the National Oceanic and Atmospheric Administration National Meteorological Center provided the rawinsonde data to NASA Langley.
6. M. P. McCormick, G. S. Kent, G. K. Yue, D. M. Cunnold, *Science* **216**, 1115 (1982).
7. We thank T. J. Pepin and M. P. McCormick for analyzing the data of 18 April and J. Laver for providing rawinsonde data. We thank all members of the Wallops Flight Center P-3 aircraft crew for their excellent support in flying these missions. We are also grateful to the lidar operations crew, B. R. Rouse of NASA Langley, and F. C. Diehl of Wyle Laboratories for their efforts in supporting these measurements.

24 July 1981; revised 11 January 1982

Stratospheric Aerosol Effects from Soufriere Volcano as Measured by the SAGE Satellite System

Abstract. *During its April 1979 eruption series, Soufriere Volcano produced two major stratospheric plumes that the SAGE (Stratospheric Aerosol and Gas Experiment) satellite system tracked to West Africa and the North Atlantic Ocean. The total mass of these plumes, whose movement and dispersion are in agreement with those deduced from meteorological data and dispersion theory, was less than 0.5 percent of the global stratospheric aerosol burden; no significant temperature or climate perturbation is therefore expected.*

The first major 1979 eruption of Soufriere, St. Vincent, took place on 13 April, and on this and the next few days several eruptions sent debris to a height of about 16 km. On 17 April, the most powerful eruption of the series sent an eruptive column to heights of 18 to 20 km, as estimated from a NASA aircraft (*1*). After this, only one more eruption, on 22 April, sent debris into the stratosphere (*2*). NASA's SAGE (Stratospheric Aerosol and Gas Experiment) satellite was launched on 18 February 1979 to provide global measurements of the vertical profile of aerosols in the stratosphere (*3*). The instrument makes solar-intensity measurements at four different wavelengths for each satellite sunrise and sunset; these measurements are inverted to give profiles of aerosol extinction that have a vertical resolution of 1 km and an accuracy of about 10 percent near the peak of the stratospheric aerosol layer. These data are also inverted to give ozone and nitrogen dioxide concentrations as a function of altitude. Measurements made on successive orbits are separated by about 24° of longitude and about 0.2° to 0.3° of latitude. As the satellite orbit precesses, geographical coverage between approximately 65°N and 65°S is obtained, a cycle taking about 1 month to complete.

Lidar (light detection and ranging) measurements made during the Soufriere eruption of 17 April are also available. These measurements were taken from an airborne system onboard a NASA P-3 research aircraft returning from a SAGE underflight mission in Brazil. The aircraft was directed to the neighborhood of the volcano, approaching it at the time of the 17 April eruption. Special missions were flown on 18 and 19 April to determine the height and location of the new stratospheric aerosol plumes (*4*).

When Soufriere first erupted, the SAGE satellite was making measurements in the Southern Hemisphere (approximately 45°S). On 23 April, the satellite was at the latitude of the volcano. Figure 1a shows a normal aerosol extinction profile as observed by SAGE on 24 April. No high-altitude cloud is present, and the extinction decreases fairly slowly as the altitude increases from about 15 to 22 km. Figure 1b shows the profile obtained on the same day, when SAGE was close to St. Vincent. This profile has a maximum at an altitude of about 20.5 km, which is approximately four times greater than the normal value. Such enhanced values at heights above the tropopause were observed on at least eight occasions in April 1979 near Soufriere (Fig. 1c). Two groups of events were seen, one over West Africa and the other over the Atlantic Ocean. These two groups are believed to have been related to separate volcanic eruptions.

