0.45 μm in addition to the 1.0 μm aerosol channel. Useful data on the former channel is limited to altitudes above 10 km and our analysis has been confined to the 1.0 μm data only. The SAGE I data set is also limited by the fact that observations were confined to sunsets only, after the first few months of observation, in order to conserve satellite power. The atmospheric attenuation measured by either satellite is over a path about 300 km in length with a 0.5 km field of view. The aerosol extinction values thus represent an average over a section of the atmosphere with these dimensions.

SAGE I and SAM II were designed for the measurement of stratospheric aerosol extinction and it was anticipated that tropospheric measurements would be hindered or possibly prevented by the presence of high altitude cloud. The former is indeed the case but significant tropospheric penetration does occur. Examples of SAGE I profiles showing such penetration are shown in Figure 1. Figure 1(a) shows the aerosol extinction increasing smoothly with decreasing altitude, no apparent discontinuity occurring at the tropopause. Figure 1(b) shows a different profile with a strong enhancement at an altitude of 10 km, presumed to be due to high altitude cloud. Table 1 shows the total number of observations made by SAGE I over a 3-month period and the relative frequency of penetration to various tropospheric altitudes for three latitude bands. It can be seen that good penetration (∼ 50%) is obtained down to an altitude of 8 kilometers or less. Greatest frequency of penetration occurs in the southern hemisphere and, as might be expected, least occurs in the equatorial zone with its higher tropopause. Table 1 shows that one may obtain a reasonable description of the free troposphere aerosol, on an average basis, down to an altitude of perhaps 5 or 6 km. Below this altitude, individual profiles, when available, will be accurate. Average values, which represent only 20% - 30% of the total potential data set, may be expected to be biased toward more transparent atmospheres and lower extinction.

3. THE EXTINCTION PROBABILITY DISTRIBUTION

Examination of the SAGE I and SAM II data shows that whereas, in the stratosphere, extinction values at a given altitude and latitude are normally fairly tightly concentrated about a mean level, the same is not true in the troposphere. In the latter case, extinction values may vary over several orders of magnitude, the higher values probably being due to attenuation by thin (sub-visible) cloud. Under such conditions, the use of the mean extinction as a measure of central tendency is of doubtful value. In order to obtain a better description, we have examined the probability distribution of the values of tropospheric extinction for different conditions. Figure 2 shows the results of such a study. Three months data, taken over the latitude bands 20°-60°S [Fig. 2(a)] and 20°-60°N [Fig. 2(b)] between March and May 1979, has been binned by altitude and extinction value. The altitude interval used is 1 km over the range 0 to 30 km and the extinction interval is $2\times10^{-5}\text{km}^{-1}$ over the range 0 to 10^{-3}km^{-1}; one extra bin has been added at each altitude which includes all measured values greater than 10^{-3}km^{-1}. This bin contains extinction values up to about 10^{-2}km^{-1}, values much greater than this level not being detectable as they reduce the measured solar radiation below the threshold of the satellite photometers. The contours in Fig. 2 show the probability of an observation falling into a given altitude-extinction bin. Superimposed on these contours are lines showing the 50% cumulative probability levels.

In the stratosphere, in both parts of Fig. 2, the extinction values are tightly bunched at a given altitude and there is no problem about defining and using a mean level. In contrast, in the troposphere below about 12 km, the values are widely separated and there is a significant number of very high values (extinction > $10^{-3}km^{-1}$) which are shown at the right-hand side of Figures 2(a) and 2(b). These values probably represent attenuation by subvisible cloud (Rao, 1975; Uthe & Russell, 1977). Rather than calculating a mean extinction level at each altitude which would be biased in the troposphere toward these very high values, that are not representative of the background tropospheric aerosol, we have chosen to use the 50% probability level, or the median, as our measure of central tendency. In the stratosphere, it approximates very well to the mean level. In the troposphere, it defines an aerosol level which is both useful and meaningful. The numerical value of the median is not appreciably affected by the inclusion of a few events, of very high extinction, due to thin cloud. Its relationship to the aerosol extinction probability distribution makes it compatible with published data on tropospheric aerosol backscatter measurements at infra-red wavelengths (e.g., Post et al., 1982).

The probability distributions for the extinction values shown in Fig. 2(a) and 2(b) show very clearly a major feature of the satellite data. Although the extinction values in the stratosphere are very similar in the two hemispheres, the northern hemisphere tropospheric values at any given altitude are significantly greater than the values at the same altitude in the southern hemisphere. This hemispheric asymmetry was a systematic feature of the data and is discussed in detail in the next section.

