the stratosphere are of greater relevance to climatic studies than the properties of tropospheric material since some material can remain in the stratosphere for months to years, whereas material in the troposphere can be removed by rain in days (*11*). The reports that follow provide a reasonably complete definition of the radiative properties of volcanic aerosols in the stratosphere and will therefore permit an assessment of their impact on regional and global radiation budgets and hence on weather and climate. For example, both the absorption and scattering coefficients of the volcanic aerosols can be determined from the ACE measurements (*2*, *14*). Whether the aerosols cause an increase or decrease in the fraction of sunlight reflected back to space depends on their single scattering albedo (ratio of scattering to the sum of the scattering and absorption coefficients), the fraction of light scattered into the backward hemisphere, and the albedo of the underlying atmosphere and surface (*15*). The very high single scattering albedo of the Mount St. Helens stratospheric aerosols (*2*), in conjunction with the backscattering ratio inferred from their measured size distribution (*3*, *9*, *16*), implies that they caused the earth's albedo to increase and hence the fraction of absorbed sunlight to decrease (*17*).

Volcanic aerosols warm the layers of the atmosphere in which they reside by absorbing both incident sunlight and thermal radiation from the lower, warmer regions of the atmosphere, and they warm or cool the troposphere and surface depending on the competition between the decrease in the amount of sunlight reaching the tropopause and the increase in the amount of downward directed thermal radiation emitted by the lower stratosphere (*15*). The size of the stratospheric volcanic particles (> 0.2 μm), in conjunction with their high single scattering albedo and sulfuric acid and silicate composition, probably result in a dominance of the first of these factors; thus a cooling is to be expected (*17*). Much more complete analyses of these data will permit an assessment of the short- and long-term climatic effects of the eruptions of Mount St. Helens as well as an extension of these results to other volcanic episodes, such as the period from 1880 to 1915, when major volcanic events were frequent and the climate was colder than during subsequent volcanically quiescent times (*18*).

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14. The absorption coefficient is found from laboratory transmission measurements made by Ogren *et al.* (*2*) on collected samples, while the scattering coefficient is obtained by applying Mie scattering theory to the measured size distributions.
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Airborne Studies of the Emissions from the Volcanic Eruptions of Mount St. Helens

Abstract. *The concentrations of particles less than 10 micrometers in diameter in the ash emissions from Mount St. Helens have been more than 1000 times greater than those in the ambient air. Mass loadings of particles less than 2 micrometers in diameter were generally several hundred micrograms per cubic meter. In the ash clouds, produced by the large eruption on 18 May 1980, the concentrations of several trace gases generally were low. In other emissions, significant, but variable, concentrations of sulfur gases were measured. The 18 May eruption produced nuées ardentes, lightning flashes, and volcanic hail.*

Mount St. Helens, which is situated about 140 km south of Seattle in the Cascade Mountains of Washington State, ended its 123 years of dormancy on 20 March 1980 with a single small earthquake registering 4.1 on the Richter scale (*1*). Seismic activity increased steadily, becoming nearly continuous by 25 March.

The first eruption, which occurred at 2036 Universal Time (*2*) on 27 March 1980, ejected volcanic material to an altitude of 4.9 km (*3*). Airborne measurements and observations made from the University of Washington's research aircraft (*4*) began on 28 March when periodic (about every 5 to 10 minutes) eruptions of ash, and more frequent but shorter duration emissions of steam, reached up to 6.1 km (Fig. 1A). The size spectra of particles were measured in a cloud of ash 13 km downwind of the mountain (Fig. 2A). The number concentrations of particles with diameters between 1 and 10 μm in this cloud were up to 1000 times greater than in the ambient air, but particles < 1 μm in diameter were found in concentrations similar to those in the ambient air. The mass concentrations of particles < 2 μm in diameter in the ash cloud and in the ambient air were about 600 and 30 $\mu g\ m^{-3}$, respectively. Gaseous sulfur, almost entirely reduced sulfur, which we presume by its smell to be H_2S, was detected in concentrations of up to 240 ppb (*5*).

Between 28 March and 17 May, when the volcanic activity was quite variable, seven flights were made. The measurements on 2, 4, 8, and 11 April showed concentrations of total gaseous sulfur ranging from 15 to 38 ppb with quite variable contributions from H_2S and SO_2. However, on 8 May the total gaseous sulfur concentrations had returned to values similar to those measured on 28 March.