In order to estimate the mass of material injected into the stratosphere and its dispersion, one must first relate the SAGE observations to the individual volcanic eruptions. To analyze the

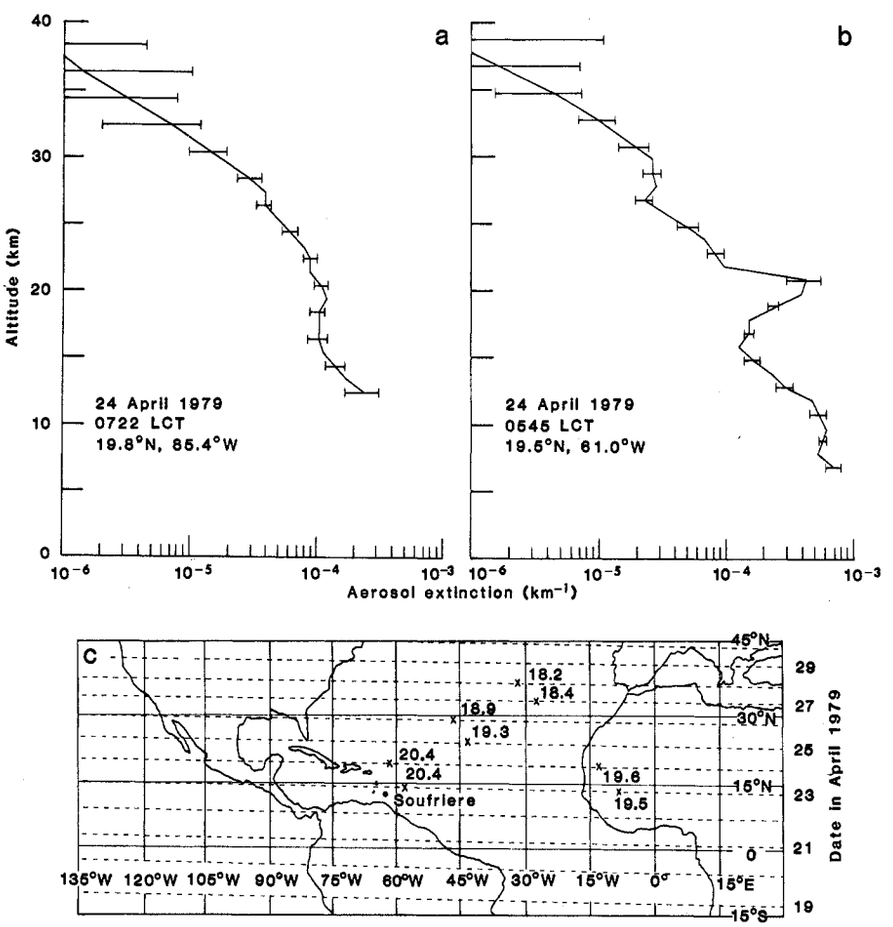

Fig. 1. (a) Normal aerosol extinction profile as determined by the SAGE satellite system. (b) Enhanced aerosol profile observed near Soufriere on 24 April 1979. (c) Map showing SAGE measurements near Soufriere in April 1979. The latitudes for each day of SAGE measurements are shown by the dashed lines. Events showing enhanced aerosol extinction in the stratosphere (50 percent or more above normal) are marked by x's; the altitude (in kilometers) of each layer peak is shown.

0036-8075/82/0604-1115$01.00/0

Table 1. Stratospheric extinction and mass loading for the April 1979 eruptions of Soufriere and for the global aerosol background.

Aerosol component	Area covered (km^2)	Vertical thickness (km)	Integrated extinction (km^2)	Estimated mass loading (metric tons)
West African plume	3.1×10^6	1.4	6.3×10^2	5.8×10^2
Caribbean–North Atlantic plume	7.7×10^6	2.1	18.8×10^2	1.7×10^3
Total	10.8×10^6	1.9	25.1×10^2	2.3×10^3
Background global value	5.1×10^8	Stratosphere (tropopause + 2 km upward)	6.1×10^5	5.5×10^5

movements of the stratospheric plumes in detail, it is desirable to have as much high-altitude meteorological information as possible from the neighborhood of the volcano and along the plume trajectory. Unfortunately, much of the observed trajectory is over the Atlantic Ocean where there are no meteorological stations. We have therefore used the standard global maps of temperature and geopotential height provided by the National Oceanic and Atmospheric Administration (NOAA) (5). These maps have been supplemented with high-altitude wind data from Barbados (150 km east of St. Vincent) and Trinidad (250 km south of St. Vincent).

