be translated into altitude and the maximum height of the volcanic eruption can then be estimated. This is an important value because the maximum height to which the cloud from an explosive eruption rises is related to (i) the rate at which pyroclastic material is produced and (ii) its thermal power output (*1*).

Satellite observations of an explosive volcanic eruption can be analyzed in the same manner as those of thunderstorms and other convective systems (*2*). Frequently an infrared-enhancement procedure based on a sequence of gray shades (including white and black) is used to emphasize certain ranges of temperature. Figure 1 is an example of this procedure for the 14 April 1979 eruption at 1150 LCT (*3*). The upper series of panels shows hourly infrared images; the lower series shows the corresponding enhanced infrared images. The nearest radiosonde observation was from Guadeloupe; its temperatures indicate that the whitest area represents a growth of the eruption to heights above 14 km. This technique indicated that all the eruptions except the first two extended above this level.

Computer analysis of some of the infrared imagery of the eruptions of 14 April (1150 LCT), 17 April, and 22 April revealed temperatures as low as −80°C. Such temperatures indicate that these ash clouds extended above 18 km and consequently penetrated into the stratosphere. Unfortunately, operational requirements prevented the National Earth Satellite Service from processing images from all the other eruptions.

As these ash clouds grew upward, they extended downstream in long plumes from St. Vincent, usually toward the east or southeast. Growth to altitudes above 14 km generally took place within 1 hour, but the horizontal expansion of the canopy continued for several hours longer. However, considerable variation was seen in the horizontal growth of these eight eruptions, and these differences also reflect the intensities of the individual eruptions.

Figure 2 shows the growth rate for each of the eight eruptions seen by the SMS-1 satellite. Eruptions 1 and 8 appear to have grown at the slowest rate and apparently were the least intense. Eruptions 3, 5, and 6 had the most rapid growth rates, and their ash clouds covered the greatest areas. Usually this horizontal expansion took place in about 4 or 5 hours. The 17 April eruption (eruption 6) is of particular interest because it appears to have been the most intense (*4*). Figure 2 indicates that this eruption resulted in the largest ash cloud, which covered an area of 96,000 km^2 after 4 hours of growth.

After about 4 or 5 hours of horizontal expansion, the ash cloud usually begins to thin out and becomes partially transparent to the infrared radiation originating from lower and warmer altitudes. The infrared temperatures are then unrepresentative because they are no longer characteristic of the ash cloud itself. As the thinning continues, the cloud becomes so diffuse that infrared cannot be used to track it.

These eight explosive Soufriere eruptions were seen very clearly with the infrared sensors aboard SMS-1. In general, explosive volcanic eruptions having columns extending upward at least into the middle troposphere can be observed with these sensors. But weaker eruptions extending only 1 or 2 km above the surface may not be apparent, and consequently three of the Soufriere eruptions could not be observed from the SMS-1. If no clouds are present, weaker eruptions may sometimes be revealed by the visible radiation sensors that are also aboard these satellites.

In light of the infrequency of volcanic eruptions in the Caribbean, it is remarkable that Soufriere experienced eight major explosive eruptions in a 2-week period, all of which could be observed by a geostationary satellite almost directly overhead. Erupting volcanoes have been photographed from satellites before, sometimes with higher resolution than that available from the SMS-1 system (*5*). However, analysis of the continuous time-lapse infrared imagery of the April 1979 Soufriere eruptions made it possible for the first time to trace the growth of a series of major eruptions and to compare their intensities.

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Meteorological Analysis of the Eruption of Soufriere in April 1979

Abstract. *Meteorological upper-air data, in conjunction with satellite imagery, lidar light detection and ranging returns, and aircraft sampling, aid in the determination of plume altitude and transport. The estimated trajectories indicate that the ash was transported eastward across the Atlantic to Africa in 3 to 5 days and that there was modest meridional transport as far as 15° poleward during the first week of travel.*

Volcanoes are of very great interest in atmospheric science because of the documented effects of large emissions on climate and because these emissions function as a natural tracer in the atmosphere. The tracking of volcanic debris has called attention to important properties of the atmospheric motion systems, and investigators have studied small- to medium-scale turbulent diffusion and global-scale transport rates, using volcano plumes as tracers.

