SAGE I and SAM II Measurements of 1 μm Aerosol Extinction in the Free Troposphere*

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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 clouds, similar measurements may be made for the free tropospheric aerosol. Median extinction values at middle and high latitudes 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 was observed in both hemispheres, in 1979–80, 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 originate 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 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. As presently proposed, WINDSAT would use a 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 is required of the global behavior of the aerosol concentration, size distribution and, in particular, the backscattering function at CO_2 laser wavelengths. 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 clouds, tropospheric measurements are not only possible but are available from a significant fraction of the total number of measurement opportunities. A survey has been made of the entire SAGE I dataset (March 1979–November 1981) including a more detailed examination of the first year of data, together with the concurrent SAM II data. This has been used to derive the global variation of the 1 μm aerosol extinction for altitudes between approximately 5 km AGL and the tropopause. In addition to the anticipated dependence upon latitude and altitude, a seasonal cycle is also evident in the aerosol extinction. The period following 1979 is significant due to 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. A preliminary study of these changes is 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]. The SAM II satellite, 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°–80°S and 64°–80°N, two measurements being made on each orbit.

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The observations of SAGE I commenced in February 1979 and, owing to a faulty satellite power supply, were terminated in November 1981. In contrast to SAM II, the SAGE I coverage is nearly global, with the latitude of observation moving during a 6-week period through about 120° of latitude, the latitude extremes being approximately 74°N and 74°S. The SAGE I satellite 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 are limited to altitudes above 10 km and our analysis has been mainly confined to the 1.0 μm data. The SAGE I dataset 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 horizontal limb path about 300 km in length with a 0.5 km instantaneous field of view. The extinction values thus represent an average over a section of the atmosphere with these dimensions. Care must be taken in interpreting the extinction as being due entirely to aerosol if it is suspected that thin high altitude cloud may have occurred along a part of the optical path.

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 clouds. Measurements are hindered, but significant tropospheric penetration does occur. Examples of SAGE I profiles showing such penetration are shown in Fig. 1. Figure 1a shows the aerosol extinction increasing smoothly with decreasing altitude, no apparent discontinuity occurring at the tropopause. Figure 1b shows a different profile with a strong enhancement at an altitude of 10 km, presumed to be due to a high altitude cloud occupying part of the optical path. 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 km or less. The greatest frequency of penetration occurs in the Southern Hemisphere and, as might be expected, the least occurs in the equatorial zone with its higher tropopause. Table 1 shows that one may obtain a reasonable description of the free tropospheric 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, but average values, which represent only 20%–30% of the total potential dataset, may be expected to be biased toward more transparent atmospheres and lower extinction.

As noted earlier, the SAGE I and SAM II satellites were designed for stratospheric rather than tropospheric measurements. Stratospheric satellite data has been the subject of an extensive correlative measurement pro-