4. VARIATION OF EXTINCTION WITH LATITUDE, ALTITUDE, AND SEASON

In order to study the variation of the aerosol extinction with latitude and season, the SAGE I data were grouped into seven latitude bands and the SAM II data in four latitude bands, as shown in Table 2. Figure 3(a) shows the altitude variation of the median SAGE I extinction for the six latitude bands observed during the period March-May 1979. Apart from data at low altitudes in the 60N - 75N latitude band, there is a general decrease in aerosol extinction with increasing altitude. In examining these and other data presented in this section, it should be remembered that below an altitude of 5 or 6 km, the fractional penetration is less than 50% and the data may have a systematic bias. This is particularly likely when the extinction is high, as in the 60°N - 75°N latitude band, and it is doubtful if in this case the decrease in median extinction for altitudes below 5 km is representative of the true aerosol characteristics. It is more likely that observations are being made down to these altitudes only when the atmosphere is relatively clean of both aerosol and cloud. A secondary feature of the variation with altitude is the greater extinction observed in the upper free troposphere within the equatorial belt (20°S - 20°N) as compared to the other latitude bands. This reflects the higher tropopause level (~16 km against ~12 km for mid-latitude) and must indicate the effects of convection in raising the aerosol to the higher levels.

Apart from the variation with altitude, the most important feature is the marked latitude asymmetry. At an altitude of 6 km, there is a steady decrease in extinction between 60N - 75N and 40-60S by approximately one order of magnitude. Although this asymmetry is present at all times of the year, it is at a maximum in March-May, both in 1979 and in the following years.

Figures 3(b)-(d) show the equivalent aerosol extinction profiles for June-August 1979, September-November 1979, and December 1979-February 1980. The features noted above are present in all these plots, the latitude asymmetry is, however, less in Figs. 3(c) and (d). The peak in aerosol extinction visible in the 20S - 20N latitude band in Fig. 3(d) at an altitude of 19 km is caused by the injection of material from the eruption of the Sierra Negra volcano on November 13, 1979 (Kent & McCormick, 1984). Analysis of SAM II tropospheric data for 1979 for latitudes between 60^{o}N and 90^{o}N and 60^{o}S and 90^{o}S shows similar characteristics to the SAGE data. In March-May, 1979, the extinction at an altitude of 6-7 km and 60^{o}-75^{o}N is about an order of magnitude greater than at the same altitude and latitude in the southern hemisphere. In September-November 1979, the asymmetry is reduced to about one-half of an order of magnitude.

Figure 3 shows the seasonal variation in aerosol extinction. In order to present this variation more clearly, Figure 4 shows the variation of the SAGE I/SAM II extinction at an altitude of 6 km as a function of latitude; data are shown for the same four seasons as defined previously. Both Figures 4(a) and 4(b) show the hemispheric asymmetry; in addition, they show a clear superimposed seasonal variation. In both hemispheres, maximum aerosol extinction is found in local Spring-Summer and minimum extinction in local Fall-Winter.

There is a relative lack of published aerosol data for the free troposphere, as opposed to the boundary layer and the stratosphere, with which to compare these observations. Many observations (e.g. Blifford, 1970; Blifford and Ringer, 1969; Cress, 1980) are confined to a limited latitude band or consist of too few measurements to determine meaningful statistical averages. The most extensive data set is that of Patterson et al. (1980) taken on two flight series, undertaken as part of the GAMETAG program, over the Pacific Ocean in 1977 and 1978. Previously unpublished data from these flights have recently been included in a NASA Contractors report (Kent et al., 1985). Data taken on these flights clearly show the latitude gradient in aerosol concentration and, hence, agrees with optical extinction characteristics described above. This variation almost certainly reflects the predominance of aerosol sources in the northern hemisphere and the relative lack of trans-equatorial transport. Quantitative comparison of extinction values at an altitude of 6 km calculated from the GAMETAG size distributions with the direct SAGE I measurements shows good agreement in the northern hemisphere. In the southern hemisphere, good agreement was obtained for the 1977 GAMETAG data, while the 1978 data indicated significantly lower extinction values. The reason for this difference is not clear but appears to be a sampling variation. It must also be remembered that the sampling volumes may differ greatly between alternative measurement systems. In the case of SAGE I/SAM II, the sample volume is approximately 300 km in length and the measured 1 μm extinction values correspond to an arithmetic average over the variations along this optical path. This is in contrast to the in situ aircraft measurements where the horizontal averaging is over at most a few tens of kilometers.

Information on the seasonal variation of aerosol concentrations is also scarce but the spring-summer maximum observed in both hemispheres is most probably related to increased convection over land at that time of year. Measurements of the infra-red aerosol backscattering function made at Boulder, Colorado shows a clear seasonal variation, minimum values being observed in fall and winter (Post, 1983; 1984). A notable feature of the seasonal variation observed in the satellite data is the very strong 1 μm extinction observed in March-May, 1979 at latitude 60^o-75^oN and which is repeated in the following two years. This is the season at which arctic haze is observed (Schnell, 1984). This haze originates in northern hemisphere industrial areas (Raatz and Schnell, 1984) and is transported long distances into the arctic. Flight measurements show the haze to occur in layers up to altitudes of about 5 km (Radke et al., 1984). The SAGE I data barely extends down to these altitudes due to the high extinction levels which cause the measured solar radiation to fall below the instrument threshold. It is possible that the increase in extinction observed in northern latitudes in Spring at altitudes 5-8 km is related to the outer haze layers at lower altitudes.