The atmospheric plume from Soufriere, St. Vincent, was not an important climate modifier. The resulting data on plume rise, deformation, and movement, when used in conjunction with meteorological structure, can extend our knowledge of highly energetic buoyant plumes in a stable atmosphere. In this report we explore how conventional meteorological data can be used in interpreting plume motion and in supplementing the special-purpose analyses. Three upper-air-network stations are within 320 km of

Table 1. Power released in the Soufriere eruptions (*9*)

Date in April 1979, time (LCT)	Maximum cloud height (km)	Q (MW)
13, 0500	10	2.7×10^6
13, 1115	12	5.9×10^6
13, 1700	17	2.6×10^7
14, 0100	15	1.5×10^7
14, 1200	18	3.3×10^7
17, 1705	20	5.0×10^7
22, 0635	18	3.3×10^7
25, 2355	15	1.5×10^7

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St. Vincent: Guadeloupe to the north, Barbados to the east, and Trinidad to the south. Unfortunately, data from Barbados, the best situated station for studying the plumes, were unavailable during the eruption period. We have analyzed the Trinidad soundings for local structure and the possible effects of eruptions and have used the large-scale network to estimate trajectories across the Atlantic to Africa.

We chose a format of time-height cross sections for the local analysis because it offers a picture of the temporal continuity. Figure 1 shows the temperature cross section and the estimated locations of the stabilized plumes. A major feature of the cross section is the temperature minimum at the tropopause, consistently located at an altitude of about 17 km. Estimated stabilization altitudes for six separate eruptions are indicated by cross-hatching at the appropriate times on Fig. 1. Three of the weaker eruptions on 13 and 14 April were stabilized within the troposphere and two additional ones appear to have stabilized at the tropopause. The eruption of 17 April had sufficient buoyant energy to penetrate through the tropopause and into the lower stratosphere. The local stratospheric temperature minimum at 23 km that appears closely associated with the top of the plume on 17 April could be a final stabilizing influence on the cloud rise or a result of the eruption. Plume-rise profiles were derived from blackbody temperatures provided by La Porte and Krueger (*1*). The altitudes reflect the equilibrium between the satellite-observed temperatures and the existing atmospheric lapse rate at the eruption time. When plume temperatures were close to tropopause temperature values, the uppermost altitude for the given temperature was selected because this represents the stable lapse-rate region that is the most likely to suppress the convection. In addition, this value is in agreement with plume altitudes observed by lidar (light detection and ranging) (*2*).

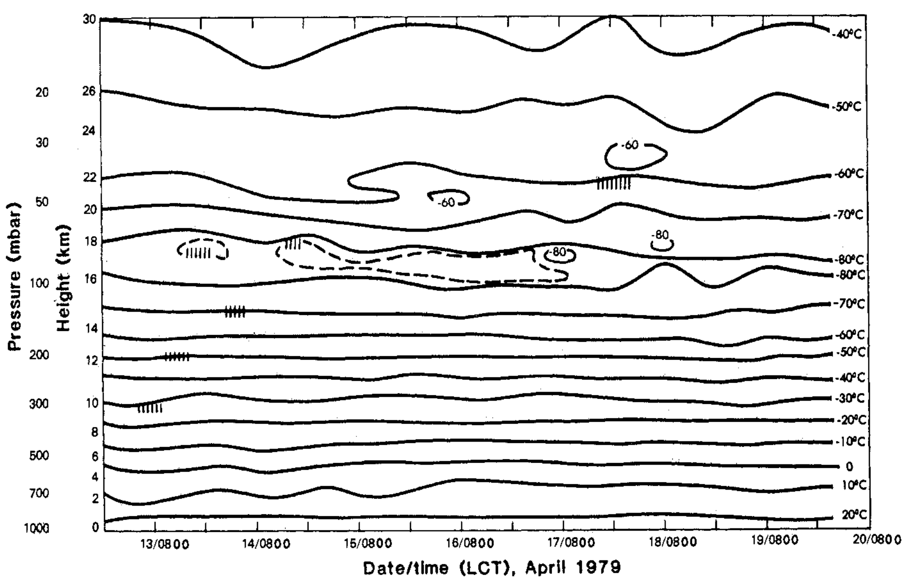

Fig. 1. Time-altitude cross section of temperature from Trinidad upper-air sounding. The estimated volcanic plume tops are shown as cross-hatched areas (*9*).