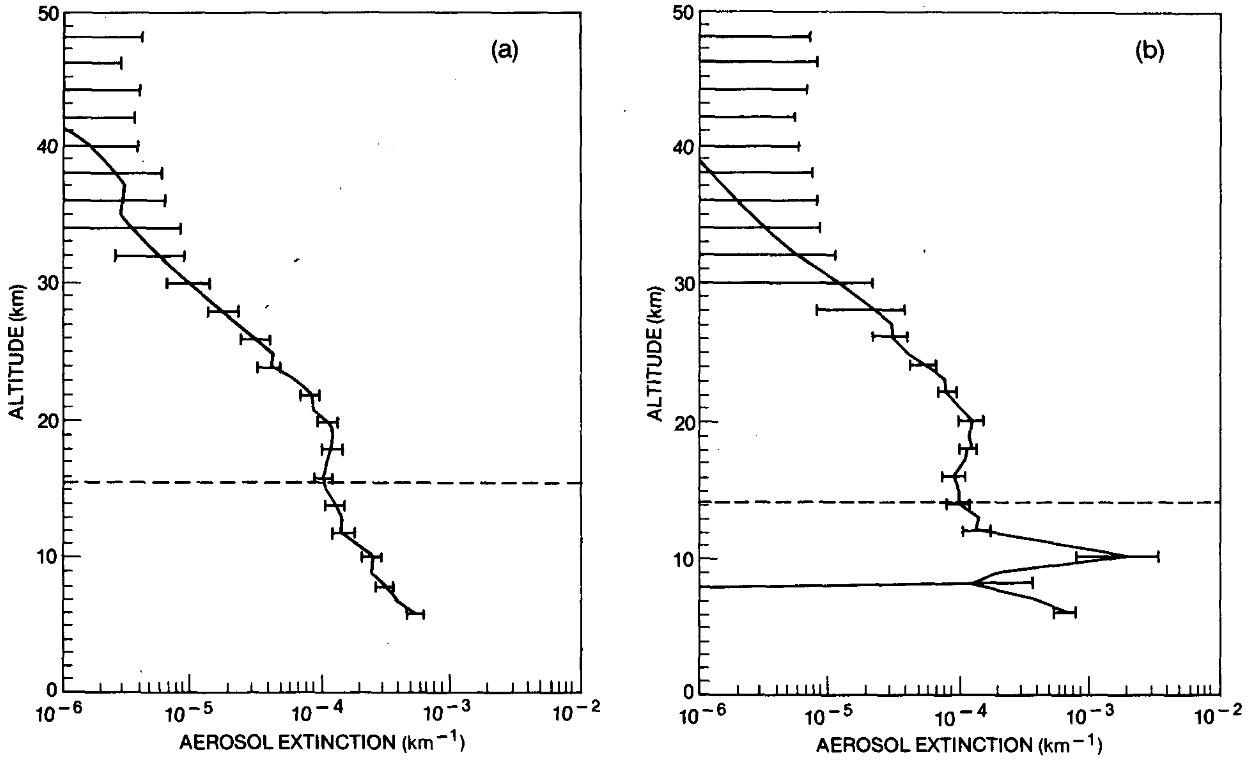

FIG. 1. SAGE I 1 μm extinction profiles showing penetration into the troposphere: (a) 1 March 1979: 37.5°S, 111.3°E. No high-altitude cloud present; (b) 2 March 1979: 34.8°S, 131.6°W. High-altitude cloud present. Dashed lines show tropopause altitudes.

TABLE 1. Relative frequency (%) of SAGE observations in the troposphere (March–May 1979).

Altitude (km)	Latitude band 60°S–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

gram that has yet to be extended to the troposphere. In this program the satellite extinction data has been compared via an optical model with simultaneously measured lidar backscattering cross sections and with in situ balloon- and aircraft-borne particle size distribution measurements (Kent and McCormick, 1984; Russell et al., 1981, 1984). It has been found that error bars, such as those shown in Fig. 1, which are based on uncertainties in the satellite and associated meteorological data, are realistic estimates of the error in the final data product. Under cloud-free, horizontally homogeneous conditions, tropospheric measurements are similar in nature to stratospheric measurements and calculated error bars should be likewise valid. Some increase in uncertainty may arise in cases where the data inversion procedure is continued below a region of high extinction (presumed to be due to thin high cloud), particularly if this is horizontally inhomogeneous. Examination of data taken in such cases with that taken in more cloud-free conditions does not, however, show any systematic bias.

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 (subvisible) 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

