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**SAGE Measurements of
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Dispersion and Loading
From the Soufrière Volcano**

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SUMMARY

Several explosions of the Soufrière volcano on the Caribbean Island of St. Vincent in April 1979 sent columns of volcanic material to stratospheric heights. Two major stratospheric plumes were produced which the Stratospheric Aerosol and Gas Experiment (SAGE) satellite system tracked to West Africa and the North Atlantic Ocean. The total mass of the stratospheric ejecta as measured by SAGE is less than 0.5 percent of the global stratospheric aerosol burden. Therefore, no significant temperature or climate perturbation is expected. The movement and dispersion of the plumes agree with those deduced from high-altitude meteorological data and dispersion theory.

INTRODUCTION

It is well known that many volcanic eruptions inject material into the stratosphere which has a pronounced effect on sunrises and sunsets as seen from the surface of the Earth, and may also have an influence on global weather patterns and climate (refs. 1 and 2). The quantity, movement, and dispersion of this material must normally be painstakingly determined from isolated measurements taken from ground stations. The recent launching of the Stratospheric Aerosol Measurement II (SAM II) and Stratospheric Aerosol and Gas Experiment (SAGE) satellite systems, specifically to monitor the stratospheric aerosol with approximately 1-km vertical resolution, has greatly enhanced our capability to study volcanic plumes (ref. 3).

The material in these plumes is usually made up of a combination of ash and gases in various proportions unique to a given volcano. The sulfur gases in the plumes convert to aerosol particles, thought to be primarily sulfuric acid, through a gas-to-particle conversion process. The exact time for this process to occur is uncertain, but some believe it to be on the order of a few months. Others have proposed that some of the sulfuric acid is produced in the magma before and/or during the magmatic eruption phase. In any case, the SAM II and SAGE sensors detect the extinction of solar radiation in the Earth's limb caused by these particles. Although SAGE measures ozone and nitrogen dioxide via their absorption of solar radiation, neither SAGE nor SAM II is sensitive to the gases spewed into the stratosphere by volcanic eruptions; they both measure the ash particles and the particles formed from the volcanic gases. The Soufrière volcano on the Caribbean Island of St. Vincent (13.3° N, 61.2° W) erupted several times in April 1979 and sent material to stratospheric heights (ref. 4). Approximately 10 days after the first major eruption, SAGE made measurements at the latitude of St. Vincent while moving from south to north. Events showing enhanced extinction in the stratosphere, attributable to material from the volcano, were observed. Similar but rather weaker events were noted as SAGE moved north during the subsequent week, and the effects disappeared at a latitude of about 40° N.

The first major eruption of the Soufrière volcano occurred April 13, 1979, and on this and the following day several eruptions sent debris to a height of about 16 km. On April 15 and 16, no explosions occurred, but on April 17, the most powerful eruption of the series took place, when the height of the eruptive column was estimated from a NASA aircraft to be between 18 and 20 km (W. H. Hunt, private communication). Following this, only the eruption on April 22 sent debris into the

stratosphere. Detailed times and estimated column heights are listed in table I (ref. 4). It should be remembered, however, that the latter are estimates and subject to considerable error. The heights at which SAGE detected material are discussed subsequently in this paper.

TABLE I.- DATES AND TIMES OF MAJOR ERUPTIONS OF
SOUFRIÈRE VOLCANO

Date	Time, GMT	Estimated column altitude, km
April 13, 1979	2108	17 to 18
April 14, 1979	1550	17 to 18
April 17, 1979	2057	18.7
April 22, 1979	1037	17

At the time of the first eruption of the Soufrière volcano, SAGE was making measurements in the Southern Hemisphere (approximately 45° S). The latitude at which the observations were being made moved north, crossing the latitude of the volcano on April 23 and reaching 45° N on April 30.

In addition to the SAGE data, lidar measurements of the atmospheric aerosol cloud produced by the Soufrière eruption of April 17 are also available (W. H. Fuller, private communication). These were taken from an airborne lidar system onboard a P-3 research aircraft returning from a SAGE underflight mission in Brazil. The aircraft was directed to the vicinity of the volcano, approaching it at the time of the April 17 eruption. Subsequently, special missions were flown on April 18 and 19 to determine the height and location of the new stratospheric aerosol plumes.

SAGE observations, made between April 23 and 28, of the stratospheric aerosol clouds produced by the various explosions of the Soufrière volcano are described in this paper. The lidar observations of April 18 and 19 are also described, and the two data sets are combined with available meteorological data. The separate aerosol clouds observed by SAGE are related to the individual volcanic explosions that produced them, and a value for the total mass of new stratospheric aerosol is obtained and compared with that from other recent volcanic eruptions.

EXPERIMENT DESCRIPTION

The Stratospheric Aerosol and Gas Experiment (SAGE) was launched February 18, 1979, on a dedicated Application Explorer Mission-B (AEM-B) spacecraft to provide global data on the vertical profile of aerosols and ozone. Figure 1 illustrates the geometry associated with the SAGE measurement technique and shows how the satellite measures solar intensity through different atmospheric layers at different altitudes during a single sunrise or sunset event encountered by the satellite. As the satellite approaches the shadow side of the Earth (spacecraft sunset), light from the

