Trajectories of the Mount St. Helens Eruption Plume

Abstract. *The plume of the major eruption of Mount St. Helens on 18 May 1980 penetrated 10 to 11 kilometers into the stratosphere, attaining heights of 22 to 23 kilometers. Wind shears rapidly converted the plume from an expanding vertical cone to a thin, slightly inclined lamina. The lamina was extruded zonally in the stratosphere as the lower part moved eastward at jet stream velocities, while the upper part slowly moved westward in the region of nonsteady transition from the westerlies to the summer stratospheric easterlies. Trajectories computed to position the NASA U-2 aircraft for sampling in the plume are described. Plume volume after 8 hours of strong volcanic emission is estimated at 2 × 10^6 cubic kilometers. Only about 1 percent of this volume is attributed to the volcano; the rest was entrained from the environment.*

Flights by U-2 aircraft were designed to obtain measurements of aerosols and gases injected into the stratosphere by eruptions of Mount St. Helens. The flight tracks and altitudes followed isobaric trajectories predicted from the analyses of 300-, 200-, 100-, 70-, and 50-mbar data of the National Weather Service. Before the major eruption of 18 May 1980, special arrangements had been made with the National Oceanic and Atmospheric Administration to transmit these high level analyses to their regional office at Redwood City, California. As expected, the strong vertical shears of the horizontal winds moved the various levels of the plume along distinctly different paths. Pilot observations and in situ measurements confirmed the predictions.

Heavy ash and water vapor loading in the upper troposphere and lower stratosphere also permitted satellite detection of the plume by both visible and infrared photography. These photographs, depicting the temporal evolution of the plume, were extremely valuable but they were also potentially misleading. As seen from the satellites, the plume resembled an emission from a gigantic smoke stack, flowing horizontally with the winds and slowly increasing in diameter. The effects of the vertical shear of the horizontal winds, of critical importance to the evolving three-dimensional structure of the plume, were simply undetected.

The effects of vertical wind shear illustrated in Fig. 1B are based on the winds and temperatures measured at Salem, Oregon, upwind from Mount St. Helens, just 3 hours before the 18 May eruption. In the troposphere, the west wind velocity increased with height to a maximum of 33 m sec^{-1} at 12 km, the tropopause height. In the isothermal stratosphere, from 12 to 20 km, the velocities decreased rapidly to only 1 or 2 m sec^{-1}. Above 20 km (~ 50 mbar) the temperatures increased with height and the winds remained light from the northwest.

The temperature profile at Salem, Oregon, indicated that the eruption plume would encounter weak buoyancy resistance as it penetrated the troposphere, moderate resistance from 12 to 20 km, and increasingly strong resistance above 20 km. If it penetrated the stratosphere to about 20 km and the entrainment of environmental momentum facilitated a rapid adjustment to the environmental winds, the predicted trajectories indicated that the plume would rotate as shown in Fig. 1B. The depiction of the leading and trailing edges of the inclined stratospheric plume is based on the initial surge at 1532 Universal Time and the final surge at 2330, after which the eruption decreased markedly in intensity. The flight paths of the U-2 aircraft are shown in Fig. 1A.

The sampling began about 24 hours after the initial eruption, at 17.7 km over northeastern Oregon and terminated at 14.0 km over central Wyoming. Flying in the plume, the pilot reported a change from a brownish color at the highest altitude to a diffuse white of increasing opacity at the lowest altitude. He established the cloud base over Wyoming at 12.8 km. This is 0.8 km higher than the level of maximum wind observed at Salem. This apparent increase in elevation of the plume's leading edge is produced by differences in the trajectories. The flow at 12 km turned southward over eastern Utah and entered western Colorado. Isentropic trajectories, computed later, showed that this air was actually descending and reached its lowest elevation (10.2 km) over Oklahoma. As the descending air warmed by compression, the associated water cloud particles evaporated, and the plume appeared to change to a whispy veil in the satellite photographs and became difficult to detect. At slightly higher altitudes the more dense plume moved eastward farther before it turned southward.

