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.

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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.

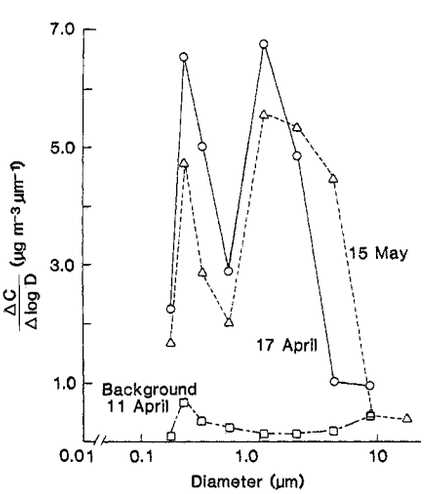

Fig. 1. Mass concentration plotted as a function of particle diameter for the outer edges of the 17 April 1979 Soufriere eruption plume at an altitude of about 3 km; in the light plume over the crater on 15 May 1979, at an altitude of about 1.8 km; and in ambient air near Barbados on 11 April 1979, at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

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the large eruption cloud (17 April) and in the light plume (15 May); ΔC is the mass concentration of particles in the size interval $\Delta \log D$, where D is the geometric mean diameter of particles collected in a given impaction stage of the QCM. Both plots have strong bimodal features, with maximum concentrations at diameters of 1.1 and 0.23 μm. A size-distribution plot for the ambient air obtained from measurements on 11 April just south of Barbados is shown for comparison. Bimodal and trimodal size-distributions were observed in the plumes from Fuego and Santiaguito in 1978 (*6*); however, these plumes contained particles with diameters larger than 25 μm. We did not find these large particles in the Soufriere plume on 17 April, probably because our sampling position was at the extreme edge of the cloud. On 15 May, the cloud consisted of very thin white puffs that probably did not contain large particles.

We carried out EDXRA on samples from the 17 April and 15 May collections. The elemental composition of the material by size (impaction stage) was similar for both sets of samples. Aluminum and silicon were abundant among the particles that ranged from 1.1 μm to several micrometers in size. Traces of sodium, magnesium, chlorine, potassium, calcium, and iron were also found in the large-particle mode. Sulfur, probably in the form of dilute sulfuric acid because of its liquid appearance and low volatility, was present in the submicrometer range and usually covered the particles. This liquid sulfuric acid was much more abundant in the 15 May sample, which was collected in the steamlike puffs near the crater. This sulfuric acid is shown covering the particles in the SEM photograph (Fig. 2). In addition to sulfur, iron was moderately abundant among the submicrometer-sized particles in samples from both 17 April and 15 May; only very small traces of aluminum, magnesium, and potassium were present. No measurable amount of silicon was detected in the submicrometer-sized particles. The quartz crystal on which the particles were collected has a strong silicon peak in the x-ray spectrum; therefore, very small quantities of silicon in the sample may be undetected when the background spectrum is subtracted. In comparison to samples collected in the eruption plume from Santiaguito in 1978 (*6*), the Soufriere samples were relatively simple in morphology. The submicrometer-sized particles in the Santiaguito samples were more crystalline-like. Chemically, the samples were similar except for the abundance of iron among the submicrometer-sized particles in the Soufriere samples.

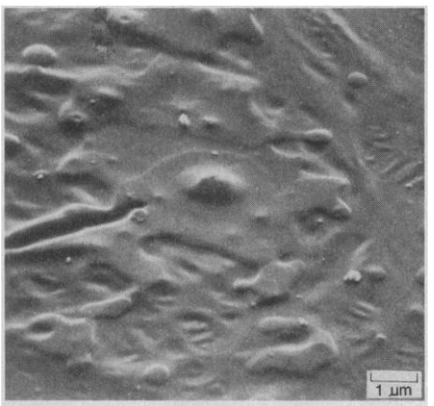

Fig. 2. Scanning electron microscope photograph of particles collected on stage 8 (0.28 μm; 50 percent impaction efficiency) of the QCM impactor from the light plume of 15 May 1979. The particles are surrounded by a wet-appearing substance containing sulfur, presumed to be sulfuric acid because of its low volatility.