Early on 18 May, seismic activity

and visible emissions had virtually ceased when suddenly a major eruption occurred at 1532. A large portion of the north face of the mountain collapsed in avalanches and pyroclastic flows, devastating a wide area north and east of the mountain; this eruption caused the first recorded human deaths due to volcanic activity in the continental United States. The explosive eruption ejected material to an altitude of about 20 km, and ash was carried eastward over Washington, Idaho, and Montana within a few hours.

We started our airborne measurements in the vicinity of Mount St. Helens at ~ 1900 on 18 May. Violent emissions of ash were still continuing at this time (Fig. 1B), numerous nuées ardentes (glowing avalanches) were cascading down the sides of the mountain, and lightning flashes, presumably caused by charge separation during particle collisions in the very dense clouds of ash, were common. We attempted to obtain our first measurements at ~ 2000 at the edge of the dark ash plume ~ 37 km downwind and east of the volcano but were driven back as the aircraft was bombarded with clumps of loosely aggregated material (up to fist size) that disintegrated on hitting the plane; similar bombs, both dry and wet, were observed on the ground 12 km from the summit of Mount St. Helens within a few minutes of the eruption (*6*). We believe these bombs were formed by the rapid aggregation of ash particles in the plume; we propose they be termed volcanic hail (*7*).

We obtained measurements of particle size distribution at the periphery of the ash plume, ~ 9.3 km downwind at ~ 2010 (Fig. 2B). For particles 0.01 to 10 μm in diameter, the concentrations in the plume varied from a factor of 4 to over 1000 times those in the ambient air. For particles < 2 μm in diameter, the mass loading in the plume was ~ 95 μg m^{-3} compared to < 0.1 μg m^{-3} in the ambient air. Optical polarization and x-ray diffraction measurements showed that the particles consisted primarily of lithic rock fragments, largely plagioclases, with some apparently juvenile glasses.

The concentrations of sulfur gases measured at the periphery of the main ash cloud on 18 May were generally only slightly greater than those found in the ambient air; nitrogen oxides and ozone remained at or below ambient concentrations. It is possible that the small quantity of sulfur gas reflects absorption of reactive trace gases on the ash plume's very large total particle surface area. However, the ash samples we have analyzed showed generally small amounts of soluble materials such as sulfate, while samples from the stratosphere collected on U-2 flights showed the main cloud to steadily increase in acidity over a period of days, evidently indicating the presence of significant trace gas concentrations (*8*). Thus these observations may reflect temporal or even altitude variations.

In addition to the dark ash plume, smaller whitish-looking clouds of effluents were observed on 18 and 19 May along the edges of the main plume (Fig. 1C) (*9*). These clouds were small enough to be penetrated completely by our aircraft. Particle size distribution measured near the center of such a cloud (Fig. 2C) showed that for particles < 0.1 μm in diameter, the concentrations were similar to those in the ambient air, but the concentrations of particles from ~ 0.1 to 30 μm in diameter were up to 100 times greater than in the ambient air. The mass concentrations of particles < 2 μm in diameter in the whitish clouds and in the ambient air were ~ 30 and 5 μg m^{-3}, respectively. The concentration of total sulfur gases in these clouds, primarily SO_2, was at least 13 ppb, compared to ~ 6 ppb in the ambient air. Nitrogen oxides and ozone concentrations in the whitish clouds were similar to those in the ambient air.

Our final measurements on this flight were taken near the top of the main ash plume (~ 5.2 km downwind) late in the evening, when the volcanic activity was much less than earlier in the day. These measurements showed a high concentration of total sulfur gases (~ 1 ppm) that consisted primarily of H_2S.

The emissions of particles and gases from the volcano measured on our next flight, much later on 19 May, were considerably lower than on the previous flight, although they were still considerable. Particle size spectra were measured on the periphery of the main ash emissions (Fig. 2D), H_2S concentrations