Trajectories calculated on the basis of the geopotential height data indicate that the material from the eruptions of 13 and 14 April (treated as a single event) moved eastward across the Atlantic Ocean and reached the coast of Africa on about 20 April. The material from the eruption of 17 April began moving eastward but then turned north after it had reached 42°W. Both trajectories agree qualitatively with the plume positions over West Africa and over the Atlantic Ocean as determined by SAGE, but the trajectory analysis predicts the arrival of material at these locations too early. Moreover, the trajectory for the eruption of 17 April does not correspond with the airborne lidar observations. This disagreement is believed to arise because global maps tend to emphasize larger scale features of the flow fields and to neglect local fluctuations, and also because the geostrophic approximation used in calculating the trajectory appears to overestimate wind speeds when used closer to the equator than about 15°N.

A somewhat simpler analysis, based on data from the local Caribbean rawinsonde stations, may be used to plausibly identify the origins of the two plumes. Because of the velocity of movement required, the plume seen over West Africa on 23 and 24 April clearly cannot be associated with the eruption of 22 April. The plume could, however, have originated from either of the eruptions of 13 and 14 April or 17 April. If it originated from the earlier eruption, a velocity of 7.4 m sec^{-1} would be required; if from the later eruption, a velocity of 12.1 m sec^{-1}. The relative plausibility of these two values has been examined in terms of data from Caribbean stations for the period just after these eruptions. For the 19.5-km (60-mbar) height at which the cloud was observed over West Africa and for the mean latitude of about 16°N at which the movement took place, 12.1 m sec^{-1} is an unreasonably high mean wind velocity. On the other hand, 7.4 m sec^{-1} is in good agreement with the observed wind velocities, an indication that the cloud originated from the eruption of 13 and 14 April. This explanation for the origin of the cloud is further substantiated by a detailed examination of the daily zonal wind behavior at Barbados and Trinidad. On 15, 16, and 17 April, strong easterly winds (5 to 15 m sec^{-1}) were observed at the 50- and 70-mbar levels. On 18, 19, and 20 April, the mean zonal wind was almost zero, which would have prevented any systematic eastward drift of the cloud produced by the eruption on 17 April.

If the West African cloud originated at St. Vincent on 13 and 14 April, the problem of identifying the source of the other and larger cloud still remains.

