Airborne Lidar Measurements of the Soufriere Eruption of 17 April 1979

Abstract. *At the time of the Soufriere, St. Vincent, volcanic eruption of 17 April 1979, a NASA P-3 aircraft with an uplooking lidar (light detection and ranging) system onboard was airborne 130 kilometers east of the island. Lidar measurements of the fresh volcanic ash were made approximately 2 hours after the eruption, 120 kilometers to the northeast and east. On the evening of 18 April, the airborne lidar, on a southerly flight track, detected significant amounts of stratospheric material in layers at 16, 17, 18, and 19.5 kilometers. These data, and measurements to the north on 19 April, indicate that the volcanic plume penetrated the stratosphere to an altitude of about 20 kilometers and moved south during the first 48 hours after the eruption.*

On 16 April 1979, the NASA Wallops Flight Center P-3 aircraft was returning to the United States after completing a series of SAGE (Stratospheric Aerosol and Gas Experiment) satellite ground-truth missions over Natal, Brazil. In support of these missions, several remote and in situ instruments for atmospheric monitoring were onboard the aircraft, including an uplooking lidar (light detection and ranging) system operating at 0.6943 μm. The lidar makes remote measurements of the total stratospheric aerosol concentration in terms of the total backscatter ratio (R_B), defined as the ratio of the total backscatter to the molecular backscatter. For example, a backscatter ratio R_B of 1.1, which is typical of a background R_B for the lower stratosphere, indicates a 10 percent enhancement over the molecular backscatter due to aerosols (*1*). En route to the mainland, the aircraft made a scheduled overnight refueling and rest stop on the island of Barbados, West Indies (13°3′N, 59°28′W). The departure of the plane from Barbados was delayed in order that it might fly a special lidar and photographic mission on 17 April in the vicinity of the recently erupted (13 and 14 April) Soufriere Volcano on St. Vincent Island (13°20′N, 61°11′W), 170 km west of Barbados.

On 17 April at 1657 LCT (*2*), as the aircraft approached St. Vincent at coordinates (13°00′N, 60°00′W) approximately 130 km east of the island, Soufriere erupted violently. The height of the eruptive column was estimated as 18 to 20 km (*3*). After photographs were taken of the dispersing ash cloud, lidar measurements were made under the easterly moving tropospheric plume approximately 120 km northeast of St. Vincent beginning at 1849 LCT. The measurements continued until 1924 LCT, when the aircraft was on its landing approach to Barbados (the flight path is shown by the dashed line in Fig. 1). A layer of volcanic material with its base at an altitude of 10 km and extending to 14 to 16 km was detected over the latitude range 13°24′N to 14°00′N on the flight track; the width of the plume measured by the lidar was 75 km. During these measurements, aircraft flight altitudes ranged from 5.5 to 1.5 km. As the aircraft was descending to an altitude of 1.5 km and when it was approximately 65 km northwest of Barbados, a dense cloud of volcanic ash was intercepted; this ash cloud reduced visibility and curtailed lidar operations. As the aircraft approached the southern tip of Barbados, the ash cloud concentration decreased; when the aircraft arrived at Grantly Adams International Airport, the sky was clear. After the aircraft had landed, a thin layer of volcanic dust was observed on its windows but hardly a trace was seen in the airport area. On the following morning, a very thin layer of dust, barely noticeable, was observed on automobile windshields. Fortunately for Barbados, the major part of the tropospheric ash plume apparently was transported just north of the island and moved off in a northeasterly direction. This was not true after the eruption of 13 April, when 135,000 metric tons of volcanic ash was estimated to have covered the island (*4*).