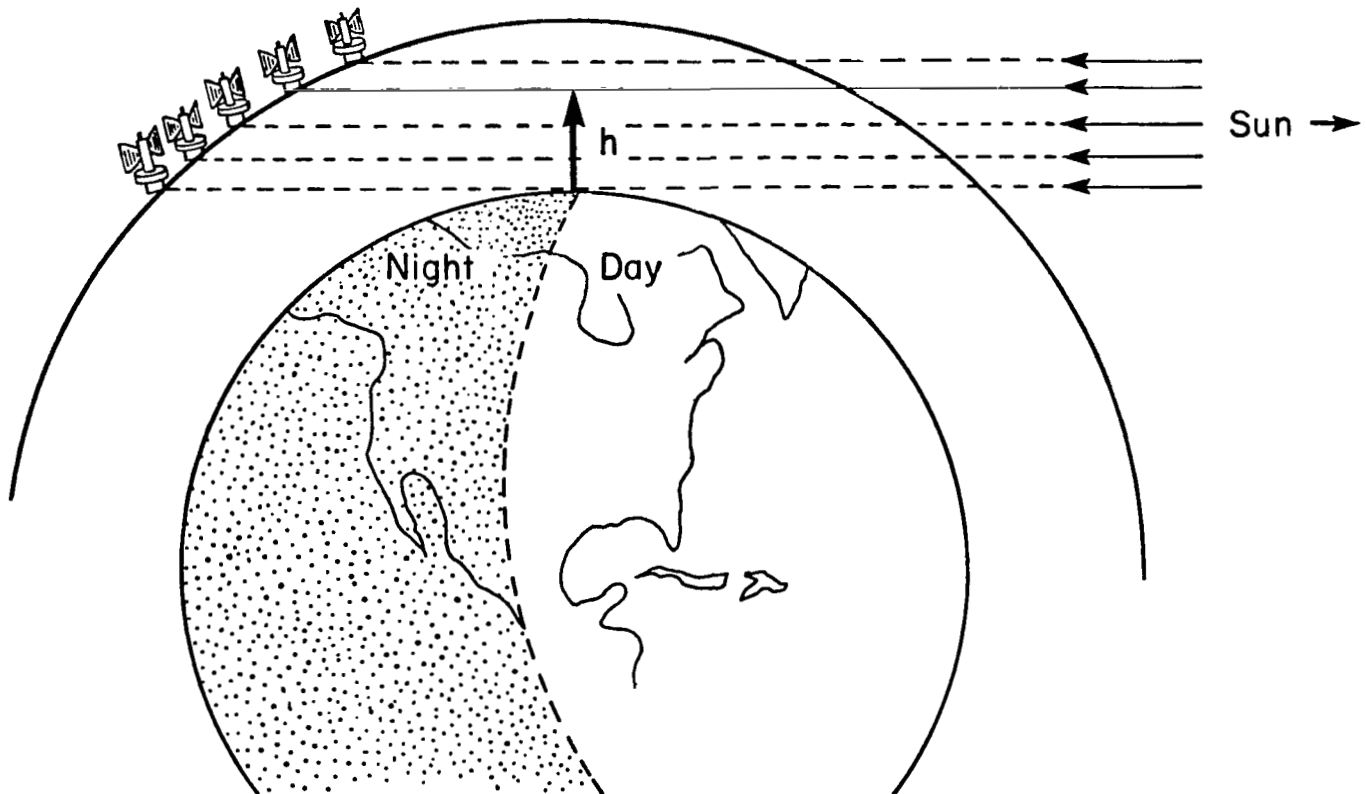


Figure 1.- Geometry of Earth, Sun, and satellite during solar extinction measurements. Different layers of the atmosphere at tangent heights h are successively sampled during each satellite sunrise or sunset event.

Sun to the satellite passes through successively lower altitude air masses until the Sun is occulted by clouds or the Earth's surface. Solar intensity measurements during this transient period provide a complete altitude scan of the atmosphere. During a satellite sunrise event, the measurement sequence is reversed. Typical measurements cover altitudes from the ground or cloud top to above 250 km, where there is essentially no atmospheric attenuation. In fact there is no appreciable extinction above about 60 km over the SAGE spectral region. These high-altitude solar intensity data provide a convenient self-calibration for occultation instruments, which is one reason why this technique is so successful. As seen from the spacecraft, the Sun rises or sets at a vertical rate of about 3 km/s. Therefore, a scan of the stratosphere takes about 20 seconds; thus, occultation instruments need only to maintain their calibration or throughput and gain characteristics for a short time. Coupled with a zero-atmosphere calibration for each event and an inherent high signal-to-noise ratio, makes this a powerful remote sensing technique.

The SAGE instrument is a four-spectral-channel Sun photometer with wavelength passbands centered at 1.0, 0.6, 0.45, and 0.385 μm , and with bandwidths at half maximum of about 0.02 μm . Solar radiation is reflected by a scan mirror and collected by a Cassegrainian telescope to produce an image of the solar disk on its focal plane. On the focal plane is a circular aperture that defines a 0.6 arc-minute instantaneous field of view (IFOV). This IFOV provides an atmospheric vertical resolution on the horizon of approximately 0.5 km altitude. Sunlight passing

through the aperture is dispersed by a holographic grating, and portions of the first-order spectrum are detected by PIN photodiodes positioned on the Rowland circle of the grating.

Immediately before a satellite sunrise or sunset event, the SAGE instrument is activated by a Sun presence sensor, which indicates that the Sun is within the field of view of the instrument. SAGE then locks onto the Sun in azimuth and scans in elevation until the Sun is acquired. The scan mirror then scans vertically, with respect to the Earth's horizon, across the solar disk at a rate of 15 arc minutes per second. The scan direction is reversed each time a Sun edge crossing occurs. The solar edge crossings are detected by detectors placed on the focal plane on either side of the circular aperture that defines the IFOV. The output from the detectors on the Rowland circle are sampled at 64 Hz and digitized with a 12-bit analog-to-digital converter. The digital data are stored onboard the satellite, along with auxiliary data about the instrument, and are later transmitted to ground stations for analysis.

The equation describing the relationship between the atmospheric aerosol extinction properties and the satellite measurements is given by

$$H_{\lambda}(t) = \iint F_{\lambda}(\theta, \phi) S_{\lambda}(\theta, \phi, t) T_{\lambda}(\theta) d\Omega d\lambda \quad (1)$$

where $H_{\lambda}(t)$ is the instantaneous irradiance measured by the instrument at center wavelength λ and time t , $F_{\lambda}(\theta, \phi)$ is the radiometer field of view function, ϕ is the azimuthal angle, Ω is the solid angle, $T_{\lambda}(\theta)$ is the transmission of the atmosphere at λ as a function of view angle θ , and $S_{\lambda}(\theta, \phi, t)$ is the extraterrestrial solar radiance profile. Effects caused by atmospheric refraction have to be included in computing $S_{\lambda}(\theta, \phi, t)$. The transmission function $T_{\lambda}(\theta)$, with the change of variable from θ to tangent height h_t , is given by the Bouguer law as

$$T_{\lambda}(h_t) = \exp\left[-\int \beta_{\lambda}(h) d\rho_{\lambda}(h)\right] \quad (2)$$

where $\beta_{\lambda}(h)$ is the total extinction coefficient of the atmosphere versus altitude h for wavelength λ , and $\rho_{\lambda}(h)$ is the optical pathlength of the Sun ray. In general, the total extinction coefficient β_{λ} at each altitude is composed of contributions from aerosol and molecular scattering and specific molecular absorptions. At the four SAGE wavelengths

$$\beta_{\lambda} = \beta_{nd}(\lambda) + \beta_{NO_2}(\lambda) + \beta_a(\lambda) + \beta_{O_3}(\lambda) \quad (3)$$

where $\beta_{nd}(\lambda)$ is the Rayleigh extinction at λ ; $\beta_{O_3}(\lambda)$, $\beta_{NO_2}(\lambda)$, and $\beta_a(\lambda)$ are, respectively, ozone, nitrogen dioxide, and aerosol extinction coefficients at λ . At the 1.0- μm wavelength, β_{λ} is composed solely of Rayleigh and aerosol contributions. Thus, aerosol extinction properties at a wavelength of 1.0 μm can be retrieved independently from satellite measurements at 1.0 μm taken together with appropriate meteorological data. Intensity measurements in the four SAGE channels are inverted to give profiles of aerosol extinction (as well as profiles for extinction due to ozone and nitrogen dioxide absorption and total molecular scattering). The aerosol

profiles have a vertical resolution of about 1 km and an accuracy, near the peak of the stratospheric aerosol layer, of about 10 percent. Details of the inversion technique used are given in reference 5.