5. VARIATION OF AEROSOL EXTINCTION WITH SURFACE CHARACTERISTICS

Most of the aerosol in the free troposphere over the remote oceans is derived, not by convection from the ocean surface, but by long-range transport of aerosol and precursor gases from over the continental land masses (WMO, 1980; Jaenicke, 1980). Some modification of the aerosol optical properties, particularly that due to loss of the largest, optically significant, particles by sedimentation, might be expected to occur during this transport. A search was made, using the SAGE I data, for any evidence of such a variation. For the purpose of this study, the global surface was divided into 10^o latitude-longitude regions and each region categorized according to the underlying surface. Five classes of surfaces were defined, ranging from 100% land surface, to 100% ocean at a distance of at least 3000 km from the nearest continental land mass.

Each SAGE I observation has been classified according to the surface type beneath the observation position, as well as by season and latitude. Median extinction values have been calculated for each altitude. The analysis shows very little significant variation of aerosol extinction with sub-surface type. In most latitude bands, any systematic difference between the extinction over land or ocean is less than the error in the median values. The only positive result to be obtained from the analysis was for the equatorial region (20^oS - 20^oN). Within this region, the median extinction, at an altitude of 6 km, decreased approximately 20% over the range of sub-surface types from land to remote ocean. This very small change is consistent with the theory of aerosol injection over land followed by slow particle sedimentation during horizontal transport.

The lack of any systematic dependence, for most of the globe, of the aerosol extinction at an altitude of 6 km upon the surface characteristics beneath the observation point indicates that air masses at these altitudes must be transported from land to ocean in a time short compared with that required for appreciable modification of aerosol properties. For typical zonal wind velocities (Lorenz, 1967), these times would be a few days to a week. It may also be noted that 6 km is rather above the altitude at which desert dust is normally transported over the oceans (Prospero and Carlson 1972; Shaw, 1980; Duce et al., 1980). The small positive result obtained for the equatorial region may be related to the lower wind velocities there and possibly also to increased convective activity over land.

6. VOLCANIC EFFECTS

It is well known that volcanic eruptions inject solid and gaseous materials into the stratosphere and that aerosols formed and deposited there have lifetimes of months or years (Deirmendjian, 1973; Deepak, 1982; Kent and McCormick, 1984). Solid particles are also injected in the troposphere where the majority of them are presumed to be fairly quickly removed by sedimentation and washout. Examination of the SAGE I and SAM II data set shows that the upper troposphere, as well as the stratosphere, has a long-lived enhancement in aerosol extinction following a significant volcanic eruption. An example of this is given in Figure 5 which shows the altitude variation of the median SAGE I extinction for September-November, 1980. At this time, the stratospheric aerosol extinction at high northern latitudes was strongly enhanced by material injected from the eruption of Mt. St. Helens (latitude 46°N) on May 18, 1980. In addition, the aerosol layer over equatorial latitudes still showed the effects of the eruption of Sierra Negra (latitude 1°S) on November 13, 1979.

The profiles in Figure 5 may be compared with those in Figure 3(c) for the same months in 1979. The stratosphere effects of the volcanic injection are clear. In addition, in 1980, the aerosol extinction in the free troposphere down to an altitude of 5 km is profoundly modified for latitude bands 40°N-60°N and 60°N-75°N. Similar differences are observed within the same latitude bands for June-August 1980 and in the 40°-60°N latitude band for December 1980-February 1981 (no data is available for the 60°N-75°N latitude band during northern winter); in all cases the enhancement appears to occur in the free troposphere down to an altitude of about 5 km. The stratospheric enhancement during this period and within these latitude bands is produced by the injection of material from the Mt. St. Helens eruption and there is little doubt that the free tropospheric enhancement must be related to the same source. Material injected directly into the free troposphere by volcanic eruptions may be expected to have a residence time short compared to those occurring here (Pruppacher and Klett, 1978). It is noticeable that the enhancement reaches its maximum amplitude close to the tropopause (~10 km at 60^{o}N) and it is likely that the aerosol in the stratosphere is acting as a reservoir from which material is being fed into the upper troposphere by sedimentation and stratospheric-tropospheric exchange processes. The data shows many interesting features which will be the object of future study. For example, comparison of the profiles in Figure 5 with those in Figure 3(c) shows that the transfer of aerosol from the stratosphere to the troposphere occurs at high latitudes, whereas no such transfer is evident at low latitudes, although volcanic material from Sierra Negra is clearly present in the stratosphere. These differences may help resolve the relative importance of sedimentation, stratospheric-tropospheric exchange and general circulation as mechanisms for transfer of material from stratosphere to troposphere or vice-versa.