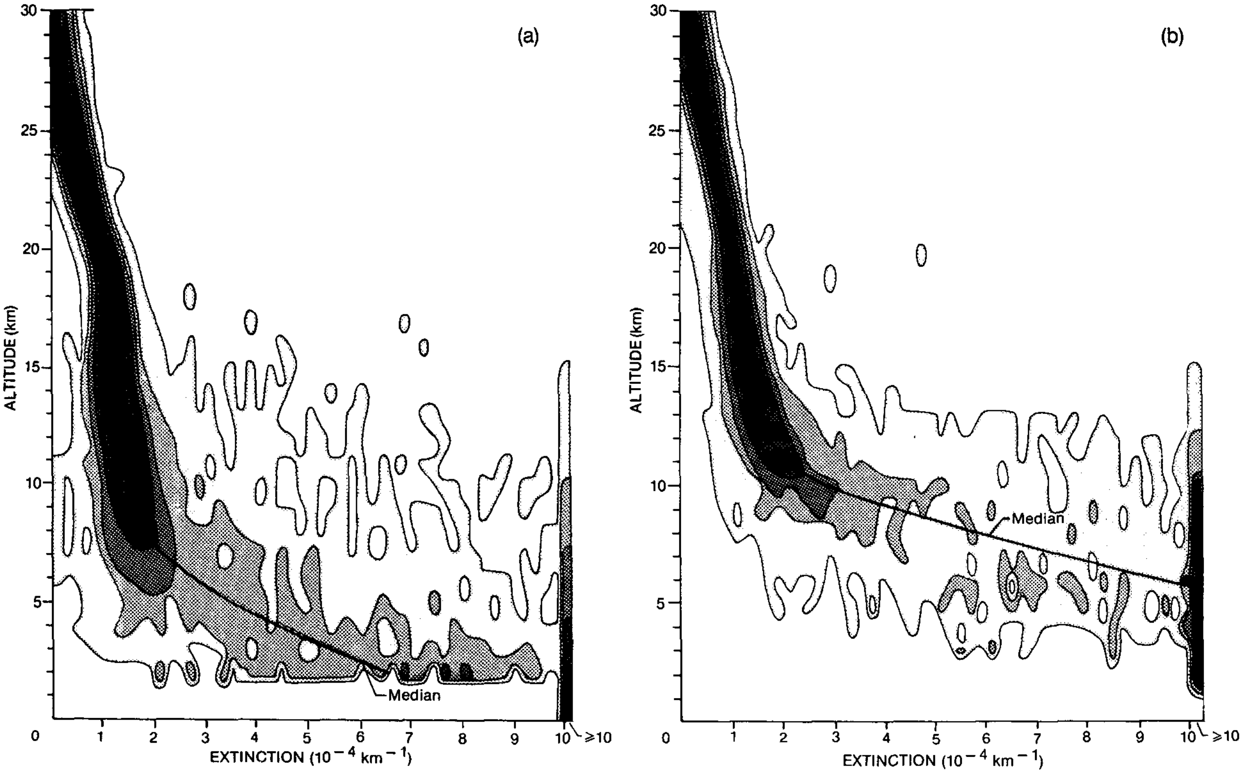

FIG. 2. Distribution of SAGE I, 1 μm extinction values, March–May 1979: (a) 20°–60°S; (b) 20°–60°N. Depth of stippling shows probability level, P; P (%) increases from open (no stippling) to solid in the following steps: $(P) = 0$, $2 > P > 0$, $5 > P \geq 2$, $10 > P \geq 5$, $20 > P \geq 10$, and $P \geq 20$.

months data, taken over the latitude bands 20°–60°S (Fig. 2a) and 20°–60°N (Fig. 2b) between March and May 1979, have been subdivided into discrete intervals according to altitude and extinction value. The altitude interval used is 1 km over the range 0–30 km and the extinction interval is 2×10^{-5} km^{-1} over the range 0–10^{-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 are not 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, as shown 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 Figs. 2a and 2b. These values probably represent attenuation by subvisible cloud (Rao, 1975; Uthe and Russell, 1977). Support for this interpretation comes from examination of the extinction obtained at a wavelength of 0.45 μm in conjunction with that obtained at 1.0 μm. For these large extinction values there is little variation of extinction with wavelength indicating that the particles along the optical path responsible for most of the extinction are large compared to the wavelengths used. This is not the case for the bulk of the extinction values where there is a strong wavelength dependence. It should nevertheless be pointed out that if a small patch of thin cloud occurs along an optical path that otherwise contains only background aerosol and the molecular atmosphere, this will increase the extinction slightly at both wavelengths and the presence of the cloud will not be easily detectable. For some parts of the globe where high altitude thin cloud is prevalent (e.g., tropical convective regions), the measured extinction at altitudes close to the tropopause may not then be entirely due to aerosol.

Rather than calculating a mean extinction level at each altitude, which would be biased in the troposphere toward the very high values that are not clearly 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 extinction level that is both useful and meaningful. The numerical value of the median would not be appreciably affected by the inclusion in the distribution of a few events, of very high extinction, due to thin cloud. Its relationship to the aerosol extinction probability distribution facilitates comparison with data of other authors who have similarly used a probability distribution approach to describe the optical properties of the tropospheric aerosol (e.g., Post et al., 1982).

The probability distributions for the extinction values shown in Figs. 2a and 2b 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 is a systematic feature of the data and is discussed in detail in section 4.

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 3a shows the altitude variation of the median SAGE I extinction for the six latitude bands observed during the period March–May 1979. Error bars show the standard error in the median value (Kendall and Stuart, 1943). Apart from the data at low altitudes in the 60°–75°N 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°–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

TABLE 2. Latitude bands used in the analysis of SAGE I and SAM II data.

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
SAM II
75°N–90°N
60°N–75°N
75°S–60°S
90°S–75°S

(20°S–20°N) as compared to the other latitude bands. This may reflect the higher tropopause level (~16 km compared to ~12 km for midlatitude) and indicates the effects of convection in raising the aerosol to the higher levels. Alternatively, the greater extinction which is particularly visible in March–May 1979 may be caused by material from the eruption of Soufriere (13.3°N, 61.2°W) on 17 April 1979 (McCormick et al., 1982).