ORBITAL CONSIDERATIONS

Measurement opportunities for satellite solar extinction techniques are limited by the satellite orbit and Earth-Sun geometry. For typical satellite orbital periods of approximately 100 minutes, there are 30 measurement events (sunrises and sunsets) per day (about 11 000 per year).

The latitudinal coverages of the SAGE measurements are illustrated in figure 2 for the first 4 months after launch. Successive sunrises or sunsets are separated by about 24° in longitude and up to about 0.4° in latitude. The latitudinal

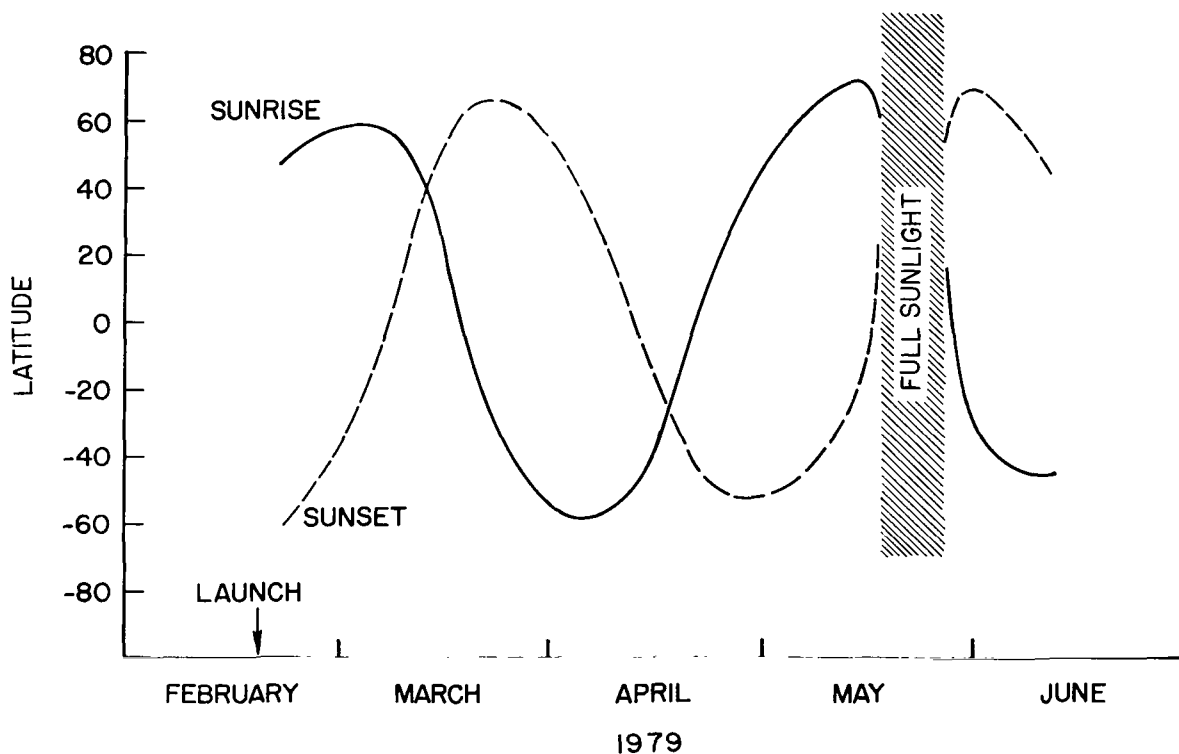


Figure 2.- Latitudes sampled by SAGE during first 3 months after launch. Both sunrise and sunset coverage are shown as well as a short period (crosshatched) where the satellite is fully sunlit and no measurements are possible.

separation of successive events depends on the particular latitude of measurement. This can be seen in figure 2 where the largest latitudinal movement is about 6° or 7° per day near the equator. A distance of only about 1° or 2° is covered per day at the highest measurement latitudes. The crosshatched area in figure 2 is a brief period when the satellite is in full sunlight and no satellite sunrises or sunsets are experienced. This happens about four times per year. The AEM-B satellite is in

a non-Sun-synchronous orbit with an inclination of 55° . This highly precessing orbit can cover 120° of latitude every 2 to 3 weeks with a total coverage over the year from about 72° S to 72° N. Figure 3 gives an idea of the geographic coverage of SAGE for 1 month. The predicted zero-altitude tangent points of the sunrise and sunset events during February 1979 are shown. For non-Sun-synchronous orbits, like the one