Small particles from volcanic eruptions, such as the submicrometer-sized particles found in the Soufriere plume, can be injected into the stratosphere. We observed submicrometer-sized sulfate particles in the stratospheric plume from the Mount St. Helens eruption (*7*). These small particles can, because of their size and optical characteristics, effectively interact with solar and terrestrial radiation. Therefore, a global distribution of such particles in the stratosphere may produce climatic effects.

DAVID C. WOODS
NASA Langley Research Center, Hampton, Virginia 23665
RAYMOND L. CHUAN
Brunswick Corporation, Costa Mesa, California 92692

References and Notes

1. W. H. Fuller, Jr., S. Sokol, W. H. Hunt, *Science* **216**, 1113 (1982).
2. All times are local civil time (LCT); add 4 hours for universal time.
3. See figure 2 in R. S. Fiske and H. Sigurdsson, *Science* **216**, 1105 (1982).
4. R. L. Chuan, in *Fine Particles, Aerosol Generation, Measurement, Sampling, and Analysis*, B. Y. H. Liu, Ed. (Academic Press, New York, 1975), p. 763.
5. Discussed in W. E. Ranz, *Principles of Inertial Impaction* (Bulletin 66, Department of Engineering Research, Pennsylvania State University, State College, 1956).
6. W. I. Rose, Jr., R. L. Chuan, R. D. Cadle, D. C. Woods, *Am. J. Sci.* **280**, 671 (1979).
7. R. L. Chuan, D. C. Woods, M. P. McCormick, *Science* **211**, 830 (1981).
8. We thank the NASA P-3 aircraft flight crew for mission support.

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Aerosols from the Soufriere Eruption Plume of 17 April 1979

Abstract. *Aerosol samples collected from the 17 April 1979 eruption plume of Soufriere, St. Vincent, at altitudes between 1.8 and 5.5 kilometers were physically and chemically very similar to the ash that fell on the island. Higher altitude samples (7.3 and 9.5 kilometers) had a much lower ash content but comparable concentrations of sulfate, which were above the background concentration found at these altitudes.*

Within 24 hours of the largest explosion of the 1979 eruption of Soufriere, that of 1657 LCT (*1*) on 17 April, an Air Force KC-135 aircraft collected filter samples and whole-air samples from the eruption plume. Scanning electron microscopy (SEM) of representative pieces of the filters was used to determine the grain size distributions and particle morphology. Nondispersive x-ray analysis provided qualitative data on the particle compositions.

Portions of the filters were leached with ultrapure water to remove soluble material. We analyzed these extracts for soluble SO_4^{2-}, NH_4^+, and total soluble nitrogen ions (ΣN), using Autoanalyzer and colorimetric techniques. The residual filters from the leaching were ashed for 24 hours at 400°C in a covered crucible to destroy the filters. The nonsoluble, nonvolatile residual ash was weighed to obtain an estimate of the mass of ash present for comparison with the results of neutron activation analysis (NAA).

We analyzed representative pieces of the filters for trace elements by NAA. The filters, along with appropriate standards, were irradiated with neutrons in the National Bureau of Standards (NBS) reactor. The induced radioactivity was measured by Ge(Li) γ-ray detectors according to the procedures used by Germani *et al.* (*2*) for the analysis of NBS standard reference materials. The ash sample was analyzed by neutron-capture prompt γ-ray activation analysis to determine the major elemental composition and some of the minor elements (*3*). The radioactive species ^{210}Pb and ^{210}Po were analyzed by α-spectroscopy on samples that were extracted from the air filters and electroplated before the radioactivity was counted.

So that we might compare the air-fall tephra with the tephra collected from the plume, we analyzed a sample collected

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