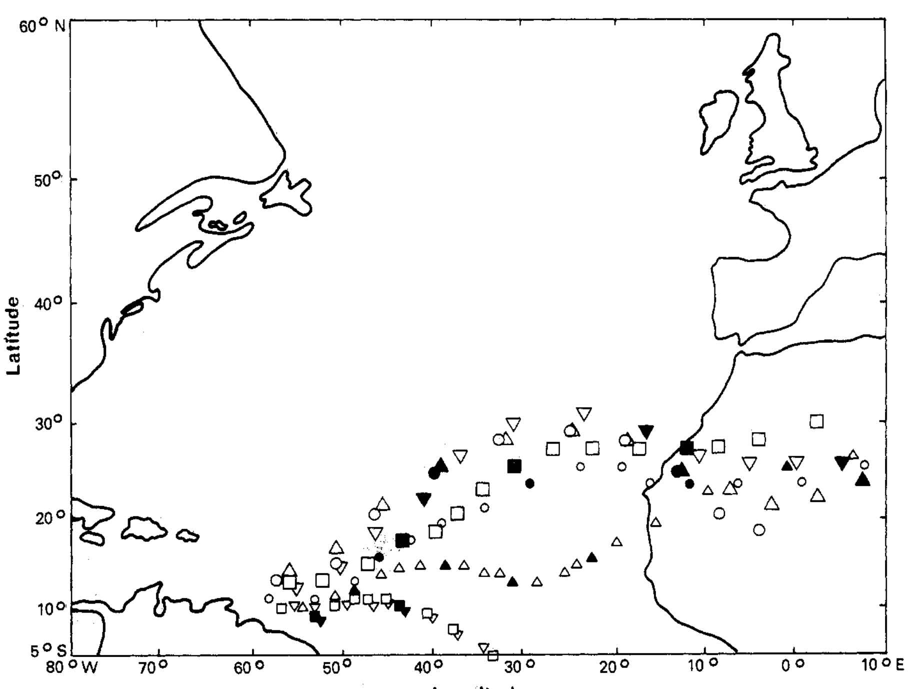

Fig 2. Isobaric trajectories at 100 and 300 mbar for 14 April 1979 (*9*): ○, initiated at 2000 LCT, 13 April; △, initiated at 0200 LCT, 14 April; ▽, initiated at 0800 LCT, 14 April; □, initiated at 1400 LCT, 14 April. Open symbols represent 6-hour positions; closed symbols are 24-hour positions. The large symbols represent the 100-mbar level.

Briggs (*3*) described a plume-rise formula developed for the description of small-scale buoyant plumes in calm conditions that is valid over five orders of magnitude. He applied it successfully to estimate the energy release of Surtsey Volcano. Friedman *et al.* (*4*) applied a similar formula for the rise of bent-over plumes where horizontal winds exceed the convective vertical velocity. Examination of satellite photographs of Soufriere eruptions suggest that the vertical plume formula is generally appropriate. We estimate the initial power released in the eruption from the formula

$$F = 0.0006\ (\Delta h)^4 S^{3/2}$$

where F is the initial buoyancy flux, Δh is the plume stabilization height, and S (the square of the Brunt-Vaisala frequency) characterizes the atmospheric stability. The rate of energy release is related to the buoyancy flux through the formula

$$Q = 0.11\ F$$

where Q has the units megawatts and F has the units meters to the fourth power per seconds to the third power. These equations assume a continuous heat source, but the results are very consistent with a set of estimates based on instantaneous sources presented by Morton *et al.* (*5*). One can estimate the total energy release from Q by multiplying by the duration of the eruption. Table

1 estimates the energy release for eight eruptions of Soufriere in April 1979 documented by satellite infrared coverage. The thermal power, 10^6 to 10^8 MW, of these eruptions is considerably larger than the 10 to 100 MW of Sakura-zima reported by Friedman *et al.* (*4*) and somewhat larger than the thermal power of Surtsey, reported by Briggs (*3*) to be 10^5 MW. Only the eruption of 17 April appears to have penetrated the stratosphere. On the basis of these observations, we can suggest that at equatorial latitudes a thermal power greater than 10^7 to 10^8 MW is necessary in order that there be a stratospheric injection of volcanic emissions. These estimates must be considered tentative since we have neglected the role of latent heat.