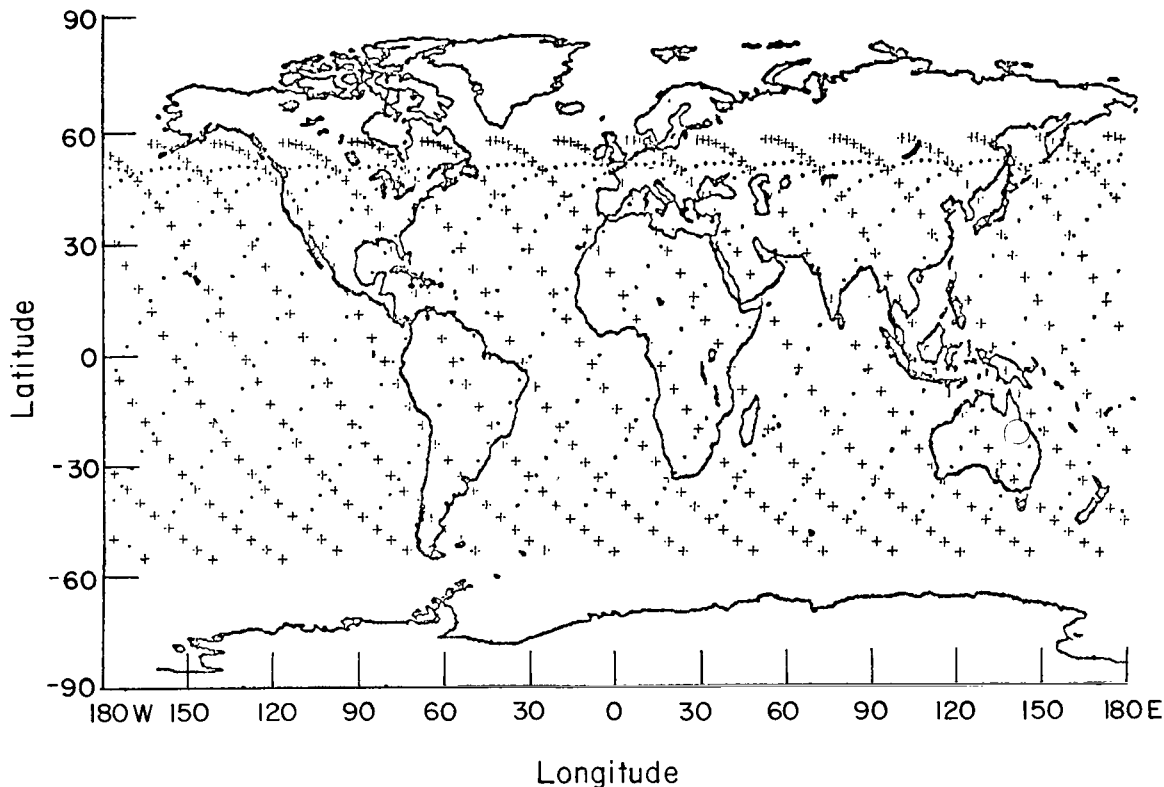


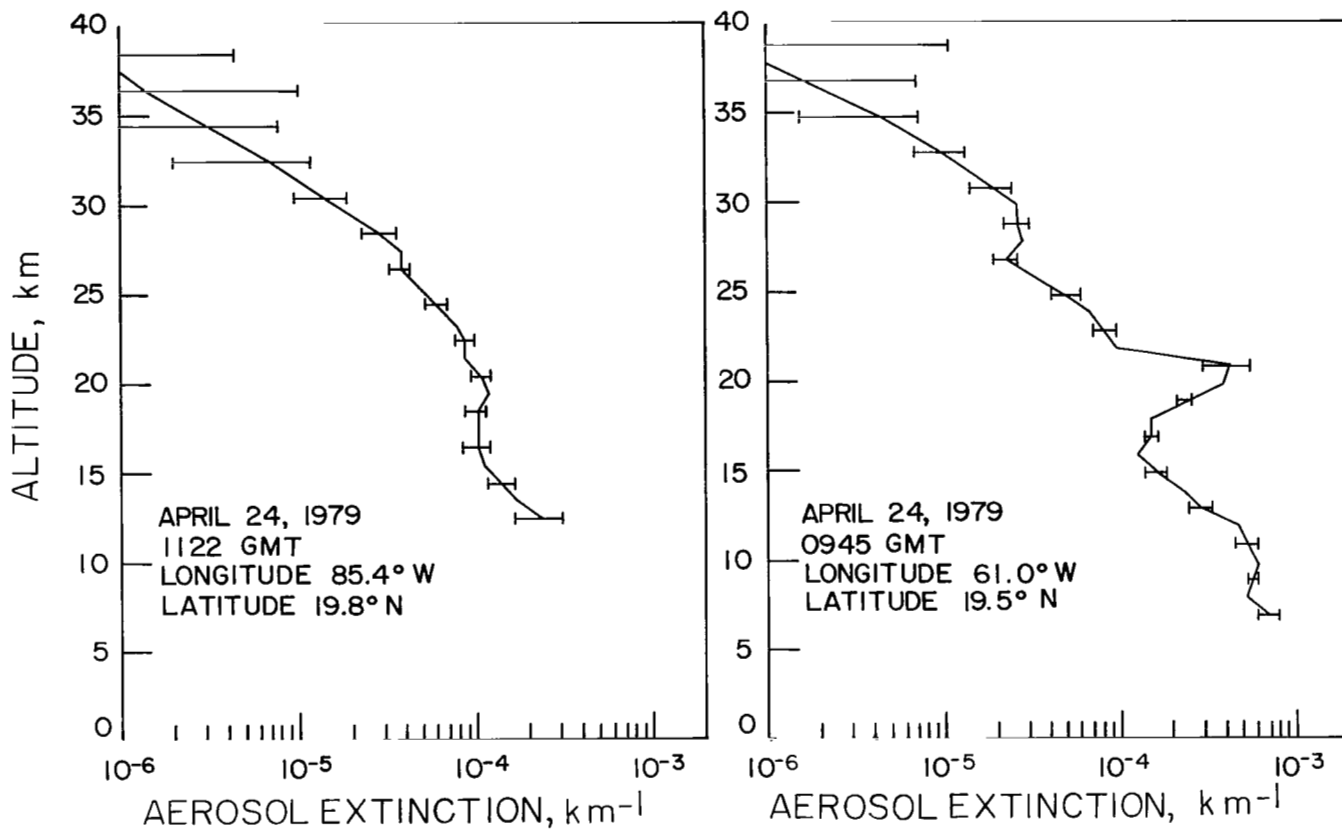
Figure 3.- The zero-altitude latitude and longitude for each sunrise (•) and sunset (+) measurement profile made by SAGE during a typical month (February 1979).

SAGE is in, the total latitudinal coverage is inversely proportional to the frequency of repeating latitude. Thus it is important to consider the trade-off between total latitudinal coverage and the frequency of repeating latitude cycles or, therefore, the number of profiles obtained in any given latitude band over a given period of time. The details of tailoring orbits for occultation measurements, as was done for the SAGE, are given in reference 6.

OBSERVATIONS

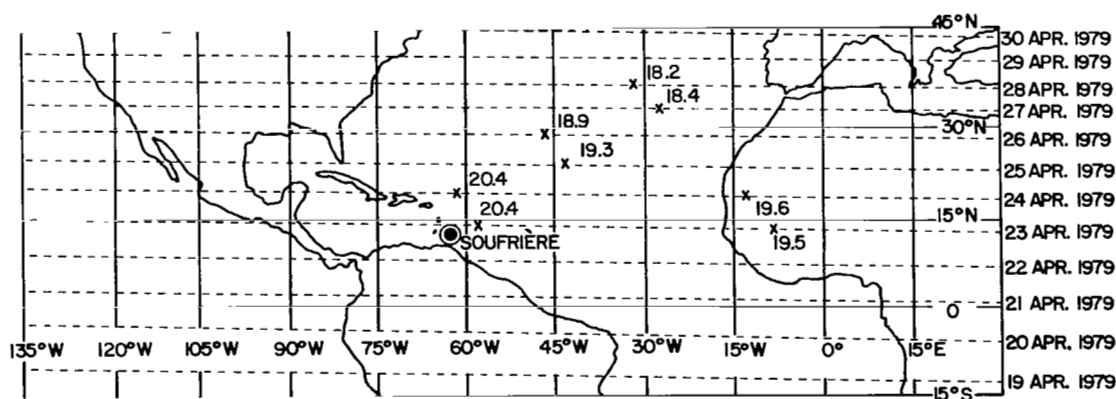
Figure 4(a) gives an example of an aerosol extinction profile. This profile was observed by SAGE on April 24, 1979, and is typical of background aerosol conditions. No enhancement over background due to a high-altitude plume is present, and the extinction decreases fairly slowly with altitude between about 12 km and 22 km. Figure 4(b) shows the profile obtained on the same day when SAGE was close to St. Vincent. The profile has a maximum which is approximately four times greater than normal at an altitude of about 20.5 km. Such enhanced values were observed on

at least eight occasions after the Soufrière eruptions in April. Figure 4(c) shows the locations of these events. The events shown in this figure have been restricted



(a) Normal aerosol extinction profile as determined by SAGE satellite system.