There appears to be no published comparable measurement of free tropospheric aerosol enhancement following the Mt. St. Helens eruption but Post (1985) has described similar observations following the eruption of El Chichon in 1982. Infra-red backscatter measurements showed an enhancement of the free tropospheric aerosol backscattering function above an altitude of about 6 km. Post (1985) was able to associate lifetimes of 208 days with the stratospheric volcanic aerosol and of 60 days with the tropospheric aerosol. He has attributed the tropospheric enhancement to the mixing downward of stratospheric air containing the volcanic aerosol.

7. CONCLUSIONS

The SAGE I/SAM II satellite instruments have been shown to provide useful data on the extinction produced by the aerosol in the free troposphere at a wavelength of 1 μm. The satellite provided almost complete global coverage between February 1979 and November 1981 although, because of absorption and scattering by tropospheric cloud, the majority of the data are confined to altitudes above about 5 km. Some data have been obtained at lower altitudes, but this is only a small fraction of the total data set and is probably not representative, corresponding as it does to the clearer cloud and aerosol free occasions. At altitudes above 5 km, the data set is extensive. Measured extinction values are sometimes very large. Such values are believed to be to the presence of cloud somewhere along the optical path. Use of an arithmetic mean to describe the average behavior at a given altitude results in a value that is biased toward the higher extinction values which are not representative of the aerosol. For this reason, we have, after detailed examination of the probability distribution function for the extinction, decided to use the median level as a relatively unbiased parameter to describe the average aerosol behavior.

The data has yielded a detailed picture of the variation of the 1 μm free tropospheric aerosol extinction with latitude, season and altitude, as well as changes following volcanic injection of material into the stratosphere. The most obvious characteristic is a pronounced hemispheric asymmetry with minimum extinction being observed in high southern latitudes. This behavior agrees with that established by the GAMETAG flight series over the Pacific Ocean in 1977 and 1978. The magnitude of the asymmetry is seasonally variable as both hemispheres also show a similar antiphase seasonal oscillation in aerosol extinction. The greatest extinction in either hemisphere is observed in local spring and summer and least in local fall and winter. This seasonal variation is in agreement with that observed by infra-red backscatter from aerosols in the free troposphere. The very large extinction values observed in the highest northern latitudes coincide in time with the occurrence of arctic haze and the two phenomena may be causally related.

A search has been made for any correlation between the magnitude of the aerosol extinction in the free troposphere and the nature of the underlying surface. With the exception of the equatorial region, no significant relationship was found, indicating that aerosols injected into the free troposphere over land change their characteristics relatively slowly as the affected air mass travels over the ocean. A more direct study of the relationship between aerosol extinction and air mass history has not been made and represents a possible direction for future work.

Significant increases in the aerosol content of the northern hemisphere free troposphere above an altitude of 5 km were observed following volcanic injection of material into the stratosphere. At the higher altitudes, this enhancement was greater than the seasonal variation in aerosol extinction. The long life-time of the extinction enhancement (many months) indicated that the aerosol was almost certainly the result of downward transfer from a stratospheric reservoir rather than that directly injected by the eruption into the free troposphere. Again, this result is in agreement with observations made using infra-red backscatter on the stratospheric and free tropospheric aerosol burden following the eruption of El Chichon in 1982.

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Table 1. Relative Frequency of SAGE Observations in the Troposphere (March - May 1979)

Altitude (km)	Relative Frequency in Each Latitude Band (%)		
	60° - 20°S	20°S - 20°N	20°N - 60°N
20	100	100	100
18	100	96	100
16	100	78	99
14	98	61	98
12	89	53	89
10	73	48	68
8	58	45	52
6	44	36	34
4	30	17	15
2	6	0	4
TOTAL NUMBER OF OBSERVATIONS	827	290	455