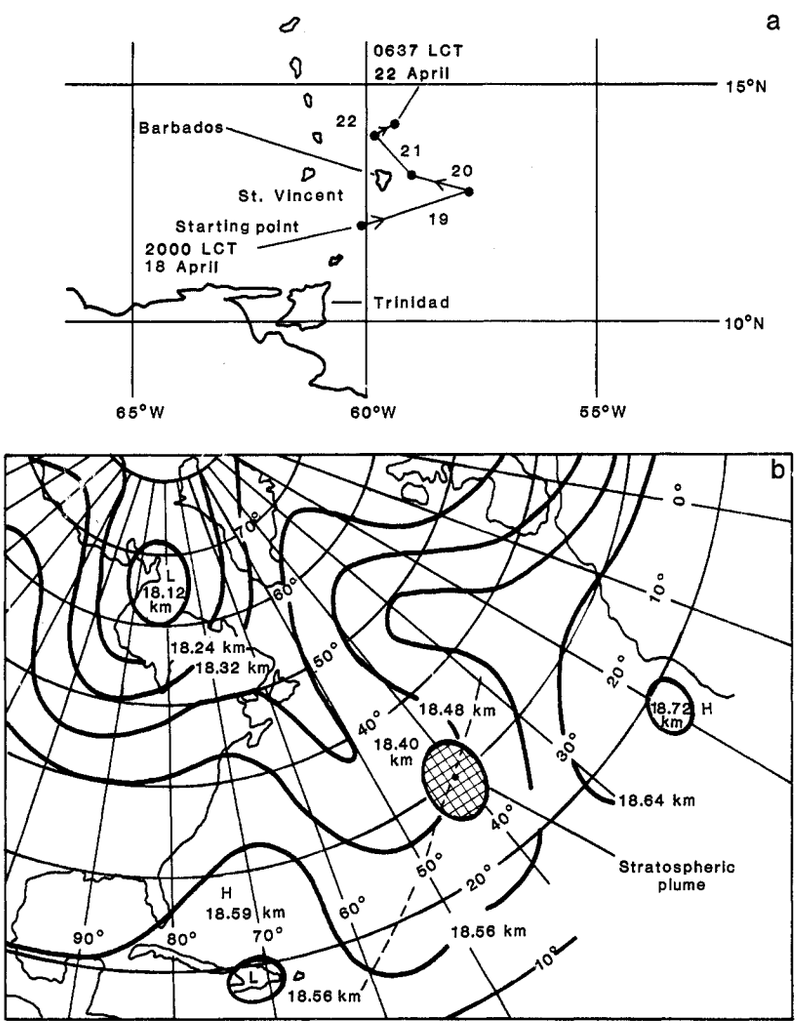

Fig. 2. (a) Calculated wind trajectory at the 50-mbar pressure level (20.7 km), for the period 19 to 22 April 1979. The starting point for the trajectory is based on the lidar data of 18 April. (b) High-altitude pressure map at the 70-mbar level at 0600 LCT on 26 April 1979. The cross-hatched area shows the position of the stratospheric plume. The heights shown are geopotential altitudes.

Backward extrapolation of the SAGE events shown in Fig. 1c would indicate that the plume extending over the North Atlantic Ocean originated at the volcano on 22 April, coincident with the final major eruption. This conclusion ignores the question of what happened to the cloud from the eruption of 17 April, which produced the highest column height of the series. For this eruption, the lidar measurements showed that the initial movement of the stratospheric part of the plume was in a southerly direction (*4*), in agreement with the local meteorological data.

Figure 1c shows that the North Atlantic plume originated near St. Vincent at a mean altitude of 20.4 km. In order to see whether this plume could be related to the 17 April eruption, we analyzed the air movements at a pressure level of 50 mbar (20.7 km), using, as before, rawinsonde data from Barbados and Trinidad. The starting point for the trajectory has been taken as 12°N, 60°W at 2000 LCT (*6*) on 18 April, on the basis of the lidar observations of the plume at this height, position, and time. Figure 2a shows subsequent movements to 0637 LCT on 22 April, when the final major eruption took place. The total movement from St. Vincent, between 17 and 22 April, is only a few degrees in both latitude and longitude; this pattern of movement would place the plume very close to the location of the SAGE observation of 23 April. Furthermore, the dispersion of the plume over this time period would allow it to extend back to the volcano, thus overlapping any plume produced by the eruption of 22 April. The SAGE observation of 23 April, therefore, is probably the plume from the eruption of 17 April, but the prevailing winds and the proximity to the volcano make it impossible to rule out some contribution from the eruption of 22 April. After 23 April, the cloud then apparently began to move rapidly northeast across the Atlantic Ocean because of the arrival of a low-pressure weather system, which, after 23 April, moved slowly northeast across the Atlantic and abated on 28 April. Figure 2b shows this meteorological situation on 26 April. The final date on which the plume was observed agrees with that on which the low-pressure region abated; the required speed of movement of about 8 m sec^{-1} is typical for this altitude and latitude.