(b) Enhanced aerosol profile observed on April 24, 1979.



(c) Locations of enhanced aerosol extinction (50 percent or more above normal) are marked by crosses. Altitude of each layer peak is shown in km. Latitudes for each day of SAGE measurements are shown by dashed lines.

Figure 4.- SAGE measurements shortly after the April 1979 eruptions of Soufrière.

to occurrences on which the enhancement was 50 percent or more above the normal value at that height and latitude, and with a peak at least 2 km above the tropopause. The latter restriction has been included to eliminate records with a possible contamination from tropospheric high-altitude water or ice clouds.

Two groups of events are seen, one over West Africa and the other over the Atlantic Ocean. These two groups are believed to be related to separate volcanic eruptions, and their interpretation is discussed in more detail in the next section. The plume which moved northeast over the Atlantic Ocean gradually descended. This is shown in more detail in figure 5, where both the layer and the tropopause height descend in a similar manner as latitude increases.

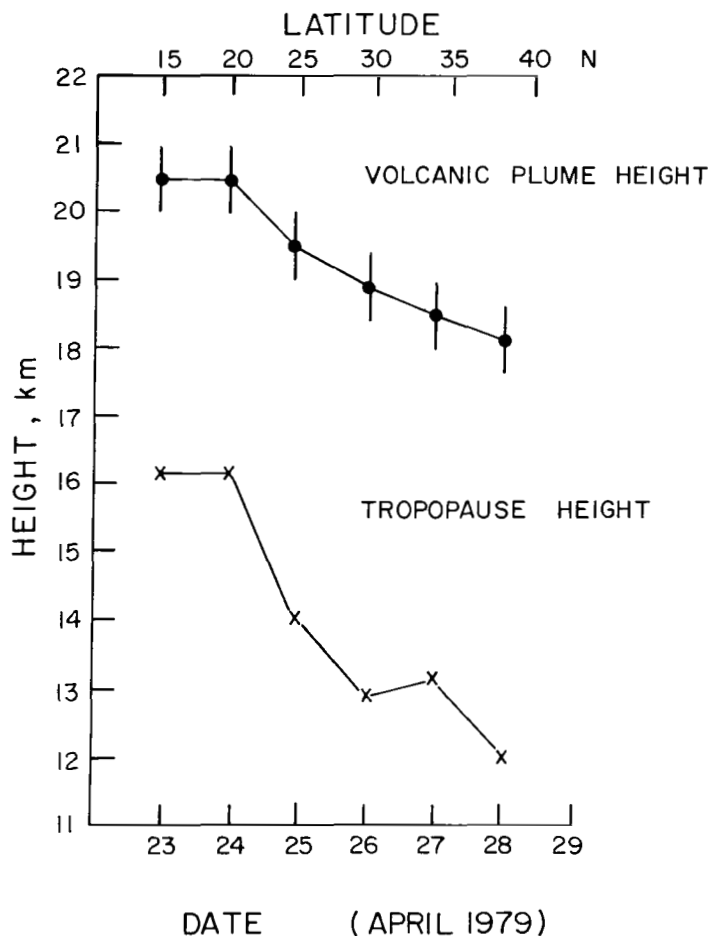


Figure 5.- Variation in height of the volcanic plume as it moved northwards over the Atlantic Ocean and of the corresponding tropopause for those locations.

In figure 6(a), the SAGE data have been redrawn in a slightly different form with the tropopause plus 2 km restriction removed. Shading is used to indicate the various plumes and their altitudes. All information for heights down to 18 km has been included. At the lower latitudes, the tropopause was occasionally above 17 km.

Nevertheless, both areas of high extinction now show extensions at low altitudes toward the south. These extensions are probably associated with the volcanic emissions and not cirrus clouds.

Figure 6(b) shows the flight path over the Caribbean for the airborne lidar system and the altitudes from which enhanced backscatter was obtained. These data show that during the 24-hour period between eruption on April 17 and the flight commencing on April 18, the stratospheric volcanic plume moved in a generally southerly direction and there was strong shearing between the movement at different altitudes. The arrows in the figure are the expected plume movements at different altitudes, based on local rawinsonde data. These data are discussed subsequently.

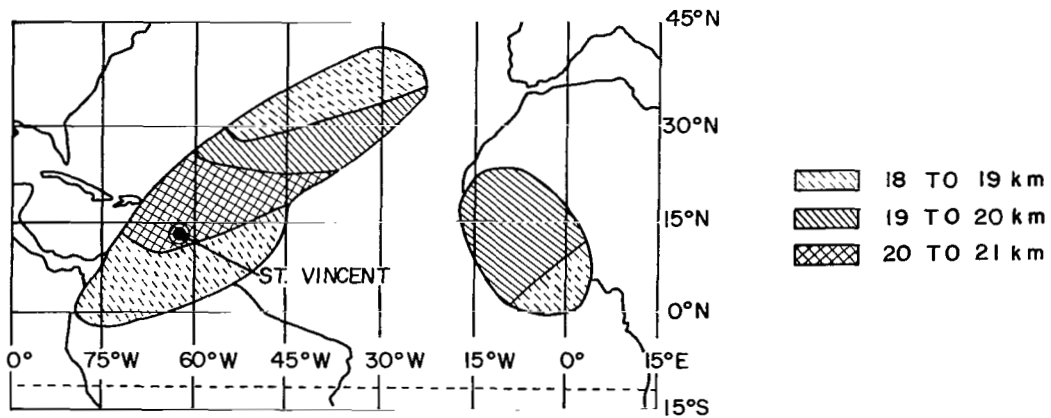
INTERPRETATION OF DISPERSION

In order to estimate the mass and dispersion of material injected into the stratosphere, the SAGE and lidar observations must first be related to the individual volcanic eruptions. The interpretation of the SAGE data in terms of the individual explosions is not immediately obvious. In order to analyze movements of the stratospheric plumes in detail, it is desirable to have as much high-altitude meteorological information as possible from the vicinity of the volcano and along the plume trajectory. Unfortunately, in this case, the observed trajectories lie over the Atlantic Ocean, where there are no meteorological stations. A large-scale analysis, therefore, would seem to offer the best hope for calculating the possible plume movements. Global maps of temperature and geopotential height for this time period were obtained from the National Oceanic and Atmospheric Administration (NOAA). These maps were based on a combination of satellite and rawinsonde observations (ref. 7). Use has also been made of high-altitude wind data (rawinsonde) from Barbados (150 km east of St. Vincent) and Trinidad (250 km south of St. Vincent).