Table 2. Latitude Bands Used in the Analysis of SAGE I and SAM II Data

(a) SAGE I

60°N - 75°N
40°N - 60°N
20°N - 40°N
20°S - 20°N
40°S - 20°S
60°S - 40°S
75°S - 60°S

(b) SAM II

75°N - 90°N
60°N - 75°N
75°S - 60°S
90°S - 75°S

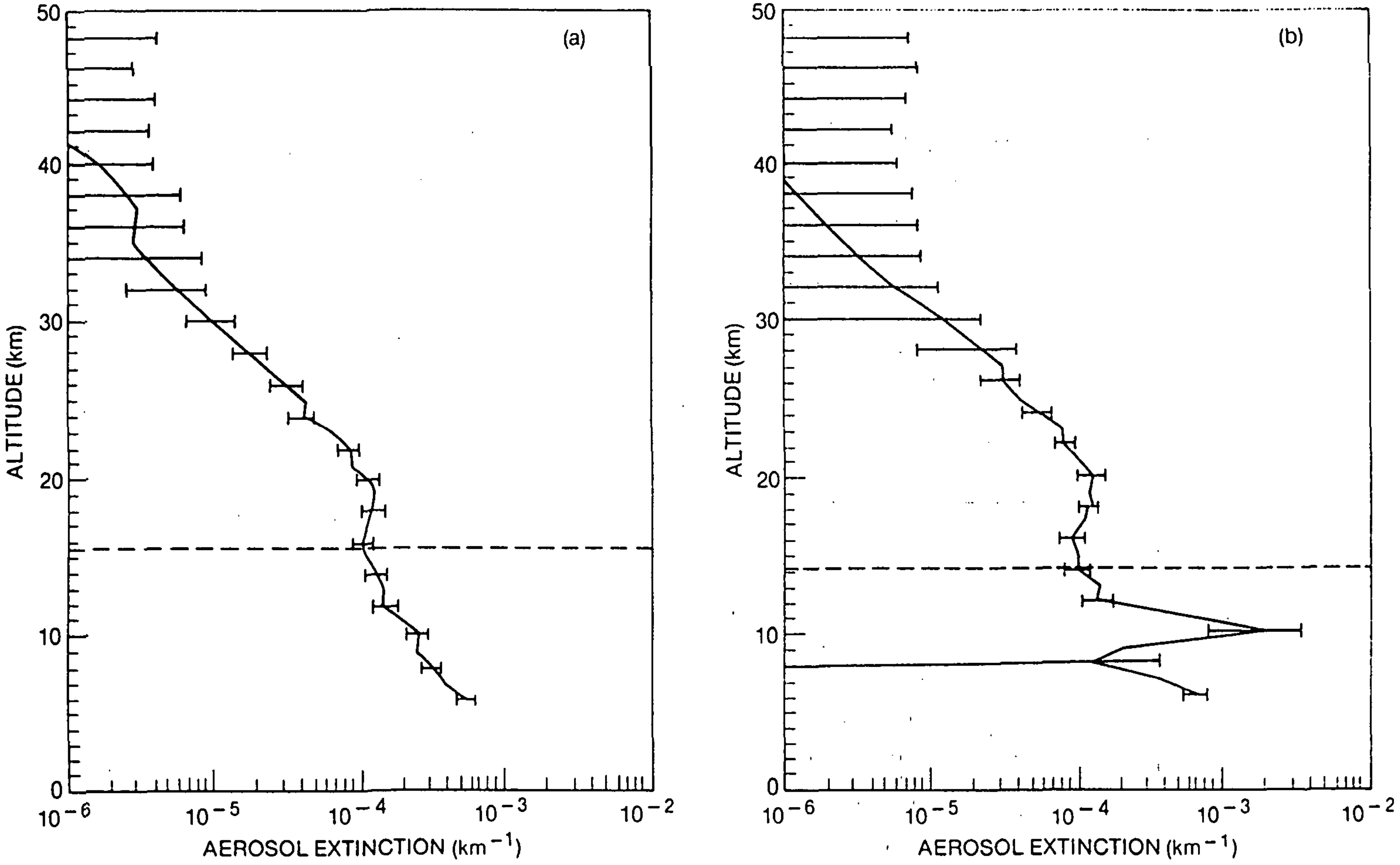

Figure 1. SAGE I 1 μm extinction profiels showing penetration into the troposphere.

(a) March 1, 1979: 37.5°S, 111.3°E. No high-altitude cloud present.

(b) March 2, 1979: 34.8°S, 131.6°W. High-altitude cloud present.

Dashed lines show tropopause altitudes.