Figure 1c indicates that the cloud extending northward over the Atlantic descended as it moved. The descent is in agreement with meteorological data, which shows that air parcels warmed as they moved northward, almost certainly because of adiabatic compression that resulted from downward motion. Calculations of the amount of vertical movement expected indicate a descent of 1 to 2 km, in agreement with the SAGE measurements.

A procedure for calculating the dispersion of a cloud before it reaches the scale of the large-scale circulation has been described by Justus and Mani (*7*). We used this procedure to determine whether it was reasonable for SAGE to have observed these clouds at the various locations and times after the eruptions. The horizontal half-width of the cloud is determined as a function of time by numerical integration; this integration is based on prescribed vertical shears of the horizontal wind, vertical stability, viscosity, turbulent length scales, initial cloud size, and a heat transfer parameter. The results of these calculations indicate that, after approximately 1 day, the cloud size probably attained the synoptic scale and subsequently expanded as the square root of time. We estimate that, after 5 days, the cloud had a radius (to half-concentration) of roughly 1000 km, and after 10 days a radius of 1400 km. These figures are in good agreement with the cloud sizes actually observed. Use of the same analysis to determine a value for the growth of the cloud in the first few hours, however, produced a much smaller value than the 100-km radius measured from an aircraft 2 hours after the eruption of 17 April (*1*).

Figure 1c can be used, in conjunction with the actual aerosol extinction values, to provide an estimate of the total mass of aerosol injected into the stratosphere. As far as the geographical extent of the plume is concerned, we have assumed that the extinction measured in each of the eight stratospheric events is representative of the aerosol spread over a rectangular area, whose dimensions are given by the longitudinal separation of SAGE events and the latitudinal separation of SAGE tracks (approximately 24° longitude by 5° latitude).

The results of the calculations are shown in Table 1, where the West African and Caribbean–North Atlantic plumes have been listed separately. The vertical thicknesses of the plumes have been determined from the extinction profile shape, and both thicknesses have been used to calculate the integrated extinction produced by the plume. This quantity is a volume integral of the extinction carried out over the area of the earth's surface covered by the plume and through the vertical thickness of the plume itself. The background global value of the integrated extinction was calculated from a point 2 km above the tropopause rather than from the tropopause because of the uncertainty about the tropopause height and the possible contamination from tropospheric clouds. On a global scale, the Soufriere event is seen to be small, contributing less than 0.5 percent to the total integrated extinction.

Conversion of these extinction values to mass-loading values that are usable by a broader segment of the science community requires a conversion factor that is derived from a knowledge of aerosol characteristics such as composition and size distribution. A model recently used for the stratospheric aerosol is one that consists of a mixture of a 75 percent solution of sulfuric acid droplets and ammonium sulfate crystals in a ratio of approximately 3:1 (*8*). This model was developed from the SAM II and SAGE ground-truth programs and is representative of the pre–Mount St. Helens background aerosol in the upper troposphere and stratosphere. It includes a variability with altitude and latitude. Mie scattering calculations have been carried out for various representative particle size distributions used in the model matched to stratospheric dustsonde measurements. These calculations yield a value for the aerosol extinction-to-mass ratio at a wavelength of 1 μm (the center wavelength of the primary SAGE aerosol spectral channel) that varies from 0.75×10^3 to 1.45×10^3 m^2 kg^{-1}. A mean value of 1.1×10^3 m^2 kg^{-1}, taken in conjunction with the value for the integrated extinction given in Table 1, yields the total global aerosol mass loading of 5.5×10^5 metric tons. This value is comparable with that of 5×10^5 metric tons given by Penndorf (*9*). Use of the same conversion factor with the Sou-

Table 2. Estimates of aerosol mass loading into the stratosphere for recent volcanoes.