On the following evening, 18 April, a mission was planned, based on the predicted volcanic plume trajectory derived from high-altitude wind fields of 17 April, 2000 LCT, obtained from the Trinidad and Aruba rawinsonde stations (*5*). The objective of the mission was to determine the height, location, and relative concentration of the fresh volcanic material that most assuredly was injected into the stratosphere. The aircraft departed Barbados at 1900 LCT and proceeded west toward St. Vincent following the flight path shown by the solid line in Fig. 1. Lidar operations began at 1915 LCT, after the aircraft leveled off at an altitude of 3.7 km. During the first 5 minutes of lidar measurements, there was no indication of abnormal amounts of stratospheric material. The first indication of a well-defined stratospheric layer was observed just southeast of St. Vincent, on the west-bound leg at 13°08′N, 60°50′W, 1922 LCT (point 1 on Fig. 1). The base of the layer was at 18.2 km, and the top at 18.8 km; a peak R_B of 11 was measured at 18.5 km. Table 1 summarizes the lidar measurements made along the flight path. Airborne lidar measurements made just prior to

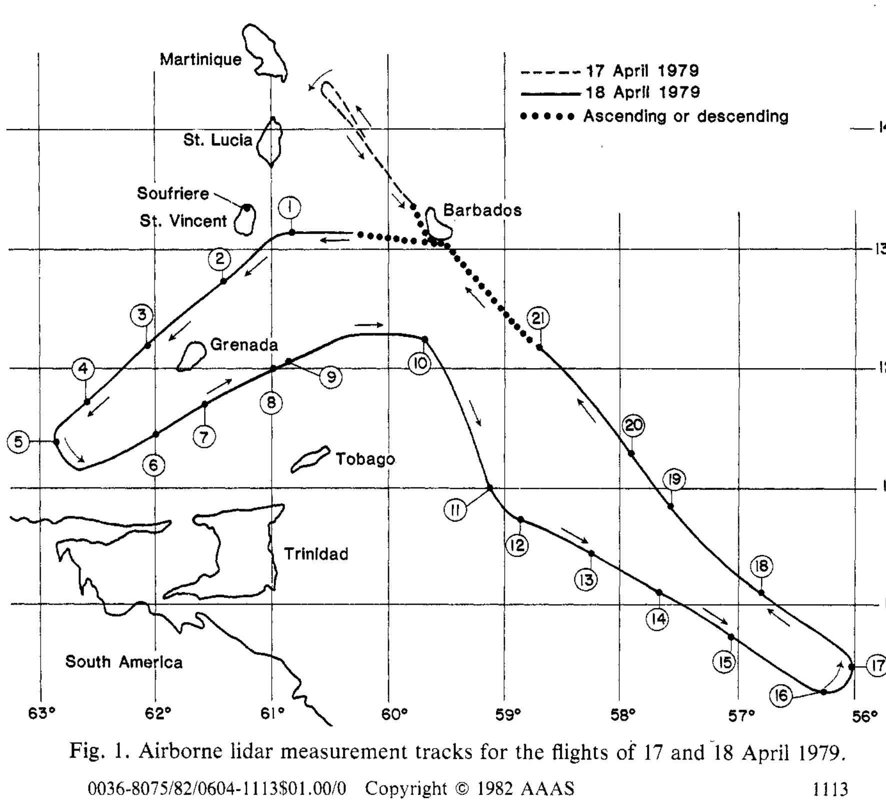

Fig. 1. Airborne lidar measurement tracks for the flights of 17 and 18 April 1979.

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Table 1. Lidar measurements of stratospheric layers along the flight path of 18 April 1979.

Data point	Time (LCT)	Coordinates	Layer base altitude (km)	Layer thickness (km)	Backscatter ratio, R_B
1	1922	13°08′N, 60°50′W	18.2	0.6	11
2	1932	12°42′N, 61°21′W	18	0.5	15
3	1943	12°13′N, 62°01′W	18	0.8	95
4	1953	11°42′N, 62°35′W	18/17	1.0/0.8	35/3
5	1959	11°21′N, 62°51′W	18/17	1.0/0.8	45/5
6	2012	11°27′N, 61°59′W	18/17	0.5/0.5	40/5
7	2017	11°38′N, 61°37′W	18/17	0.6/0.6	38/2
8	2026	12°00′N, 61°00′W	18	0.5	10
9	2028	12°03′N, 60°56′W	19.5/18	0.5/0.8	1.5/2
10	2048	12°14′N, 59°39′W	19.5	0.4	2.5
11	2102	10°57′N, 59°08′W	19.5/17	0.5/0.5	2/3
12	2106	10°43′N, 58°50′W	17	0.5	11
13	2114	10°25′N, 58°15′W	16	0.5	2
14	2121	10°05′N, 57°42′W	17/16	0.5/0.5	2/8
15	2130	9°40′N, 57°01′W	17	0.6	2
16	2142	9°14′N, 56°12′W	17	0.6	1.8
17	2145	9°24′N, 56°02′W	17	0.6	1.6
18	2158	10°05′N, 56°48′W	17	0.7	2.2
19	2211	10°50′N, 57°33′W	17	0.7	2
20	2218	11°18′N, 57°55′W	19.5	0.4	1.2
21	2232	12°11′N, 58°41′W	19.5/18	0.8/0.7	2/4.5