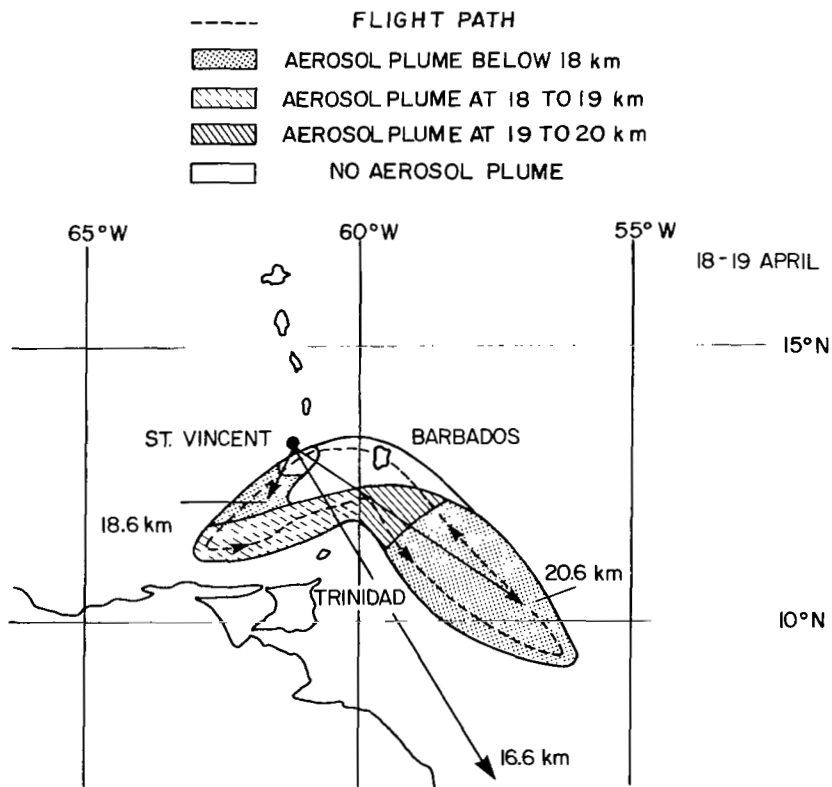
The high-altitude winds in the vicinity of the volcano generally show the following main features:

1. A strong zonal component, along with a weak and somewhat erratic meridional component.
2. A reversal in the zonal component at a height of 19 to 20 km. The wind direction above this height is toward the West and below it toward the East.
3. A fairly rapid increase in wind speed with increasing latitude. The profile and height of the zonal wind reversal remain similar.

Trajectories for the material injected into the stratosphere by the explosions of April 13 and 17 have been calculated. These calculations were made using winds devised geostrophically from the NOAA geopotential height maps. They were based on the assumption that the injected material remains on the 70-mbar surface (1 mbar = 100 Pa). These trajectories indicate that the material from the explosion of April 13 moved eastward across the Atlantic Ocean and reached the coast of Africa



(a) Map showing areas and altitudes of enhanced extinction (50 percent or more above normal) as observed by SAGE between April 21 and 28, 1979.



(b) Airborne lidar observations in the vicinity of St. Vincent, April 18 and 19, 1979. Also shown are the calculated air movements at three pressure levels during the interval between the eruption at 2057 GMT on April 17, 1979, and the time of the flight.

Figure 6.- SAGE and lidar measurements of Soufrière plumes.

about April 20. The material from the explosion of April 17 commenced moving in an eastward direction but then turned north after it reached longitude 42° W. Both trajectories agree qualitatively with the position of the plumes over West Africa and over the Atlantic Ocean as determined by SAGE, but the trajectory analysis predicts the material arrives at these locations too early. Moreover, the trajectory for the explosion of April 17 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 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 detailed comparison was made of winds derived geostrophically from the NOAA maps with the measured values from two groups of Caribbean meteorological stations. The results of this analysis indicate that acceptable agreement was obtained for stations between 16° and 19° N, but for stations between 10° and 13° N, the geostrophic wind exceeded the true wind speed by roughly a factor of two.

A somewhat simpler analysis, based on data from the local Caribbean rawinsonde stations, may be used in attempting to identify the origins of the two plumes. It is clear, from consideration of the velocity required, that the plume seen over West Africa on April 23 and 24 cannot be associated with the explosion of April 22. It could, however, originate with either of the explosions of April 13 and 14 (considered as a single event), or 17. In the former case, an eastward velocity of 7.4 m/s would be required; in the latter, an eastward velocity of 12.1 m/s. The relative plausibility of these two values may be examined in terms of data from Caribbean stations. Table II lists the observed mean wind velocities for the period between April 15 and 24, 1979, and table III lists the required eastward velocity

TABLE II.- CARIBBEAN MEAN WIND VELOCITIES (APRIL 15 TO 24)

Station	Latitude	Altitude, km	Eastward velocity, m/s
Barbados and Trinidad (average)	12° N	18.6	3.5
		20.7	3.9
San Juan	18.5° N	18.6	7.8
		20.7	-2.0

TABLE III.- PARAMETERS OF STRATOSPHERIC CLOUD OVER WEST AFRICA

Height, km	19.5
Mean latitude (average of measurements on April 23 and 24)	16° N
Required eastward velocity if originating on April 13 or 14, m/s	7.4
Required eastward velocity if originating on April 17, m/s	12.1

for transport to Africa by April 23. Wind data are shown in table II for the 50- and 70-mbar levels (20.7 and 18.6 km) which bound the altitude of the West African

stratospheric cloud. Because the latitude of the cloud is no longer the same as that of St. Vincent, wind data for San Juan, Puerto Rico, have been added to those for Barbados and Trinidad. The strong latitudinal variation in the wind is clear and comparison of the values in table II with those in table III indicates that it is very unlikely that the cloud originated from the April 17 explosion. The hypothesis that it originated from the April 13 and 14 explosions is further substantiated by a detailed examination of the daily zonal wind behavior at Barbados and Trinidad. On April 15, 16, and 17, strong eastward winds (5 to 15 m/s) were observed at the 50- to 70-mbar level. On April 18, 19, and 20, the mean zonal wind was close to zero, preventing any systematic eastward drift of the cloud produced by the eruption of April 17. One further point may be noted. Figure 6(a) shows that, for the West African cloud, the lower altitude part of the cloud has moved farther, and, therefore, considerably faster, than the upper altitude part. This corresponds to the normally observed decrease of the eastward zonal wind with increasing altitude during this season in the lower stratosphere.

Although it has been deduced that the West African cloud originated at St. Vincent April 13 and 14, the problem of identifying the source of the other and larger cloud still remains. The SAGE events shown in figure 4(c) seem to indicate that the plume extending over the North Atlantic Ocean originated at the volcano on April 22, coincident with the final major explosion. This ignores the question of what happened to the cloud from the explosion of April 17, which produced the highest column of the series. Figure 6(b) shows the heights at which the airborne lidar system observed the aerosol cloud from this particular eruption. Also shown is the expected movement at three pressure levels based on the rawinsonde data from Barbados and Trinidad, during the interval between the eruption and the flight time (approximately 28 hours). Allowing for the fact that the meteorological information is available only at rather coarse time intervals, the agreement between the lidar observations and the predictions is good, both in terms of the mean movement and the shear between different levels. The southerly movement, particularly at the lower altitudes, is also shown in figure 6(a), where excess extinction at heights of 17 to 18 km was observed by SAGE well south of St. Vincent on April 21 and 22.