Date	Volcano	Aerosol injected (metric tons)	References
March 1963	Agung, Bali	3×10^7	(*10, 11*)
October 1974	Fuego, Guatemala	6×10^6	(*10, 11*)
October 1974	Fuego, Guatemala	3×10^6	(*12*)
January 1976	Augustine, Alaska	6×10^5	(*11*)

friere extinction values gives a stratospheric aerosol mass loading of 2.3×10^3 metric tons. It is normally assumed that part of the newly injected aerosol consists of fine ash that has a considerably higher refractive index (*10*). Even if all the injected material consisted of fine ash with the same particle size distribution, which is very unlikely, the total mass would be reduced by only 25 percent to about 2×10^3 metric tons. Regardless of these uncertainties, the injected mass is undoubtedly small as compared with that estimated for the volcanoes listed in Table 2, most of which had an atmospheric input that was greater by two orders of magnitude or more than that of Soufriere (*10–12*). We do not expect, therefore, that Soufriere will induce any significant long-term temperature perturbation either in the stratosphere or at the earth's surface, nor will it represent a climate perturbation (*13*).

This study represents the first opportunity to use the SAGE satellite system to study the effects of a volcanic eruption on the stratosphere. Although the April 1979 Soufriere eruption is not expected to cause any long-term climatic change, its study has demonstrated the capability of SAGE to identify, track, and provide quantitative estimates of the mass loading of stratospheric volcanic plumes, even when these are produced by relatively small volcanic eruptions, and thus to provide useful information for inputs to multidimensional transport models and models for climate change.

The SAGE satellite has continued to make observations of the stratospheric aerosol and has detected the effects of at least three other volcanic eruptions, Sierra Negra in the Galápagos Islands, Mount St. Helens in Washington, and Ulawun in Papua New Guinea, all of which produced much more significant stratospheric perturbations than Soufriere.

M. PATRICK MCCORMICK
NASA Langley Research Center, Hampton, Virginia 23665
G. S. KENT, G. K. YUE
Institute for Atmospheric Optics and Remote Sensing, Hampton 23666
D. M. CUNNOLD
Georgia Institute of Technology, Atlanta 30332

References and Notes

1. See figure 2 in R. S. Fiske and H. Sigurdsson, *Science* **216**, 1105 (1982).
2. J. B. Shepherd *et al.*, *Nature (London)* **282**, 24 (1979).
3. M. P. McCormick, P. Hamill, T. J. Pepin, W. P. Chu, T. J. Swissler, L. R. McMaster, *Bull. Am. Meteorol. Soc.* **60**, 1938 (1979).
4. W. H. Fuller, Jr., S. Sokol, W. H. Hunt, *Science* **216**, 1113 (1982).
5. W. L. Smith, H. M. Woolf, C. M. Hayden, D. A. Wark, L. M. McMillin, *Bull. Am. Meteorol. Soc.* **60**, 1177 (1979).
6. All times are local civil time (LCT); add 4 hours for universal time.
7. C. G. Justus and K. K. Mani, *Pure Appl. Geophys.* **117**, 513 (1978).
8. P. B. Russell, T. J. Swissler, M. P. McCormick, W. P. Chu, J. M. Livingston, T. J. Pepin, *J. Atmos. Sci.* **38**, 1279 (1981).
9. R. Penndorf, *Report FAA-EE-78-29* (prepared for the High Altitude Pollution Program, U.S. Department of Transportation, Washington, D.C., 1978).
10. R. D. Cadle, C. S. Kiang, J. F. Louis, *J. Geophys. Res.* **81**, 3125 (1976).
11. R. D. Cadle, F. G. Fernald, C. L. Frush, *ibid.* **82**, 1783 (1977).
12. A. L. Lazrus, R. D. Cadle, B. W. Gandrud, J. P. Greenberg, B. L. Huebert, W. I. Rose, Jr., *ibid.* **84**, 7869 (1979).
13. J. E. Hansen, W.-C. Wang, A. A. Lacis, *Science* **199**, 1065 (1978).
14. We thank J. Laver of NOAA's National Meteorological Center for providing the meteorological data in such a timely manner, and we acknowledge the valuable assistance of W. P. Chu and T. J. Swissler at the Langley Research Center in all aspects of the SAGE data processing.