the eruption at more northern and southern latitudes indicate that an R_B value of 1.1 was typical for the lower stratosphere. The tropopause height measured at the Trinidad station (10°35′N, 61°20′W) at 2000 LCT was 16.2 km. The 18-km layer remained quite intense as the aircraft made a turn to the southwest; for example, at 1932 LCT at point 2 (12°42′N, 61°21′W), an R_B of 15 was measured. The enhanced returns continued along the southwest-bound leg, a maximum R_B of 95 being measured at 18 km at point 3 (12°13′N, 62°01′W) at 1943 LCT. Shortly thereafter, the aircraft climbed to an altitude of 4.7 km to avoid a cloud deck. The first indication of a second enhanced layer of stratospheric material was observed at 17.0 km at point 4. The aircraft continued on the southwest-bound leg to the most westerly point on the track at 11°21′N, 62°51′W, and then it began a gradual turn eastward. The original flight plan specified that the aircraft proceed due east along 11°N and then turn southeast at 59°W. However, because of high clouds over the Tobago area, the aircraft headed northeast to avoid this weather activity. The double layer of stratospheric material (17 and 18 km) remained present for about half the northeast-bound leg to point 7. After this point, the 17-km layer disappeared and the single 18-km layer at point 8 decreased in intensity to $R_B = 10$. At point 9, a higher layer (at 19.5 km) was first observed. Also at this time, a thick cirrus cloud deck was observed at 12 km. At 12°17′N, 60°19′W, 2035 LCT, the aircraft had to climb to 5.8 km to avoid high clouds. At point 10, the aircraft changed direction and headed south-southeast. At this point, the 18-km layer was no longer observed; however, the 19.5-km layer was still present at an intensity of $R_B = 2.5$. The 17-km layer reappeared at point 11. At point 12, the aircraft turned due southeast; the 19.5-km layer disappeared, and the intensity of the 17-km layer increased to $R_B = 11$. The 17-km layer remained until point 13, where a lower layer was observed (at 16 km). Although the base of this layer was slightly below the tropopause height of 16.2 km, the top extended to 16.5 km and had characteristics similar to those of the layers at the higher altitudes. We assumed, therefore, that these lower layers were not cirrus clouds. This 16- or 17-km layer was present continuously from point 13 to point 17. The aircraft made a gradual northwest turn, paralleling the southeast run while maintaining the 5.8-km altitude. The 17-km layer remained present, although relatively weak, to point 19 on the northwest-bound track. At point 20, the 19.5-km layer reappeared, its intensity increasing to $R_B = 2$ at point 21. At this point, the 18-km layer reappeared, but, as the aircraft began its descent to Barbados at 2233 LCT, the 18-km layer disappeared. Because of low cloud cover in the Barbados area, no usable lidar data were obtained from this point until the landing at the airport at 2245 LCT.

On the following evening, 19 April, plans were made to conduct lidar measurements from Barbados en route to Wallops Island, Virginia. The objective of this mission was to determine the northerly extent of the stratospheric layers detected on the flight of 18 April. The aircraft departed Barbados on 19 April at 1830 LCT, heading toward St. Lucia, then north to Martinique, over Antigua, and northwest toward the U.S. mainland. Heavy cloud cover above the aircraft prevented lidar measurements over large segments of the track; however, lidar returns at 1845 LCT (13°24′N, 60°12′W) showed no indication of abnormal stratospheric material. At several points along the northward track, lidar measurements showed no significant stratospheric material. These data indicate that either the volcanic-injected stratospheric material was transported out of the area in the intervening 24-hour period or, more likely, the volcanic material was not initially transported northward.