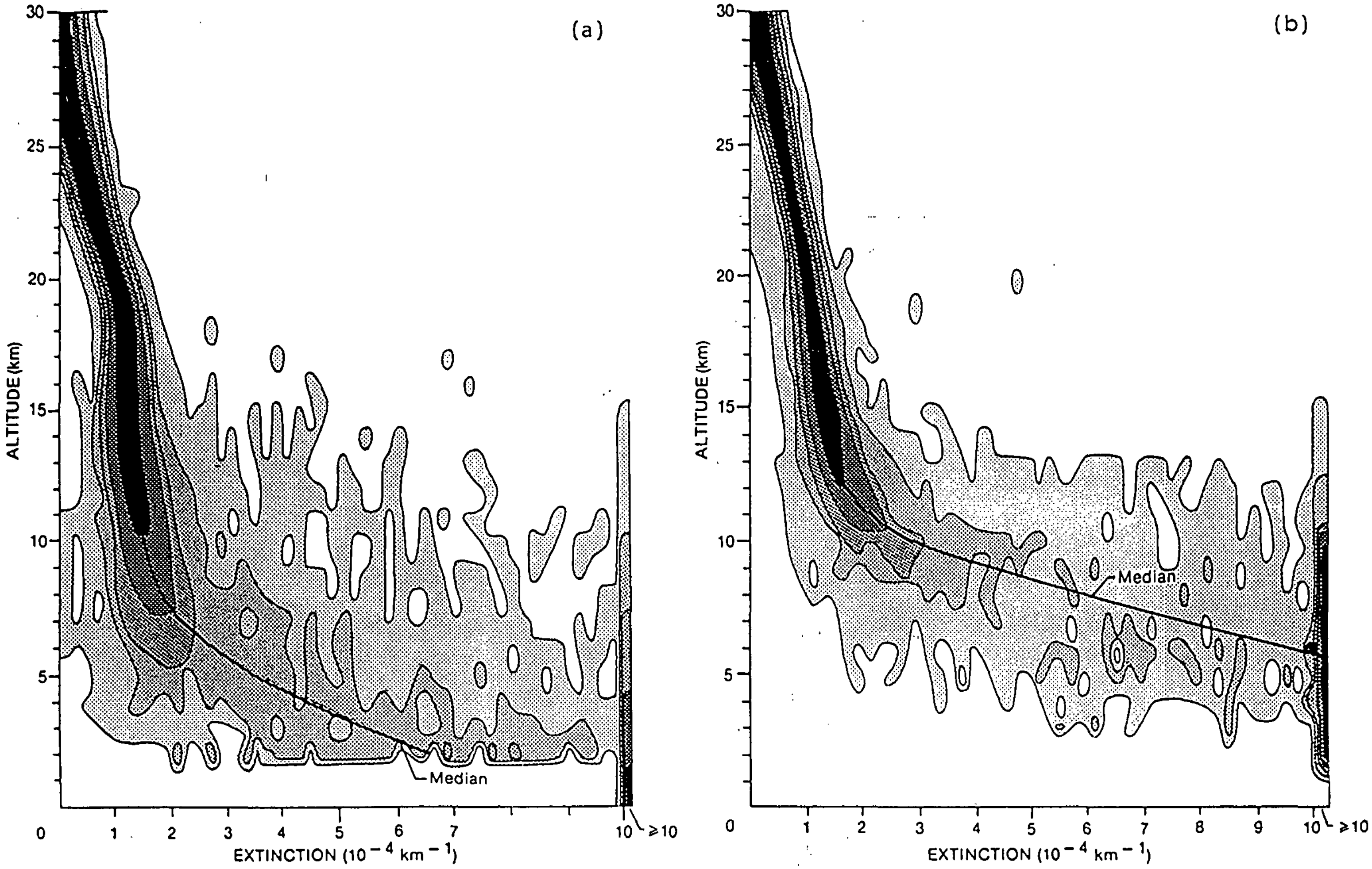

Figure 2. Distribution of SAGE I, 1 μm extinction values, March-May, 1979.

(a) 20°-60°S (b) 20°-60°N

Probability (%)	Pattern	Probability (%)	Pattern
P = 0	□	10>P≥5	▓
2>P>0	░	20>P≥10	▩
5>P≥2	▒	P≥20	■