The sequential satellite photographs allow us to estimate the winds near an altitude where plume material can be identified by tracking the movement of the cloud with time. Nine estimates of wind velocity were obtained in this way for altitudes varying from 1 to 20 km. These estimated wind vectors agree quite closely with the Trinidad radiosonde winds. Direction differences are less than 10°, and speed differences are generally less than 5 m sec^{-1}. Virtually all the major volcanic debris moved in the band of westerlies at an altitude between 4 and 20 km. Material apparently did not reach the easterly flow above 20 km, and the particulates in the low-level easterly trade winds did not reside in the atmosphere long enough to reflect any significant motion toward the west.

In addition to the plume rise and initial movement of debris, the meteorological trajectories over several days are very important for the prediction and assessment of plume effects and the interpretation of downwind ground-based observations. Trajectories were prepared for starting times every 6 hours over the 2-week period of eruptions, using methods described by Heffter (*6*). Figure 2 shows examples of isobaric trajectories for two pressure levels in the upper troposphere initiated during the eruption activity of 14 April. Most of the calculated trajectories during the 2-week period pass over the west coast of Africa at latitudes of 15°N to 25°N. The travel time to Africa is in the range of 3 to 5 days, and the average zonal wind speed is 12 to 20 m sec^{-1}. Global circumnavigation would take 22 to 36 days at that average velocity. Kent and Philip (*7*) observed particulate material at an altitude of about 16 km by lidar at Kingston, Jamaica, 2.5 weeks after the eruption sequence. They interpreted the anomalous lidar scattering as volcanic ash carried eastward in the upper troposphere from St. Vincent to Jamaica.

The transport time observed by Kent and Philip is slightly smaller than the extrapolation from the trans-Atlantic trajectories. The difference may be due to temporal or spatial changes in zonal wind speed, or it may be that Kent and Philip observed the leading edge of material carried at an altitude of strong zonal flow. Long-range diffusion estimates and observations discussed, for example, by Gifford (*8*) suggest cloud diameters on the order of 10^3 km after 2.5 weeks of travel. This is equivalent to a plume passage time of about 12 hours at 25 m sec^{-1}. This amount of lateral growth would reduce aerosol loading by 10^3 to 10^4 from early (1 hour) values. Kent and Philip also noted an apparent reduction in aerosol loading during the passage because of dispersion and scavenging. They stressed that they did not observe the lower stratospheric material.

One additional set of trajectories is of interest. The 300-mbar tracks on 26 April go southward over Trinidad, then make a clockwise loop, and move eastward across the Atlantic. Ash fall was observed at Trinidad after this eruption. This observation tends to support the meteorological trajectories.

One can estimate meridional movement from the trajectories by noting the meridional limits of a series of tracks. We analyzed the full set of trajectories for the 16-day period surrounding the eruptions for the limits of northward and southward excursions. The tropospheric trajectories at 300 mbar tend to remain in the original latitude band, although a slight equatorward transport is seen. At 100 mbar, near the tropopause, there is evidence of more vigorous transport to latitudes as far as 30°N. The fact that Kent and Philip (*7*) did not observe stratospheric dust on the first circumnavigation could be explained if the plume at that altitude passed well north or south of their lidar site.

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Skirt Clouds Associated with the Soufriere Eruption of 17 April 1979

Abstract. *A fortuitous and dramatic photograph of the Soufriere eruption column of 17 April 1979 displays a series of highly structured skirt clouds. The gentle distortion of thin, quasi-horizontal layers of moist air has been documented in meteorological situations. It is proposed that at St. Vincent subhorizontal layers of moist air were intensely deformed by the rapidly rising eruption column and were carried to higher altitudes, where they condensed to form the skirt clouds.*

At the time of the powerful explosion of Soufriere Volcano on 17 April 1979 at 1657 LCT (*1*), photographs were taken by K. Rowley from a small aircraft about 5 km from the volcano (see cover). There have been and will be many opinions offered on the mechanisms that created this impressive cloud structure. I present here one set of explanations based on discussions with several scientists of different disciplines whose curiosities were piqued by this unusual photograph.

Among the more interesting features of skirt clouds are (i) their nearly vertical orientation, (ii) the dramatic outline and the thin zone of cloud material, and (iii) the occurrence of several skirts at different altitudes. Scorer (*2*) has described skirt clouds associated with ordinary cumulonimbus convection. Smooth pileus

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