Apart from the variation with altitude, the most important feature is the marked latitude asymmetry. At an altitude of 6 km, there is a decrease in extinction between 60°–75°N and 40°–60°S by approximately one order of magnitude. Although this asymmetry is

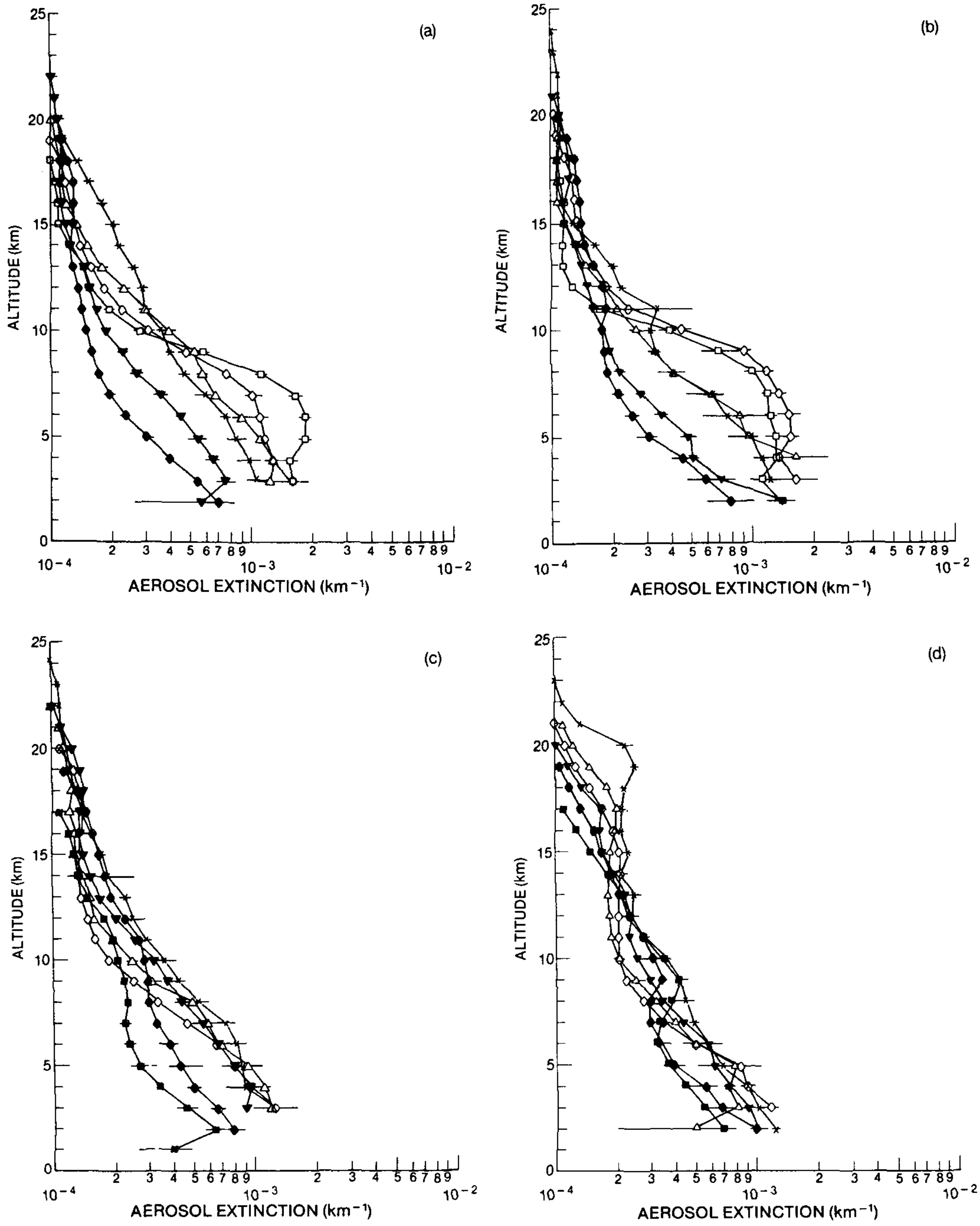

FIG. 3. Median 1 μm aerosol extinction profiles for SAGE I data shown as a function of latitude band: (a) March–May 1979, (b) June–August 1979, (c) September–November 1979 and (d) December 1979–February 1980. Open square, 60°–75°N; open diamond, 40°–60°N; open triangle, 20°–40°N; asterisk, 20°S–20°N; closed triangle, 40°–20°S; closed diamond, 60°–40°S; closed square, 75°–60°S.

present at all times of the year, it is a maximum in March–May, both in 1979 and in the following years.