A few hours after the U-2 made the lower stratospheric sampling flight over Wyoming, this same portion of the plume passed over Laramie, Wyoming, where a series of balloons were launched to make aerosol measurements. These measurements indicated a thin layer of aerosols whose central elevation increased with time (*1*).

Again, when viewed locally, the plume

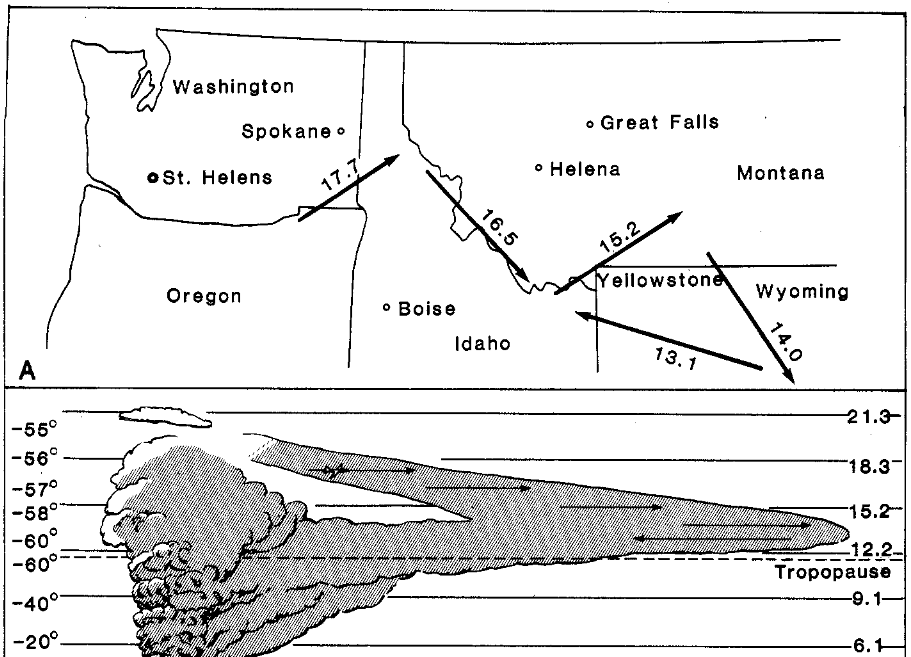

Fig. 1. (A) Vector flight paths for U-2 on 19 May 1980. (B) Vertical cross section illustrating plume tilt caused by wind shears. Environmental temperatures are to left of the plume and altitudes converted from feet to kilometers are to the right.

0036-8075/81/0220-0819$00.50/0

appeared to be rising with time, a process requiring ascending motions, diabatic heating, or both. Instead the air was descending slightly, and the apparent rise was produced by an increase in the travel time due to the decrease in wind speeds with height, a fact established by the first flight of the U-2.

The same flight confirmed a plume penetration to at least 18 km, rapid adjustment to the local wind velocity and subsequent plume distortion, as well as the expected dilution of ash loading with height due to sedimentation and to entrainment of clean air. If the plume had actually reached greater heights it would have been still hovering over the volcano. A U-2 pilot on a photographic mission on 20 May reported such a cloud at heights exceeding 21.6 km.

Trajectories derived from the constant pressure charts are shown in Fig. 2. The upper tropospheric (300 mbar) and lower stratospheric (200 mbar) trajectories (Fig. 2A) resemble the plume as seen by the satellite. They followed the flow at or near jet level, turning southeastward as the air passed a ridge and then descended slowly. The black arrow traces the more southerly displacement of the air as it descended isentropically from the 200-mbar level. This fast moving portion of the plume traversed the globe in about 15 days, traveling at an average zonal speed of approximately 25 m $\sec^{-1}$.