24 July 1981; revised 11 January 1982

Fine Particles in the Soufriere Eruption Plume

Abstract. *The size distributions of fine particles measured at tropospheric altitudes in the periphery of the eruption plume formed during the 17 April 1979 eruption of Soufriere Volcano and in the low-level effluents on 15 May 1979 were found to be bimodal, having peak concentrations at geometric mean diameters of 1.1 and 0.23 micrometers. Scanning electron microscopy and energy-dispersive x-ray analysis of the samples revealed an abundance of aluminum and silicon and traces of sodium, magnesium, chlorine, potassium, calcium, and iron in the large-particle mode. The submicrometer-sized particles were covered with liquid containing sulfur, assumed to be in the form of liquid sulfuric acid.*

On 17 April 1979, a NASA research aircraft carrying an airborne lidar (light detection and ranging) system (*1*) and an in situ aerosol sensor approached St. Vincent to investigate Soufriere Volcano, which had erupted several times since 13 April. The largest eruption of the series took place at approximately 1657 LCT (*2*) on 17 April, when the aircraft was approaching the island from Barbados. The eruption plume, a very thick, dark-gray cloud, rose to about 18 to 20 km while moving east-northeast (*3*). The aircraft flew westward south of St. Vincent at an altitude of about 3 km, coming to within about 45 km of the visible plume before turning northwest. A quartz crystal microbalance (QCM) cascade impactor (*4*), in operation during the period of closest approach, sampled particles in the periphery of the cloud. A return sampling mission, using the same instrumentation, was conducted on 15 May 1979, after the eruptions had ceased but while the volcano was still fuming light steamlike puffs. On this second mission, the aircraft flew over the crater and through patches of the light plume.

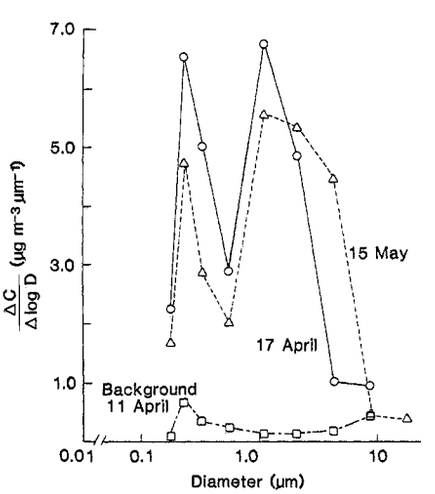

Fig. 1. Mass concentration plotted as a function of particle diameter for the outer edges of the 17 April 1979 Soufriere eruption plume at an altitude of about 3 km; in the light plume over the crater on 15 May 1979, at an altitude of about 1.8 km; and in ambient air near Barbados on 11 April 1979, at an altitude of about 3 km.

The QCM is a multistage cascade impactor that classifies particles into ten size intervals by inertial impaction. The particle diameters (the impaction efficiency is 50 percent), as determined from the theory of Ranz and Wong (*5*), are as follows: stage 1, > 25 μm; stage 2, 12.4 μm; stage 3, 6.2 μm; stage 4, 3.0 μm; stage 5, 1.4 μm; stage 6, 0.78 μm; stage 7, 0.39 μm; stage 8, 0.28 μm; stage 9, 0.19 μm; and stage 10, 0.18 μm. Each impactor stage is composed of a piezoelectric microbalance that measures size-fractionated mass as the particles impact. The QCM retains the impacted particles for postflight examination by scanning electron microscopy (SEM) and energy-dispersive x-ray analysis (EDXRA) to determine morphology and elemental composition for elements having atomic numbers of 11 or more. The QCM was first used to sample volcanic effluents from Fuego and Santiaguito in Guatemala in 1978 (*6*).

Figure 1 shows size-distribution plots ($\Delta C/\Delta \log D$ as a function of D) obtained from measurements in the periphery of

0036-8075/82/0604-1118$01.00/0