Figures 3b–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. 3c and d. The peak in aerosol extinction visible in the 20°S–20°N latitude band in Fig. 3d at an altitude of 19 km is caused by the injection of material from the eruption of the Sierra Negra volcano on 13 November 1979 (Kent and McCormick, 1984). Analysis of SAM II tropospheric data for 1979 for latitudes between 60°N–90°N and 60°S–90°S shows similar characteristics to the SAGE data. In March–May 1979, the extinction at an altitude of 6–7 km and 60°–75°N is about an order of magnitude greater than at the same altitude and latitude in the Southern Hemisphere. In Septem-

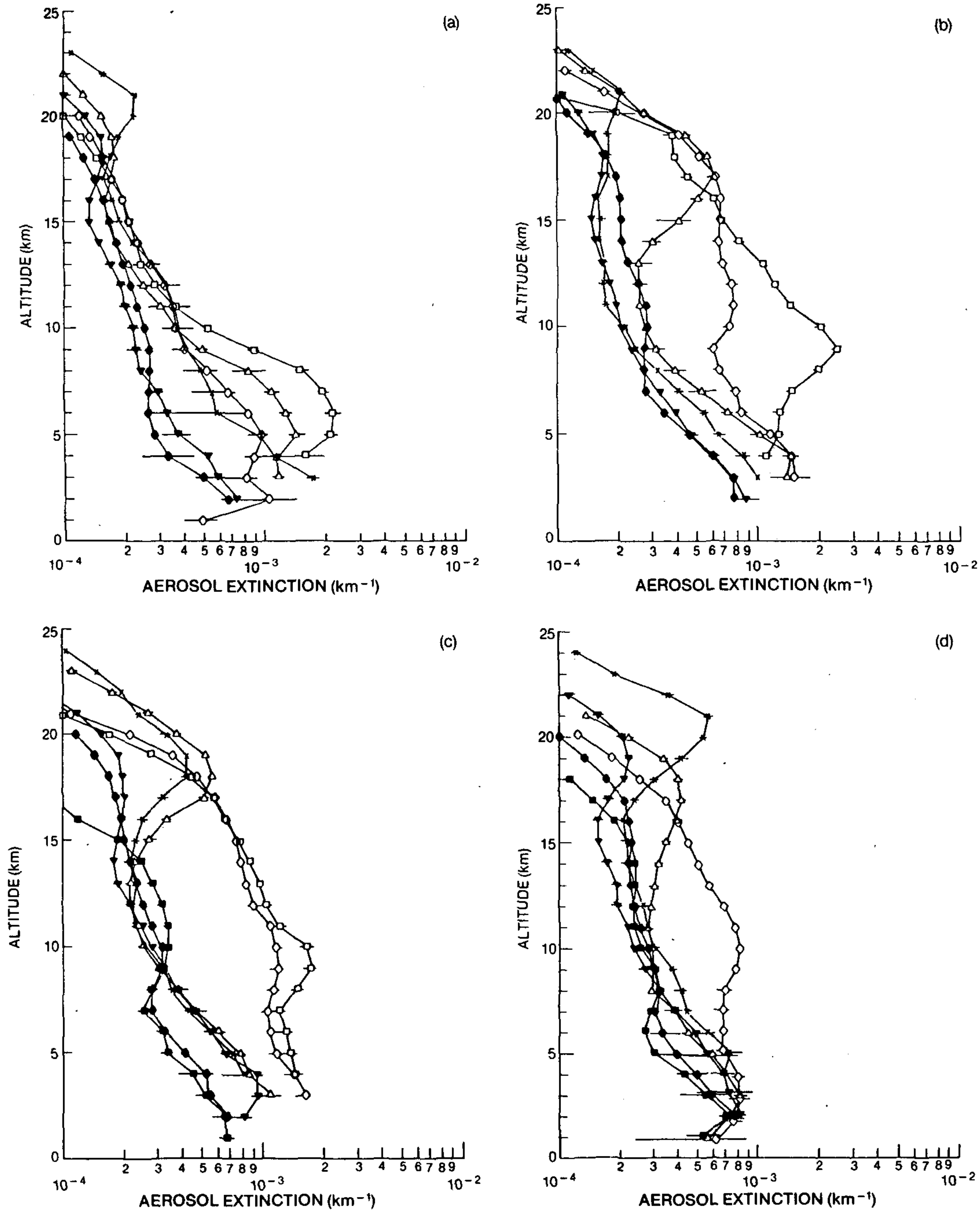

FIG. 4. As in Fig. 3 for 1980.

ber–November 1979, the asymmetry is reduced to about one-half of an order of magnitude.

