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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clouds are a common occurrence near the top of a convective shaft when an existing shallow layer of moist but unsaturated air is lifted to the condensation level by convective vertical motion. If the convection is sufficiently vigorous, it can penetrate the layered pileus before it has lost its identifying character, and the stratified cloud layer will remain as a skirt cloud around the convective tower. Many pileus cloud occurrences last for only a few minutes, and the turbulent velocity fields around convective towers often distort the stratified layer so that only a fragment of the skirt may be discernible. Moreover, meteorologically induced vertical velocities seldom exceed 1 m sec^{-1}. Such a small vertical velocity will not distort a skirt cloud very far from the horizontal, whereas the vigorous (50 m sec^{-1}) ascent (*3*) associated with the 17 April eruption column apparently had the capacity for extreme distortion. Skirt clouds similar to those in the cover photograph have been observed during atmospheric tests of nuclear weapons (Fig. 1).

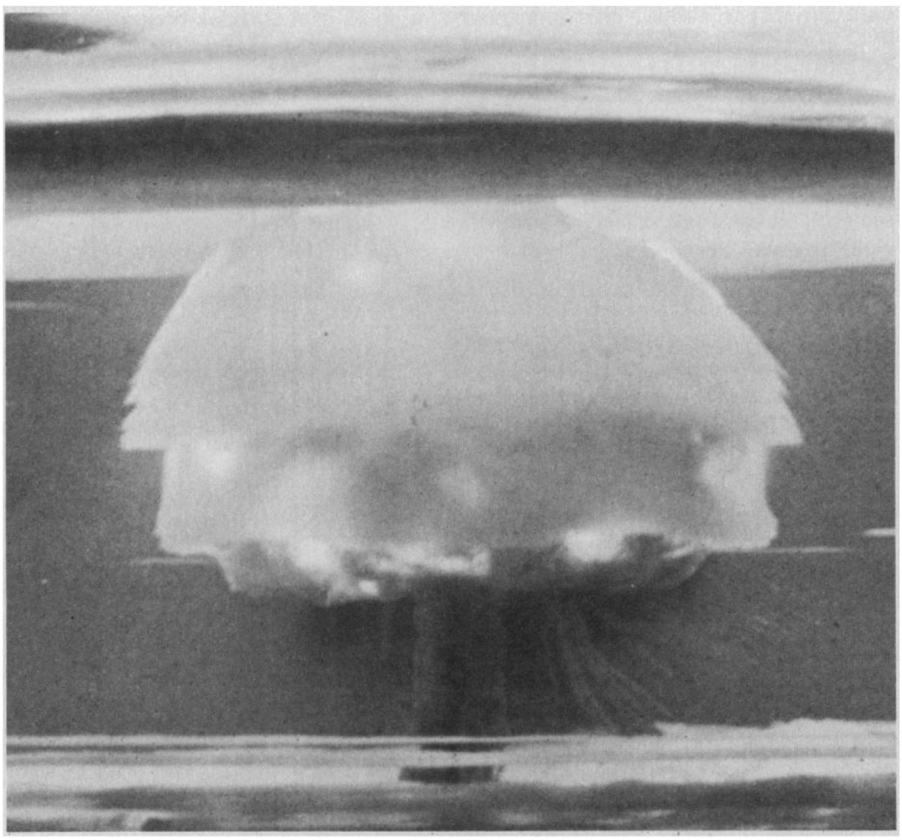
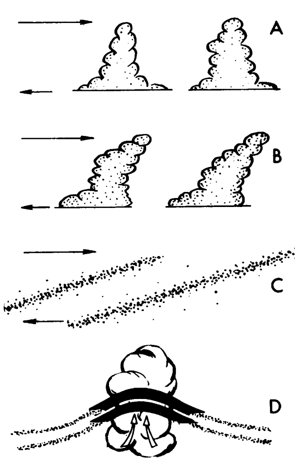


Fig. 1. Skirt clouds associated with a nuclear detonation in the South Pacific.

Distinct outlines are characteristic of cloud formation stages before turbulent diffusion has a chance to "smear" the boundaries. A thin skirt merely suggests that it was created from a thin moist layer. The presence of thin layers of moist air oriented quasi-horizontally, sometimes at several elevations separated by dry air, has been explained by Scorer (*2*).

A distribution of cumulus clouds will create a series of moisture-saturated columns, as sketched in Fig. 2A. If the clouds exist in a region of wind shear, as in the trade wind belt around St. Vincent, the moist columns will be distorted into quasi-horizontal narrow bands (Fig. 2, B and C). Eventually the cloud droplets will evaporate, leaving stratified, but invisible, layers of high and low humidity. When a powerful convective column, such as that produced by a volcanic explosion, penetrates the stratified region, the moist layers are dragged upward (Fig. 2D). At the appropriate condensation level for a given moist layer, visible cloud material will form, with a sharp demarcation from the saturated layer below; this process gives a distinct bottom to the skirt.

The Trinidad upper-air sounding obtained several hours after the 17 April explosion (Fig. 3) shows three moist layers in the lower portion of the sounding. There is, of course, no evidence to suggest that these same layers extended to the St. Vincent area, but their presence in Trinidad at about the same time suggests that similar layers could have been present in the region above Soufriere just before the 17 April eruption.



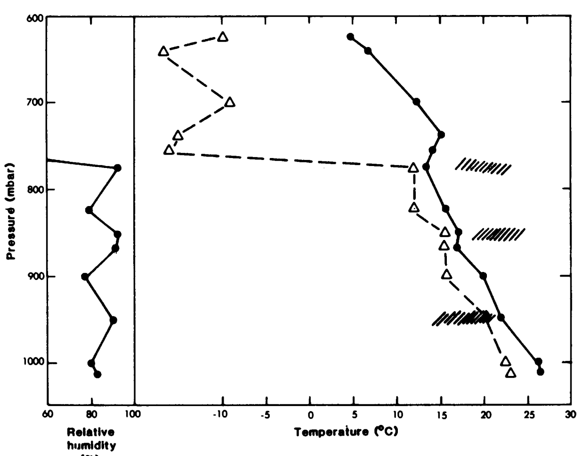


Fig. 2 (left). Suggested mechanism for the formation of skirt clouds: (A) the initial stage of cumulus clouds; (B) wind shear begins to deform these clouds; (C) continued shear and evaporation of cloud droplets forms invisible stratified layers (stippled pattern) of high- and low-humidity air; (D) violent upward motion of the eruption column deforms these layers and carries them upward to altitudes where they condense to form the skirt clouds. Fig. 3 (right). Upper-air temperature and humidity sounding at Trinidad, 2000 LCT, 17 April 1979. The dashed line is the dew-point temperature, and the solid line is the ambient temperature. Hatched areas mark thin layers where the relative humidity exceeds 90 percent.

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4. W. Clements, G. Heiken, E. Jones, R. Brownlee, and others at the Los Alamos National Laboratories provided stimulating discussion. I thank K. Rowley, formerly with the University of the West Indies (Trinidad), for supplying the photograph of the skirt clouds. I extend my appreciation and admiration to D. Richardson, who piloted the small aircraft from which the cover photograph was taken.

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