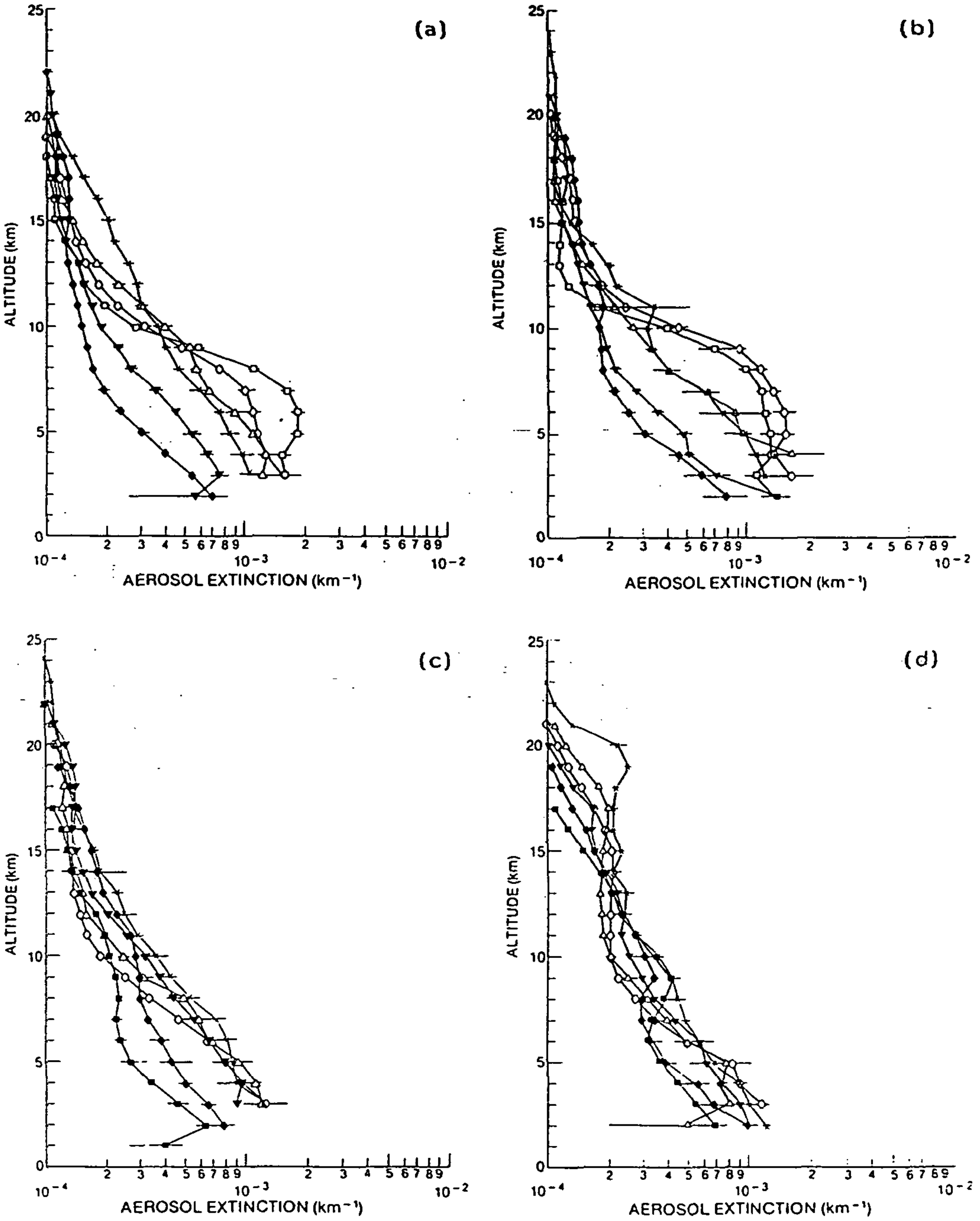

Figure 3. Median 1 μm aerosol extinction profiles for SAGE I data shown as a function of latitude band.

(a) March - May, 1979
(b) June - AUgust, 1979
(c) September - November, 1979
(d) December 1979 - February, 1980