Figures 4a–d and 5a–c show the available data for 1980 and 1981, respectively, in the same manner as that shown in Figure 3a–d for 1979. There are clearly major differences between the years, particularly in the upper troposphere. These differences are believed to be caused by volcanic injection and will be discussed in more detail in section 6. However, the Northern Hemisphere seasonal maximum in March–May is present in very similar form in all three years. The Northern Hemisphere maximum in June–August, clearly visible in 1979, is not distinguishable in 1980 and 1981 as this period follows the eruptions of St. Helens (18 May 1980) and Alaid (27 April 1981) and the effects of these eruptions as shown in Figs. 4b and 5b are considerable.

Figure 3 shows the seasonal variation in aerosol ex-

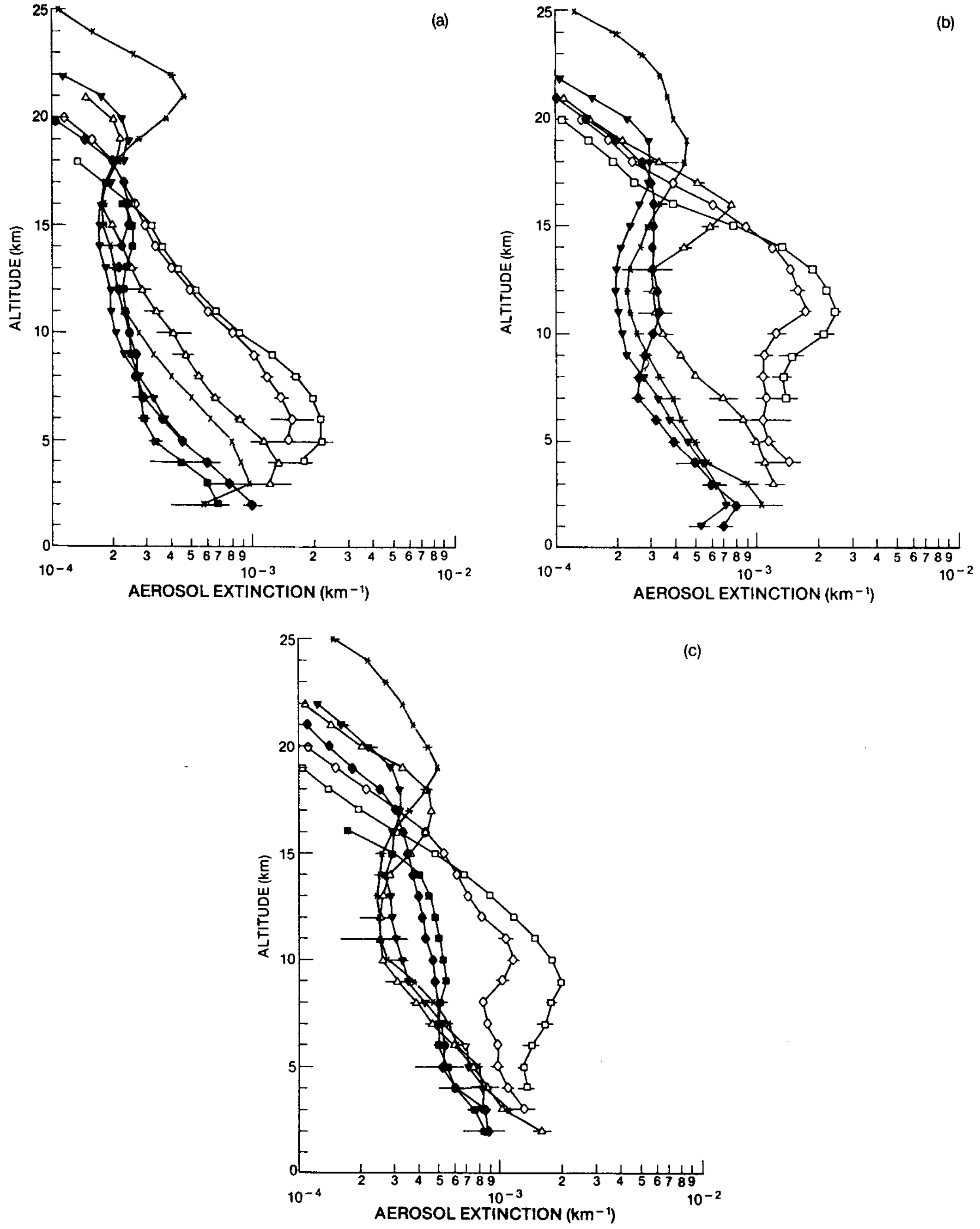

FIG. 5. As in Fig. 3 for 1981.