At 100 mbar (~ 16 km) the much slower speeds and the changing pressure pattern produced the most southerly transport (Fig. 2B). This portion of the plume was crossing Louisiana 4 days after the eruption and subsequently spread out over the southeastern United States. The distinctly different trajectories at the 70-mbar (~ 18.5 km) and 50-mbar (20.5 km) pressure levels are evident in Fig. 2B. Their southward and eastward movements are reversed on 20 May. Later the air moved northward into western Montana, northern Idaho, and Washington and then proceeded northwestward, across British Columbia and the Gulf of Alaska.

On 22 May the U-2 was sent to western Montana to intercept this slowly moving upper plume. West of Helena, the pilot penetrated a still visible cloud at 20.2 km. Two days later the SAGE satellite detected an enhanced aerosol layer off the Pacific Coast at 22 to 23 km. These measurements, one direct and one remote, indicate a deep penetration of 10 to 11 km into the stratosphere. As a consequence of extreme altitude range and the wind reversal with height, the lower portion of the plume moved rapidly eastward while the upper portion moved slowly westward.

Thus the stratospheric portion of the eruption cloud, containing small aerosols and trace gases at enhanced concentrations, wrapped around the globe, not as an expanding horizontal plume but as an extremely thin, inclined lamina. Lidar measurements show that this lamina remained discrete and identifiable for months, although it was gradually dispersed by horizontal shears and small-scale turbulent motions.

The predicted trajectories for the U-2 flights made on 27 May and 14 and 17 June, after the 25 May and 13 June eruptions, are described in (*2*). On the last two flights the highest altitude samples, from about 18 to 19 km, were made in the thin lamina produced by the major eruption of 18 May.

Some estimates can be made about the plume that formed from the 18 May eruption. After 8 hours of volcanic emission, the plume volume was computed to be approximately 2×10^6 km^3. Because of adiabatic expansion and massive entrainment, only a small percentage of this volume can be attributed to the volcano. If 1 percent of the volume is derived from the volcano and a cross-sectional area at the crater top is 4 km^2, then the mean exit velocity of the emission would be about 175 m $\sec^{-1}$ or half the speed of sound at 300 K. With this velocity and a net vertical travel of 20 km (23 km minus the mountain height), the mean acceleration must equal $-0.077g$, where g is the acceleration of gravity.

Contributing to this deceleration are the vertically integrated mean buoyancy, nonhydrostatic pressure gradient, aerosol-ash mass loading, and the mixing or entrainment terms. Because of sign reversals with height, the means for the first two terms are probably small and will be neglected.

To estimate the mass loading, the volume of ash deposited was computed from a contoured map of ash depth. This map contained two areas of maximum depth, one adjacent to the northeast face of the mountain and the other downwind under the main plume. Excluding the first maximum plume, the volume