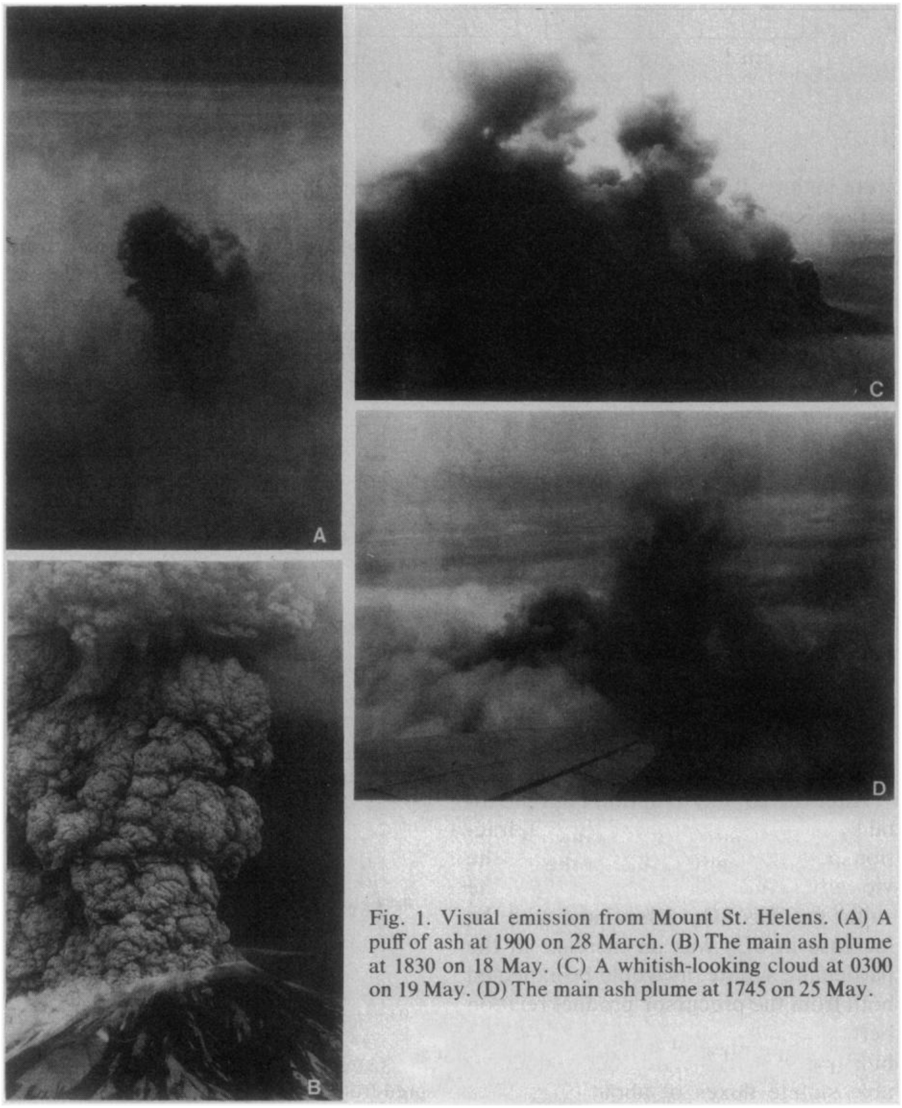

Fig. 1. Visual emission from Mount St. Helens. (A) A puff of ash at 1900 on 28 March. (B) The main ash plume at 1830 on 18 May. (C) A whitish-looking cloud at 0300 on 19 May. (D) The main ash plume at 1745 on 25 May.

