Reports

Measurements of the Volcanic Plumes of Mount St. Helens in the Stratosphere and Troposphere: Introduction

The following reports describe extensive measurements of the properties of the gases and aerosols (particles) in the volcanic clouds produced by the eruptions of Mount St. Helens from March through August 1980. Volcanic material was first injected into the atmosphere on 27 March 1980. This material, as well as that introduced by subsequent eruptions during the next 2 months, was confined to the troposphere. On 18 May the first of several major explosions occurred in which some of the volcanic cloud penetrated well into the stratosphere. The nature of the volcanic activity at Mount St. Helens from the end of March through June is described in (1).

Measurements of the volcanic clouds in the troposphere were made close to the volcano from the University of Washington's B-23 aircraft and the National Center for Atmospheric Research's QueenAire plane (1-3) during both minor and major eruptions. The observations of the volcanic plumes in the stratosphere (Table 1) were obtained from experiments flown on a U-2 aircraft participating in NASA's Aerosol Climatic Effects (ACE) program (4). The data obtained from these experiments, in conjunction with spatial mapping of the aerosols' extinction coefficient by NASA's SAM II and SAGE satellite experiments (5), form a comprehensive data set for assessing the climatic effects of stratospheric aerosols. Data from an earlier set of U-2 flights were used to define the properties of the background or unperturbed stratosphere. Data on Mount St. Helens were obtained within a day or two of each of the major explosions as well as at later times, including flights on 14 and 17 June through material that had circled the earth once. The dispersal of the volcanic plumes by winds, which resulted in very different trajectories for material at different altitudes, is described in (6).

The volcanic plumes in the troposphere showed orders of magnitude more sulfur gases than were found in background air. The volcanic emission flux of sulfur gas exhibited sizable increases after the first major explosion on 18 May, with SO_2 and H_2S alternately being the dominant sulfur gas species (1). Although H_2S was not detected in any of the stratospheric samples, SO_2 was considerably enhanced in plumes several days old, but not in a plume several weeks old. Carbonyl sulfide (OCS), the dominant sulfur gas in the background stratosphere, showed only very modest increases in abundance (7). Significant increases were also detected in the stratosphere in the concentration of chlorine- and nitrogen-containing gases (7) and water vapor (8).

Both in the troposphere (1, 3) and in the stratosphere (3, 9, 10), the volcanic aerosols consisted of a mixture of micrometer- and submicrometer-sized ash particles and concentrated sulfuric acid droplets. The ash had both glassy and crystalline material, reflecting its derivation from juvenile volcanic magma and the old, outer structure of the volcano, respectively (1, 9). An enhanced concentration of certain elements with increasing altitude may imply a greater magmatic component for the higher altitude material (10). Due to gravitational sedimentation, larger particles were found in the tropospheric samples than in the stratospheric ones; most of the particles in the stratosphere were several tenths of a micrometer in size (3), while a strong enhancement of micrometer-sized particles was observed in the tropospheric samples (1, 3). Sulfuric acid was present chiefly as a coating on the ash particles in the troposphere and as both separate small particles and large composite particles in the stratosphere (3, 9).

Sulfuric acid particles in the background stratosphere are thought to be generated from sulfur gases through a series of gas-phase oxidation and hydration reactions (11). Experience with other major volcanic explosions, such as that of Mount Agung on Bali in 1963, show that it takes several months for large quantities of volcanic sulfur gases to be converted to sulfuric acid aerosols, probably because the sulfur gases deplete the concentration of radicals such as OH. However, around Mount St. Helens some sulfuric acid was present in tropospheric samples only a few hours old. Thus, sulfuric acid was generated very rapidly in the troposphere or the volcano, or both, perhaps as a result of a combination of solution-phase chemistry and an enhanced level of free radicals in the volcanic plumes. In addition, substantial and rapid (that is, in a few days) gas-to-particle conversion took place in the stratosphere as judged by (i) the enhanced concentrations of cloud condensation nuclei in the stratospheric volcanic plumes (12), which is the first observation of the in situ formation of new, very small sized sulfuric acid droplets in the stratosphere; (ii) a large increase in the abundance of sulfuric acid between the samples obtained 1 and 4 days after the first major explosion (13); and (iii) the dramatic decline in the ratio of SO_2 gas to sulfuric acid droplets with time after the first explosion (7, 13). Such a rapid conversion of gas to aerosols in the stratosphere could be due to a combination of factors, including the limited amount of sulfur gases injected and hence the smaller amount of oxidants required, as compared to bigger events; the enhanced level of water vapor initially present in the plume, which may have led to a higher concentration of gases with an odd number of hydrogen atoms; and, possibly, liquid-phase chemistry (11).

The properties of volcanic material in

Table 1. Major volcanic explosions of Mount St. Helens and associated U-2 flights.

Date of explosion (1980)*	Date of U-2 flight	Sampling location
18 May	19 May 1980	Washington, Idaho, Montana, and Wyoming
	22 May 1980	Idaho and Montana
	14 June 1980	Montana
	17 June 1980	Wyoming and Colorado
25 May	27 May 1980	West coast of Canada
13 June	14 June 1980	Montana
None	16 July to 19 July 1979†	Alaska

*Dates are based on Universal Time. †This flight series was held in conjunction with a ground-truth exercise for the SAM II and SAGE satellite experiments and provided data on the stratosphere before the explosions of Mount St. Helens.

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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3. R. L. Chuan, D. C. Woods, and M. P. McCormick [*Science* **211**, 830 (1981)] obtained measurements in both the stratosphere and troposphere.
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13. B. Gandrud and A. Lazrus, *ibid.*, p. 826. Also see (*10*) on the temporal evolution of the mass density and composition of the volcanic aerosols in the stratosphere.
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.
15. J. B. Pollack, O. B. Toon, C. Sagan, A. Summers, B. Baldwin, W. Van Camp, *J. Geophys. Res.* **81**, 1071 (1976); J. A. Coakley, Jr., and G. W. Grams, *J. Appl. Meteorol.* **15**, 679 (1976). See also (*19*).
16. Mie theory can be used for this purpose since the particles were typically separate sulfuric acid droplets or ash particles with a sulfuric acid coating (*3, 9*).
17. J. B. Pollack, O. B. Toon, D. Wiedman, *Geophys. Res. Lett.*, in press; J. B. Pollack, paper presented at the International Radiation Symposium, Fort Collins, Colo., August 1980. See also (*15*).
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20. The success of the U-2 flights through the volcanic plumes of Mount St. Helens was due in large measure to the efforts of W. Page, E. Danielsen, and the U-2 pilots and ground support personnel at NASA Ames Research Center. These ACE activities were sponsored by the Climate Program Office of NASA.

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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 μg 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

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