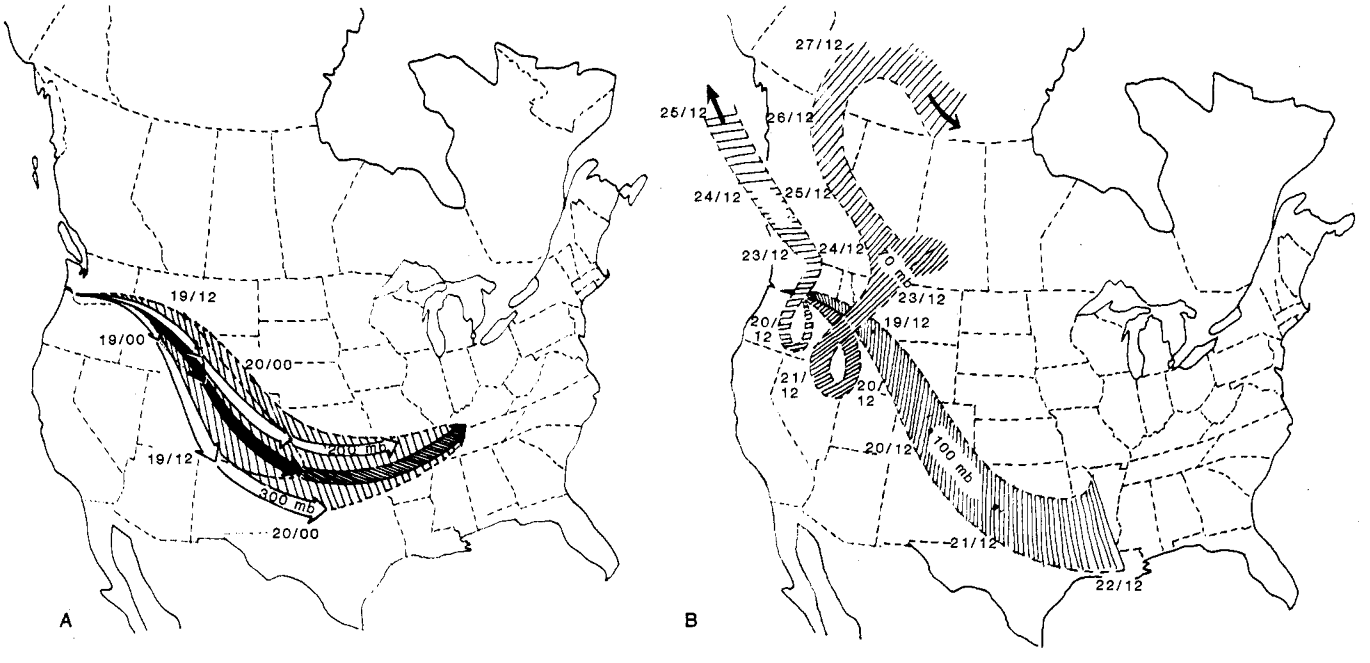

Fig. 2. (A) Upper tropospheric and lower stratospheric trajectories for 18 May eruption. (B) Lower mid-stratospheric trajectories for 18 May eruption. Date/time denotes Universal Time.

thought to be attributed to the main plume was 0.6 km^3. If it has a bulk density of 0.5 g cm^{-3} because of loose packing (3), the average mass mixing ratio at the volcano would be approximately 0.025, and the acceleration caused by mass loading would be $-0.025g$ or 32 percent of the required mean value. Dilution by entrainment would reduce the mean value of this term, so that even if the mass is underestimated by a factor of 2, the dominant term must be the last, the mixing term. Thus, qualitatively, the very small percentage of the plume volume attributed to the volcano is supported. If a larger percentage is assumed, the mean exit velocity increases. Since the required deceleration increases with the square of the exit velocity, a much larger entrainment is required, opposing the assumption. A large entrainment of horizontal momentum also helps explain the rapid adjustment of the plume to the winds.

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4. The author gratefully acknowledges the excellent cooperation of the NOAA personnel in the Analysis and Information Branch of the Climate Analysis Center, Washington, D.C., and in the National Weather Service and Satellite Service office at Redwood City, Calif.

18 September 1980; revised 22 December 1980

Gaseous Constituents in the Plume from Eruptions of Mount St. Helens

Abstract. *Measurements in the stratosphere of gaseous constituents in the plume of Mount St. Helens were obtained during five flights of the NASA U-2 aircraft between 19 May and 17 June 1980. Mixing ratios from gas chromatographic measurements on samples acquired about 24 hours after the initial eruption show considerable enhancement over nonvolcanic concentrations for sulfur dioxide (more than 1000 times), methyl chloride (about 10 times), and carbon disulfide (more than 3 times). The mixing ratio of carbonyl sulfide was comparable to nonvolcanic mixing ratios although 3 days later it was enhanced two to three times. Ion chromatography measurements on water-soluble constituents are also reported. Very large concentrations of chloride, nitrate, and sulfate ions were measured, implying large mixing ratios for the water-soluble gaseous constituents from which the anions are derived. Measurements of radon-222 present in the plume are also reported.*

As part of an investigation of the distribution in the stratosphere of precursor gases and their role in sulfuric acid aerosol formation, we conducted a series of experiments in California and Alaska during the summer of 1979 (1). Typical mixing ratios by volume were about 0.4 to 0.1 part per billion (ppb) for OCS (carbonyl sulfide) and 0.04 to 0.05 ppb for SO_2 at altitudes from 15 to 21 km. An upper limit of about 1 part per trillion (ppt) at an altitude of 15 km was attributed to CS_2.