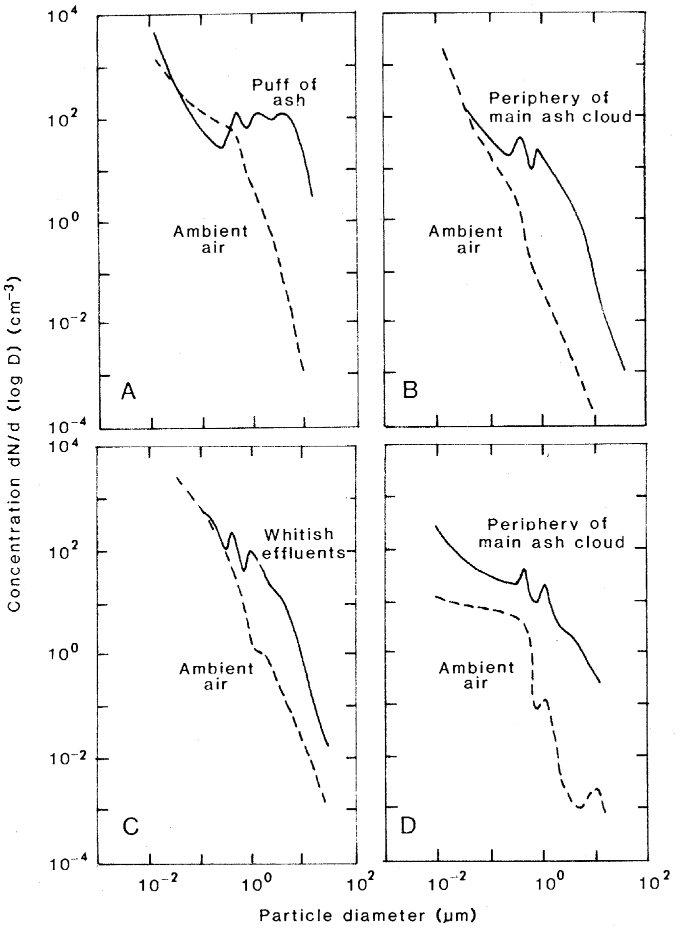

Fig. 2. Size spectra of small particles: (A) in a puff of ash at an altitude of 3 km and 13 km downwind of the volcano at 2239 on 28 March; (B) at the periphery of the dark ash cloud at an altitude of 3 km and 9.3 km downwind of the volcano at 2010 on 18 May; (C) near the middle of the whitish-looking clouds at an altitude of 3.2 km and 130 km downwind of the volcano at 0230 on 19 May; (D) at the periphery of the main ash cloud at an altitude of 2.7 km and 22 km downwind of the volcano at 2140 on 19 May.

were high (~ 0.5 ppm), but SO_2 concentrations were near ambient values.

Mount St. Helens exploded violently for the second time at 0932 on 25 May when ash was ejected to an altitude of 13.7 km (Fig. 1D). Particle size measurements obtained in the periphery of the main ash plume just after 1800 were similar to those obtained on 18 May. Unlike the 18 May measurements, we detected consistently high amounts of total sulfur gases, up to 110 ppb, with 13 to 95 ppb of H_2S and 3 to 6 ppb of inert sulfur-containing gases.

Measurements on 30 May and 4 June showed continuing gaseous emissions but much reduced ash emissions. A significant fraction of the smaller particles on these 2 days consisted of soluble material, with quantities of $SO_4^{=}$, Br^-, F^-, and Cl^-.

After the 25 May eruption both the total sulfur gas emissions and the SO_2 fraction increased dramatically, and after the violent eruption of 13 June most of the sulfur gas was SO_2. Associated with the increase in SO_2 was an increase in the particulate sulfate, as would be expected both from the precursor-product relation between SO_2 and SO_4^{2-} and the possibilities of direct injection of H_2SO_4. Soluble sulfate fluxes of about 25 g sec^{-1} were measured on both 4 and 18 June. During this period a significant fraction of the aerosol contained spherical fume particles and haloed particles that appear to have been impure H_2SO_4 droplets similar to those found at Augustine Volcano, Alaska, in January 1976 and April 1977 (*10*). On 18 June the hot outgassing plume generated a small cumulus cloud that capped the caldera. The cloud droplets were found to have a $pH \leq 1$.

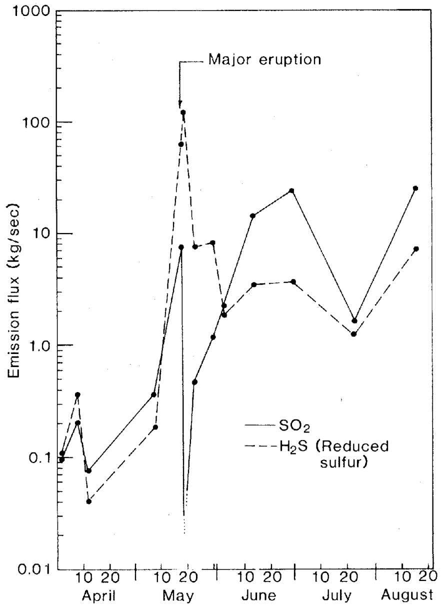

Fig. 3. Emission fluxes of SO_2 and H_2S measured from Mount St. Helens.

Elevated NO_2 concentrations were observed only on one occasion. On 13 June, after the third violent eruption sequence, concentrations approaching 400 ppb were observed at a range of 8 km, resulting in an estimated emission flux of 7 kg sec^{-1}.

The gaseous sulfur emissions summarized in Fig. 3 as total fluxes were deduced from multiple traverses of the plumes and simultaneous measurements of horizontal winds. The emission fluxes for 18 May, however, are based on more fragmentary data of plume volume and are, therefore, subject to large potential error. These fluxes are quite similar to those we measured from the Augustine Volcano during its eruptive phase in February 1976 (*9*).

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