Figure 4(c) also shows that the North Atlantic plume originated near St. Vincent at a mean altitude of 20.4 km. In order to see if this could be related to the April 17 eruption, an analysis of the air movements at a pressure level of 50 mbar (20.7 km) has been carried out using rawinsonde data from Barbados and Trinidad. The starting point for the trajectory was 12° N 60° W at 0000 GMT on April 19, which is based on the lidar observations of the plume at this height, position, and time. Subsequent movements up to 1037 GMT on April 22, when the final major eruption occurred, are shown in figure 7. The total movement, then, from St. Vincent between April 17 and 22, is only a few degrees in longitude and latitude, placing it very close to the location of the SAGE observation of April 23. Furthermore, it is reasonable that the dispersion of the plume over this period would allow it to extend back to the volcano, thus overlapping any plume produced by the explosion of April 22. The SAGE observation of April 23, therefore, most likely pertains to the plume due to the eruption of April 17, but the proximity to the volcano and the prevailing winds make it impossible to rule out some contribution due to the eruption of April 22. Similar considerations apply to the observations made subsequently.

It appears that the clouds still in the vicinity of St. Vincent on April 22 and 23 commenced to move rapidly northeastward over the Atlantic Ocean. The explanation lies in the arrival of a new weather system into the area. During the period April 20 to 23, a strong low-pressure trough extended southward along the Atlantic

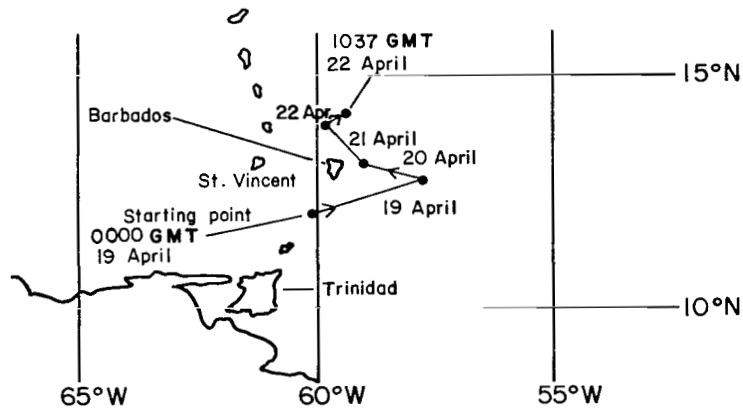


Figure 7.- Calculated wind trajectory at 50-mbar pressure level (20.7 km) for the period April 19 to 22, 1979. Starting point for trajectory is based on lidar data of April 18.

coast of the United States into the Caribbean. In conjunction with a high-pressure area centered east of the Caribbean, this produced a movement to the northeast, the beginning of which is apparent in figure 7. Subsequent to April 23, the low-pressure region moved slowly northeast across the Atlantic and finally abated on April 28. It seems clear that the plume was moved by this system, and figure 8 depicts the meteorological situation at 70 mbar on April 26 when the plume was observed at approx-

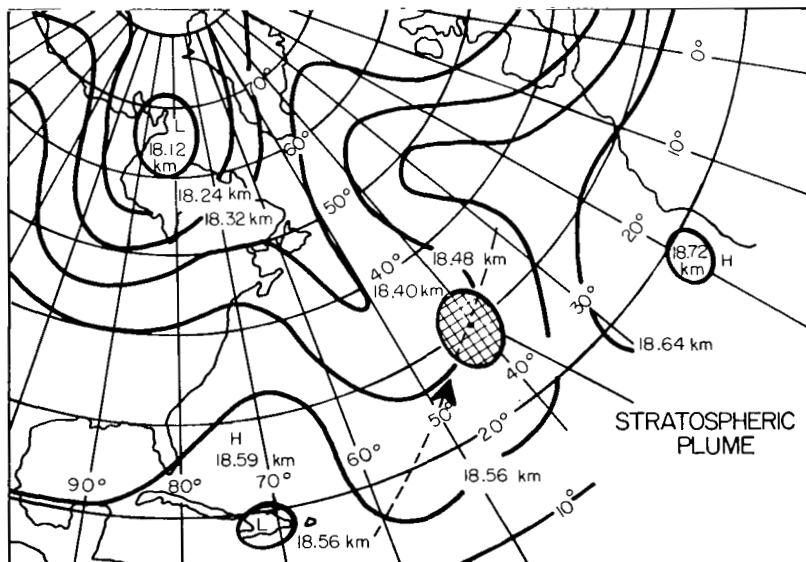


Figure 8.- High-altitude pressure map at 70-mbar level at 1200 GMT on April 26, 1979. Crosshatched area shows position of stratospheric plume on this day; dashed line indicates trajectory of plume on preceding and following days.

imately 30° N. The final date on which the plume was seen agrees with that on which the low-pressure region abated; the required speed of movement of about 8 m/s is typical for this altitude and latitude region.

Figure 4(c) indicates that the cloud extending northward over the Atlantic descended as it moved. This is in agreement with general deductions based on the 70-mbar temperature map for April 18 over this region. This map shows that air parcels traveling northward tended to warm up, a feature that remained true throughout the following week. This warming is almost certainly caused by adiabatic compression due to downward motion. Calculations have been carried out to determine the amount of descent expected, assuming that an air parcel follows an isentropic trajectory. These showed that a parcel at a height of 20 km and a latitude of 10° N would have been expected to descend between 1 and 2 km by the time it reached 40° N. This value is in agreement with the SAGE measurements given in figures 4(c) and 5.

In order to assess the observability of the volcanic clouds by SAGE, the dispersion (spreading) of the cloud as well as the motion of the center of mass must be estimated. In principle, the dispersion could be estimated from the details of the local wind field. However, the meteorological information was considered to be inadequate; it was therefore decided to estimate the dispersion climatologically. A procedure for calculating the dispersion of a cloud prior to its reaching the scale of the large-scale circulation has been described in reference 8. The horizontal half-width of the cloud is determined as a function of time. This is done by numerical integration based upon 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. It is estimated that after 5 days the cloud had a radius (to half-concentration) of roughly 1000 and 1400 km after 10 days. This may be compared with the observed size of the cloud when it reached 30° N, 9 days after the eruption of April 17 and 4 days after that of April 22. As may be seen in figure 6(a), the observed half-width was then about 900 km with an estimated standard error of 400 km. This value is in good agreement with the model values. However, use of the same analysis to arrive at a value for the growth of the cloud in the first few hours produces a radius of about 30 km, considerably smaller than the 150- to 200-km radius measured from an aircraft 2 hours after the eruption of April 17 (W. H. Hunt, private communication). The discrepancy here may be due to local atmospheric disturbance produced by the eruption itself.