The 18 and 25 May and 13 June 1980 eruptions of Mount St. Helens presented an opportunity to study the input of volcanic emissions into the stratosphere. Between 19 May and 17 June 1980, we participated in five sampling flights over the northwestern United States on the NASA U-2 aircraft, in locations predicted to be in the trajectory of the plumes.

A flow-through cryogenic collection method, in which condensable constituents are trapped in a glass sampler at liquid-nitrogen temperature (2), was used to sample large volumes of air. Four cryogenic collectors were used on each flight, and 19 samples were collected.

After the residual air in each sample was removed by evacuation with a sorption pump, the samples were transferred to glass bulbs (200 to 250 ml). The samples were analyzed by gas chromatography. Sulfur constituents were separated by Chromosil-310 or Porapak-PS columns and measured with a flame photometric detector. A photoionization detector was used in CH_3Cl measurements. We adapted ion chromatographic methods for measurement of anions derived by dissolving the water-soluble constituents (3). Because of the large enrichment (over 1000-fold) of the cryogenically collected samples, we estimated a lower limit of measurement to be a few parts per trillion by volume.

All measurements were quantified by calibration based on reference standards. Primary standards were prepared from pure gases, each separately mixed with CO_2 and stored in concentrations approximating the enriched stratospheric samples. Commercial standards were also used, either directly or for preparing secondary standards. The accuracy of the standards ranged from 2 to 10 percent, depending on the constituent and method of preparation.

The 19 samples collected were analyzed for OCS and SO_2. Table 1 shows the results of gas chromatography analysis for those constituents with enhanced mixing ratios. In the first set of analyses of the sulfur constituents of the samples taken at 15.2 and 16.5 km on flight 36, several replicate trials were within the normal scatter for SO_2 measurements. Only one injection was made for the sample collected at 14 km in the first analysis. A decrease in the level of the SO_2 signals was observed in the second analysis a day later; the decay may have been caused by some chemistry that occurred in the sample bottle. The mixing ratios of the three SO_2 samples from flight 36 (Table 1) are derived from the first analysis and are considered lower limits. Some samples in Table 1 showed a marked decrease in the SO_2 signal between the first and second trial. This is the result of temporary column degradation or chemical decay of SO_2 in the sample bulb, or both. This effect is not observed in analyses of reference standard mixtures.

The OCS results obtained from flight 36 samples show mixing ratios that do not appear to be enhanced compared with those of the unperturbed stratosphere (1, 2). On the other hand, CH_3Cl mixing ratios are enhanced compared with those reported for the unperturbed stratosphere (4). Measurements on samples from a higher altitude plume (flight 37, Table 1) showed persisting enhancement of the CH_3Cl mixing ratio. The SO_2 mixing ratio, however, decreased to about that for the unperturbed stratosphere, except for the sample taken at 20.1 km. In contrast, the OCS mixing ratios are enhanced in samples from this flight except for the one taken at 20.7 km. These results indicate nonuniform distribution of these gases in the plume.

We also detected CS_2 in flight 36 samples. Because the signals were small and difficult to quantify, the CS_2 mixing ratios are reported with an uncertainty of about a factor of 2. For the 14.0-km sample, the mixing ratio is ≤ 55 ppt and for the 15.2-km sample, 2.8 ppt. We have not observed any H_2S signals in our measurements.

For ion chromatography measurements, solutions were prepared by dissolving in water a portion of the sample (Table 2). Air was not excluded in pre-

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