tinction for 1979, a year with no major volcanic eruptions outside the tropical regions. In order to present this variation more clearly, Fig. 6 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 Figs. 6a and 6b show the hemispheric asymmetry; in addition, they show a 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 dataset 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, agree with the optical extinction characteristics described above. This variation almost certainly reflects the predominance of aerosol sources in the Northern Hemisphere and the relative lack of transequatorial 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 (Kent et al., 1985). 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 possibly

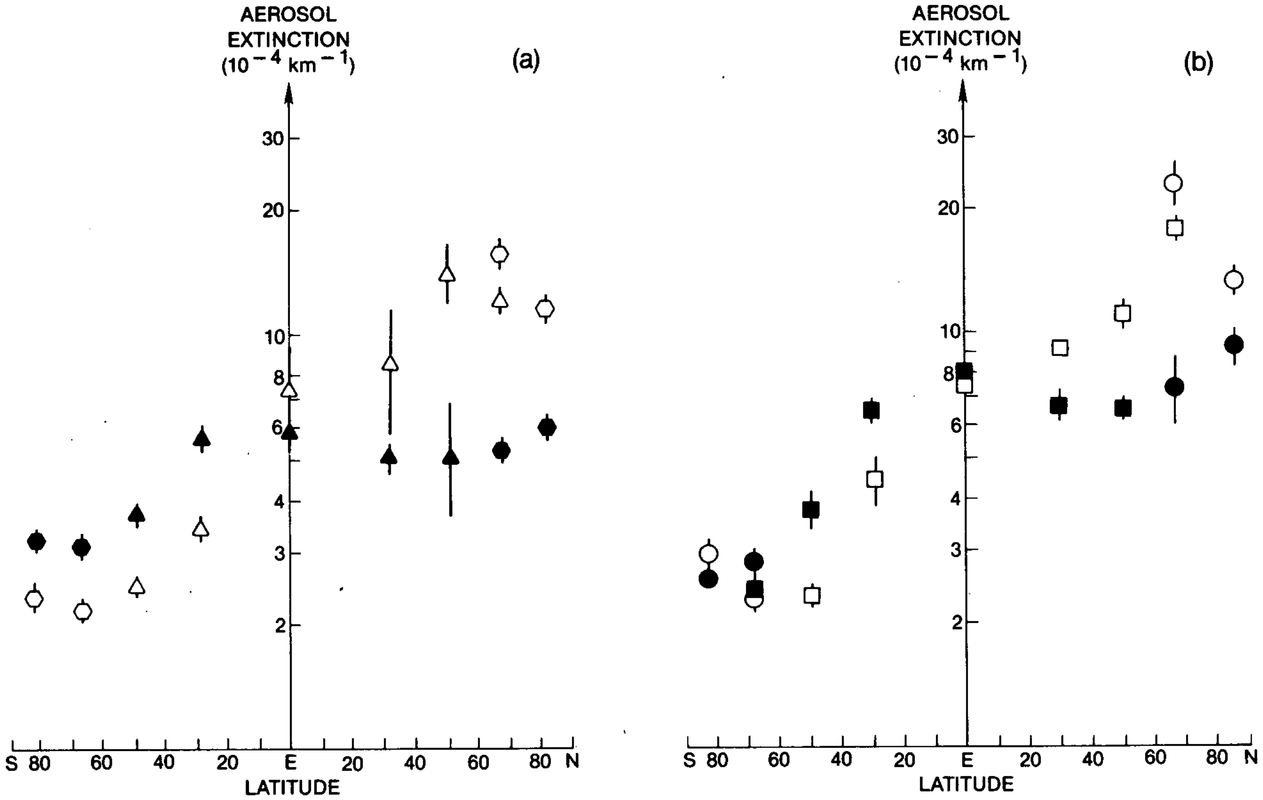

FIG. 6. SAGE I/SAM II median 1 μm aerosol extinction profiles at an altitude of 6 km. (a) Solstices: open triangle, SAGE, June–Aug. 1979; open hexagonal, SAM II, June–Aug. 1979; closed triangle, SAGE, Dec. 1979–Feb. 1980 and; closed hexagonal, SAM II, Dec. 1979–Feb. 1980. (b) Equinoxes: open square, SAGE, Mar.–May 1979; open circle, SAM II, Mar.–May 1979; closed square, SAGE, Sept.–Nov. 1979 and; closed circle, SAM II, Sept.–Nov. 1979.