The airborne lidar measurements described above indicate that the stratospheric material from the volcanic eruption of 17 April was initially confined to four well-defined layers: 19.5, 18, 17, and 16 km. The lidar data also show that, during the 24-hour period immediately after the eruption, these layers moved in a generally southerly direction, and there is an indication that some shearing took place between movement at the different altitudes. The southward movement of the stratospheric plume is in agreement with predictions based on the local high-altitude wind data obtained from the Barbados and Trinidad rawinsonde stations. A complete trajectory analysis of the local and large-scale movement of the volcanic material from the Soufriere eruption series of 13, 14, 17, and 22 April, based on these lidar data, SAGE satellite data, and meteorological data, is presented by McCormick *et al.* (6). All these data support the conclusion that the volcanic material from the 17 April eruption penetrated the lower stratosphere to altitudes of about 20 km and initially moved southward.

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References and Notes

1. P. B. Russell *et al.*, *J. Atmos. Sci.* **38**, 1295 (1981).
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. *Advocate News*, Bridgetown, Barbados, West Indies, 17 April 1979.
5. T. J. Pepin of the University of Wyoming and M. P. McCormick of NASA Langley Research Center performed these analyses. J. Laver of

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.

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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

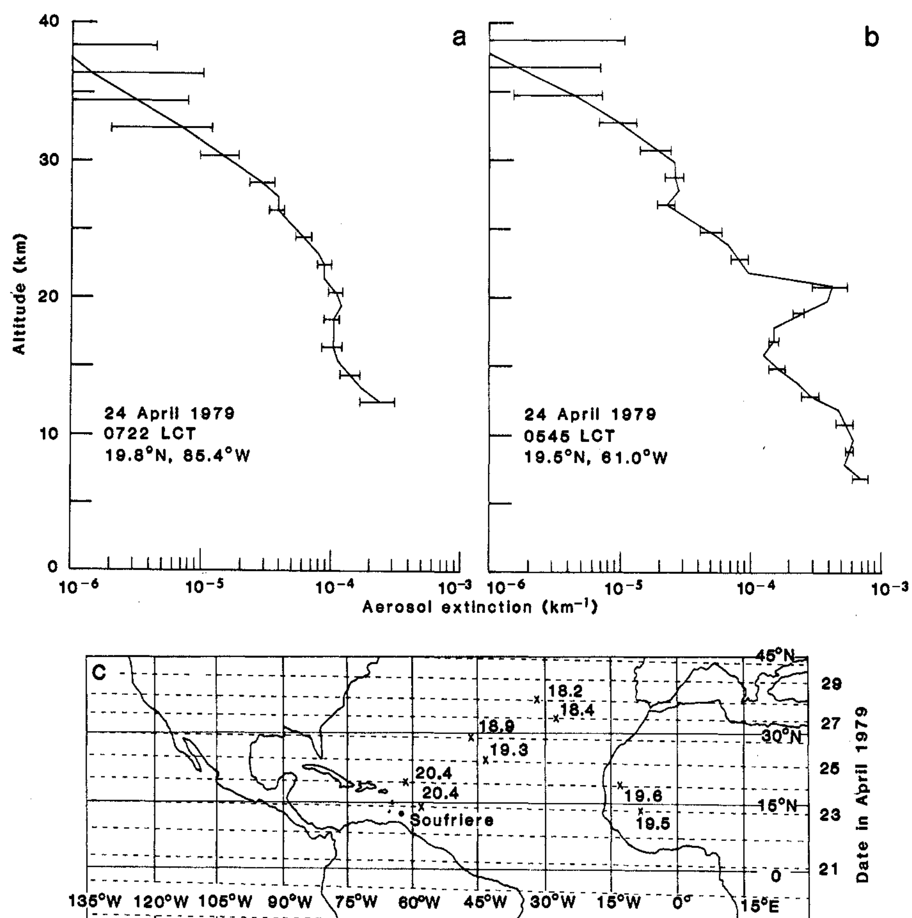

Fig. 1. (a) Normal aerosol extinction profile as determined by the SAGE satellite system. (b) Enhanced aerosol profile observed near Soufriere on 24 April 1979. (c) Map showing SAGE measurements near Soufriere in April 1979. The latitudes for each day of SAGE measurements are shown by the dashed lines. 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.

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