MASS LOADING ANALYSIS

It is possible to use the map in figure 4(c), in conjunction with the actual extinction values, to provide an estimate of the total mass of new stratospheric aerosol created by these volcanic eruptions. Such an estimate is subject to some error, as the geographical sampling by SAGE is somewhat coarse and, in order to convert the extinction values into a mass loading, a model for the aerosol particle size distribution and composition must be employed. As far as the geographical extent of the plume is concerned, it has been 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).

An intermediate step in the calculation of the mass loading is the integrated extinction B_{aI} defined by the following equation:

$$B_{aI} = \sum_{\text{Plume}} A(\beta_{ah} - \beta_{anh}) \Delta h$$

where

- β_{ah} extinction due to aerosols at a height h in the plume
 β_{anh} normal background extinction due to aerosols at a height h
 Δh height interval (1 km in practice)
 A area of Earth's surface covered

The summation is carried out from the bottom to the top of the plume. The results of the calculations are shown in table IV, where the West African and Caribbean-North Atlantic plumes have been listed separately. Only the events of April 23 and 24 are

TABLE IV.- ATMOSPHERIC EXTINCTION AND STRATOSPHERIC AEROSOL MASS LOADING
 FROM SOUFRIÈRE, ST. VINCENT

	Area of Earth 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	$0.58 \pm 0.2 \times 10^3$
Caribbean-North Atlantic plume	7.7×10^6	2.1	18.8×10^2	$1.7 \pm 0.6 \times 10^3$
Total	10.8×10^6	1.9	25.1×10^2	$2.3 \pm 0.7 \times 10^3$
Background global value	5.1×10^8	Stratosphere (tropopause + 2 km upwards)	6.1×10^5	$5.5 \pm 1.1 \times 10^5$

included in the values shown for the integrated extinction and mass loading for the Caribbean-North Atlantic plumes. This is because it is thought that the remainder of this plume emerged from, and contains some of, the same material that was seen on these 2 days. The value shown for the layer thickness is the width of a rectangle whose area is equal to that under the layer peak and whose length is fitted to the layer peak. As might be expected, the integrated extinction for the Caribbean-North

Atlantic plume is greater than for the West African plume because the former contains the material injected into the stratosphere by the largest explosion of the series. Also shown in table IV are corresponding values for the entire global stratospheric aerosol, estimated from SAGE global data. These are obtained by integrating zonally averaged SAGE extinction profiles from a level 2 km above the tropopause up through the stratospheric aerosol layer. It can be seen that, on a global scale, the Soufriere event was small, contributing less than 0.5 percent to the total integrated extinction.

Conversion of these extinction values to mass loading values which are usable by a broader segment of the scientific community requires a conversion factor which should be derived from a knowledge of the aerosol composition and size distribution. A model recently employed 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 (ref. 9). This model was developed from the SAM II and SAGE ground-truth program and is representative of the background aerosol in the upper troposphere and stratosphere prior to the eruption of Mount St. Helens. 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 which were matched to stratospheric dustsonde measurements. These calculations yield a value for the extinction-to-mass ratio for the aerosol, at a wavelength of $1\ \mu\text{m}$ (the center wavelength for the primary SAGE aerosol spectral channel), that varies from 0.75 to $1.45 \times 10^3\ \text{m}^2/\text{kg}$. Taking a mean value of $1.1 \times 10^3\ \text{m}^2/\text{kg}$ in conjunction with the value for the integrated extinction in table IV yields the total global background aerosol mass loading of 5.5×10^5 metric tons. This is comparable with the value 5×10^5 metric tons given by Penndorf (ref. 10). Use of the same conversion factor with the Soufriere extinction values gives a stratospheric aerosol mass loading of 2.3×10^3 metric tons. Estimates of error in these figures for mass loading are given in table IV and amount to approximately ± 35 percent in the case of the volcanic aerosol and ± 20 percent for the background aerosol. These estimates are based on a consideration of the errors in the actual measurement of the extinction, in sampling, in the estimates of the area of the Earth's surface covered, and in the extinction-to-mass conversion ratio. In addition, a small error may arise due to uncertainty of the composition of the newly injected or formed aerosol, which may contain a certain amount of fine ash with a considerably higher refractive index (ref. 11). Table V shows estimates published by other workers for the mass of aerosol injected into the stratosphere by other recent volcanoes. The value shown for

TABLE V.- ESTIMATES OF AEROSOL MASS LOADING FOR OTHER VOLCANOES

Date	Volcano	Aerosol injected into stratosphere, metric tons	Reference
March 1963	Agung	30×10^6	11, 12
October 1974	Fuego	6×10^6 3×10^6	11, 12 13
January 1976	St. Augustine	0.6×10^6	12

Agung includes fine ash as well as sulfuric acid, and the higher value for Fuego, as well as that given for St. Augustine, was obtained by scaling from the Agung eruption. The lower value for Fuego is based on an estimate of the stratospheric sulfate, 6 months after the eruption, which has been interpolated back to the time of the eruption. All the estimates must be regarded with caution as being subject to considerable inaccuracy. Despite this, the much smaller scale of the Soufrière eruption is not likely to be significant in error. It is not expected, therefore, that Soufrière will induce any significant temperature perturbations, in either the stratosphere or at the Earth's surface, or represent a climate perturbation (ref. 2).

CONCLUSIONS

This study represents the results of the first opportunity of the Stratospheric Aerosol and Gas Experiment (SAGE) satellite system to study the stratospheric effects of a significant volcanic eruption. Based on the analysis of data obtained shortly after the eruption of the Soufrière volcano on the Caribbean Island of St. Vincent, the following conclusions can be drawn:

1. The SAGE system is able 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.

2. The SAGE data may be integrated with data from other sources, e.g., lidar, and with meteorological information to provide a consistent history of the movement of a stratospheric plume.

3. The separate explosions of the Soufrière volcano produced two major stratospheric plumes. The observed movements of these plumes correspond well with those expected on the basis of the available meteorological data, and their dispersion after a few days agrees with the predictions of a climatological model.

4. The mass of material injected into or formed in the stratosphere by the Soufrière eruptions was relatively insignificant on a global scale and was two or more orders of magnitude less than estimates of the mass injected by other recent volcanic eruptions. No significant climate effect is expected to have been produced by this eruption.

SAGE has continued to make observations of the stratospheric aerosol and has detected to date the effects of at least two other volcanic eruptions, Sierra Negra in the Galápagos Islands and Mount St. Helens in Washington state, both of which produced much more significant stratospheric perturbations. The analysis of these data will form the subject of future publications.

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