related to increased convection over land at that time of year. Measurements of the infrared aerosol backscattering function made at Boulder, Colorado shows a clear seasonal variation, minimum values being observed in the fall and winter (Post, 1983; 1984). A notable feature of the seasonal variation observed in March–May 1979 at latitude 60°–75°N 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 over 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 extend down to these altitudes due to the high extinction levels that cause the measured solar radiation to fall below the instrument threshold. It may nevertheless be possible that the increase in extinction observed in northern latitudes in spring at altitudes 5–8 km is related to the arctic haze layers at lower altitudes. An alternative explanation—that the high extinction in the upper troposphere observed at this time of year might be due to downward transport of aerosol from the stratosphere—appears not to be acceptable. The extinction ratio (aerosol extinction/molecular extinction) in spring 1979 is greater in the upper troposphere than it is in the stratosphere. This ratio is approximately conserved under transport and the given result is incompatible with downward transport as the main mechanism for production of the high tropospheric extinction.

5. Variation of aerosol extinction with surface characteristics

Most of the aerosol in the free troposphere over the remote oceans originates not by convection from the ocean surface, but by long-range transport of aerosol and precursor gases from over the continental land masses (World Meteorological Organization, 1980; Jaenicke, 1980). Some modification of the aerosol optical properties, particularly that due to loss of the largest, and 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° 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 subsurface 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°S–20°N). Within this region, the median extinction, at an altitude of 6 km, decreased approximately 20% over the range of subsurface 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 short time 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 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 into 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 datasets show that the upper troposphere, as well as the stratosphere, has a long-lived enhancement in aerosol extinction following a significant volcanic eruption. Two Northern Hemisphere eruptions of significance occurred during the lifetime of SAGE I: St. Helens (46.2°N) on 18 May 1980 and Alaid (50.8°N) on 27 April 1981. Material injected into the stratosphere from these eruptions became dispersed over latitudes north of about 40°N and relatively little material moved southwards. Peak stratospheric effects were observed about 3 months after these eruptions, following gas-to-particle conversion in the injected material. Figures 4 and 5 show not only the strong stratospheric enhancements in extinction following these eruptions but also significant effects in the upper troposphere. In addition, the stratospheric aerosol layer over equatorial latitudes still shows the effects of the eruption of Sierra Negra (latitude 1°S) on 13 November 1979.

The profiles in Figs. 4 and 5 may be compared with those in Fig. 3 for the same months in 1979, a year free from major volcanic activity in the Northern Hemisphere. The seasonal maximum at altitudes of 5 or 6 km at high northern latitudes in March–May of all three years has already been noted. In addition, in 1980 and 1981, the aerosol extinction in the free troposphere down to an altitude of 5 km is profoundly modified for latitude bands 40°–60°N and 60°–75°N. This enhancement has its maximum in June–August in both years consistent with the maximum stratospheric enhancement. The peak enhancement in 1980 is followed by a slow decay until March–May 1981, to be followed by the fresh enhancement following the eruption of Alaid; the data following this eruption also shows the beginning of the decay phase. The close tracking of the stratospheric and tropospheric effects indicates a strong coupling between the two regions. Material injected directly into the free troposphere by volcanic eruptions may be expected to have a short residence time compared to those occurring here (Pruppacher and Klett, 1978). It is noticeable that the enhancements reach their maximum amplitude close to the tropopause (~10 km at 60°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 show many interesting features that will be the object of future study. For example, comparison of the profiles in Figs. 4 and 5 with those in Fig. 3 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 the transfer of material between the stratosphere and the troposphere.

There appears to be no published comparable measurement of free tropospheric aerosol enhancement following the St. Helens eruption, but Post (1985) has described similar observations following the eruption of El Chichón in 1982. Infrared 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 satellites provided almost complete global coverage between February 1979 and November 1981 although, because of attenuation by tropospheric clouds, the majority of the data is confined to altitudes above 5 km. Some data have been obtained at lower latitudes, but this is only a small fraction of the total dataset and is probably not representative, corresponding as it does to the less cloudy and aerosol-free occasions. At altitudes above 5 km, the dataset is extensive. Measured extinction values are sometimes very large. Such values are believed to be due 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 that are not representative of tropospheric 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 have 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 observed by the GAMETAG flight series over the Pacific Ocean in 1977 and 1978. The magnitude of the asymmetry is seasonally variable, both hemispheres in 1979 showing 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 infrared 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. It is possible that the two phenomena are 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 in 1980 and 1981 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 lifetime 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 infrared backscatter on the stratospheric and free tropospheric aerosol burden following the eruption of El Chichón in 1982.

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