LATITUDE BAND

□ 60N-75N
○ 40N-60N
△ 20N-40N
✶ 20S-20N
▼ 40S-20S
◆ 60S-40S
■ 75S-60S

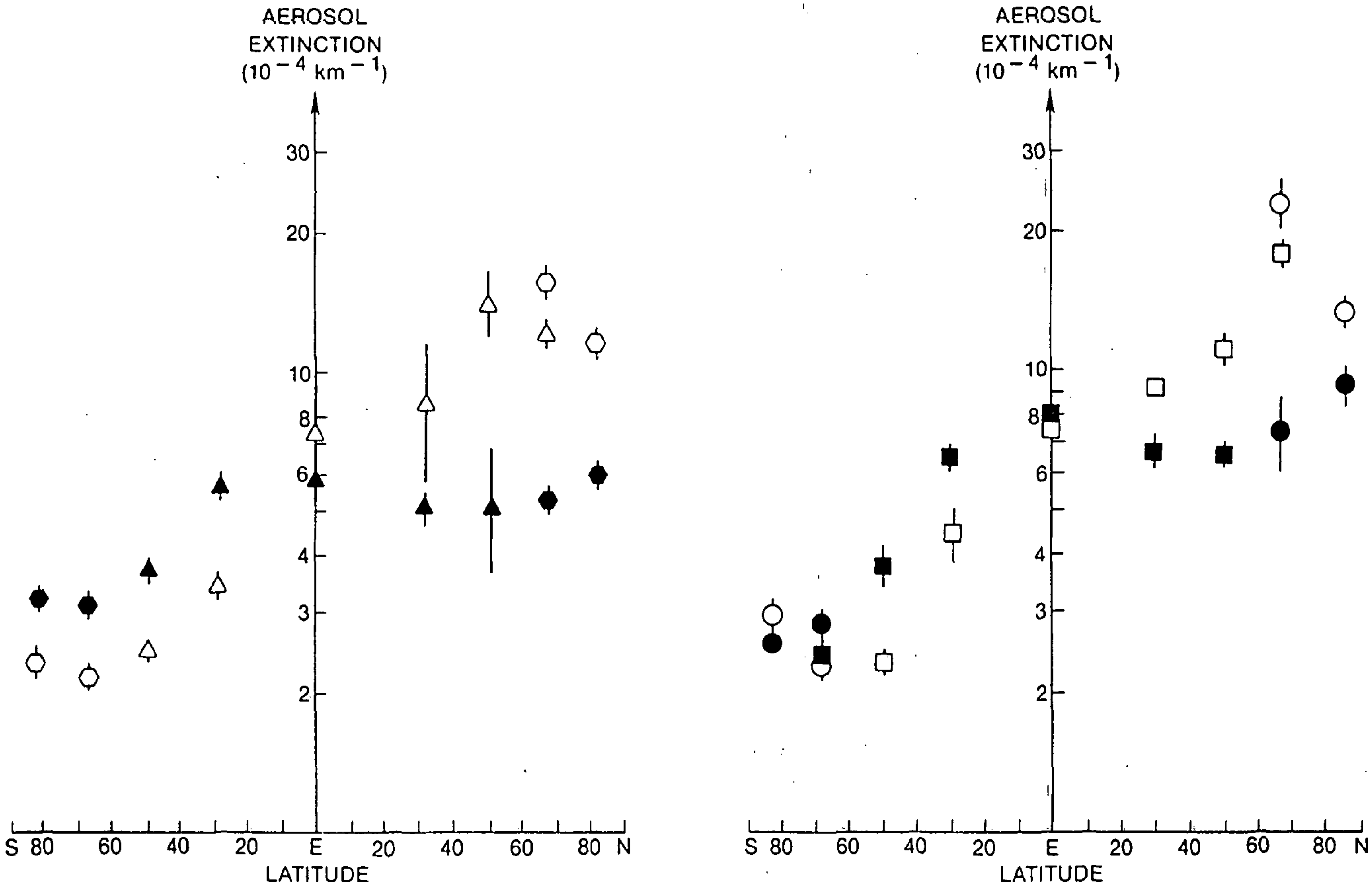

Figure 4. SAGE I/SAM II median 1 μm aerosol extinction profiles at an altitude of 6 km.

(a) Equinoxes. (b) Solstices.

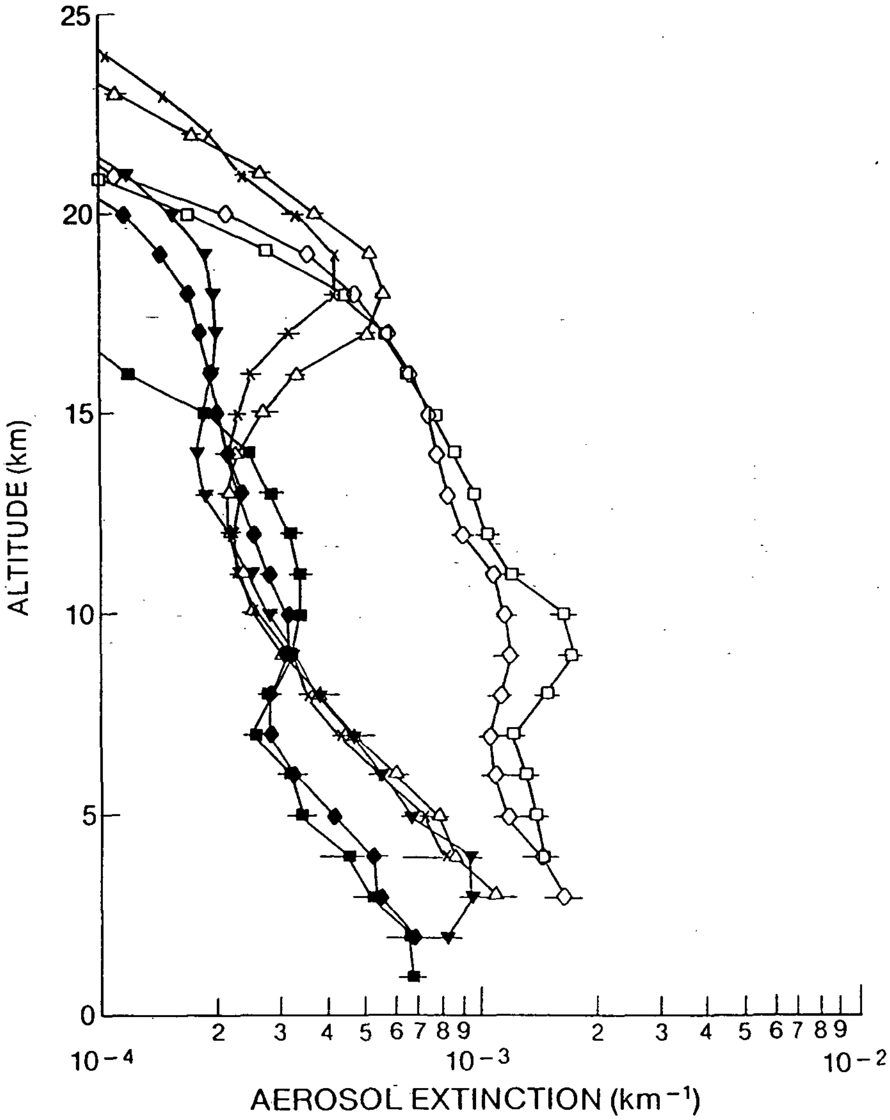

Figure 5. Median 1 µm aerosol extinction profiles for SAGE I data, September - November, 1980, following the eruptions of Sierra Negra and Mount St. Helens.

LATITUDE BAND

□ 75N-60N
◇ 40N-60N
△ 20N-40N
x 20S-20N

▼ 40S-20S
◆ 60S-40S
■ 75S-60S