Explosive Emissions of Sulfur Dioxide from the 1992 Crater Peak Eruptions, Mount Spurr Volcano, Alaska

By Gregg J.S. Bluth, Courtney J. Scott, Ian E. Sprod, Charles C. Schnetzler, Arlin J. Krueger, *and* Louis S. Walter

CONTENTS

ABSTRACT

Sulfur dioxide clouds from three explosive eruptions of Crater Peak vent of Mount Spurr during the Summer of 1992 were detected, tracked, and measured by NASA's Total Ozone Mapping Spectrometer (TOMS). From the TOMS data we calculated that the August 18 eruption produced the largest sulfur dioxide emission of the three events at 400±120 kilotons (kt) SO_2, followed by the September 16–17 and June 27 eruptions (230±70 kt and 200±60, respectively). The June SO_2 plume remained primarily over eastern Alaska and Canada's Yukon province, and it was observed by TOMS for 7 days. The August cloud drifted southeast along Canada's Pacific coast before being carried eastward, and after 8 days it was finally viewed passing over England. The September cloud traveled the most rapidly of the three: southeast across Canada and the northern United States, then northeast over Toronto, and finally over Greenland 5 days later. TOMS data for the August and September eruptions revealed that the two gas plumes increased in SO_2 amounts over the first 2 days—well after the eruptions had ceased. The TOMS data and other available evidence suggest that significant quantities of hydrogen sulfide, in addition to sulfur dioxide, may have been explosively outgassed by these two eruptions. The maximum injection altitudes of the ash clouds, matching of SO_2 cloud positions to known wind conditions, and the dispersion rates of the gas clouds all suggest that at least half of the sulfur dioxide emitted by the Crater Peak eruptions reached the lower stratosphere.

INTRODUCTION

Mount Spurr, Alaska (61°30'N, 152°25'W) had been inactive since 1953 but during the Summer of 1992 erupted violently three times and sent large amounts of ash and gas into the atmosphere. Because of prevailing meteorological conditions, each eruption cloud followed unique dispersal paths. The SO_2 produced by these three eruptions was observed by the Total Ozone Mapping Spectrometer (TOMS), on board NASA's Nimbus-7 satellite. We used the TOMS data to analyze the eruption clouds for their SO_2 contents, areal extents, and dispersion patterns.

The Nimbus-7 satellite is in a polar sun-synchronous orbit and crosses the equator every 26 degrees (2,800 km) of longitude at local noon, observing the whole Earth once a day (13.7 orbits per day). Scans consisting of 35 data scenes cover the 2,800-km-wide orbit swaths; each scan takes about 8 seconds to complete. The ground resolution of the TOMS ranges from 50 km at nadir to approximately 200 km at the orbit edges (average resolution is 66 km). The TOMS instrument has provided global SO_2 and ozone data since late 1978 by measuring the ultraviolet albedo, which is the ratio of backscattered Earth radiance to incoming solar irradiance (Krueger, 1983). The amount of SO_2 is calculated on the basis of characteristic attenuation of the ultraviolet signal. The TOMS instrument gives no direct indications of SO_2 cloud altitude; altitude can be derived by comparison of cloud movement to known or modeled wind velocity and directions (see Schoeberl and others, 1993).

Sulfur dioxide concentrations are calculated in milli-atmosphere centimeters (matm-cm), which express the column thickness of the gas at standard temperature and pressure (STP). The tonnage of SO_2 over

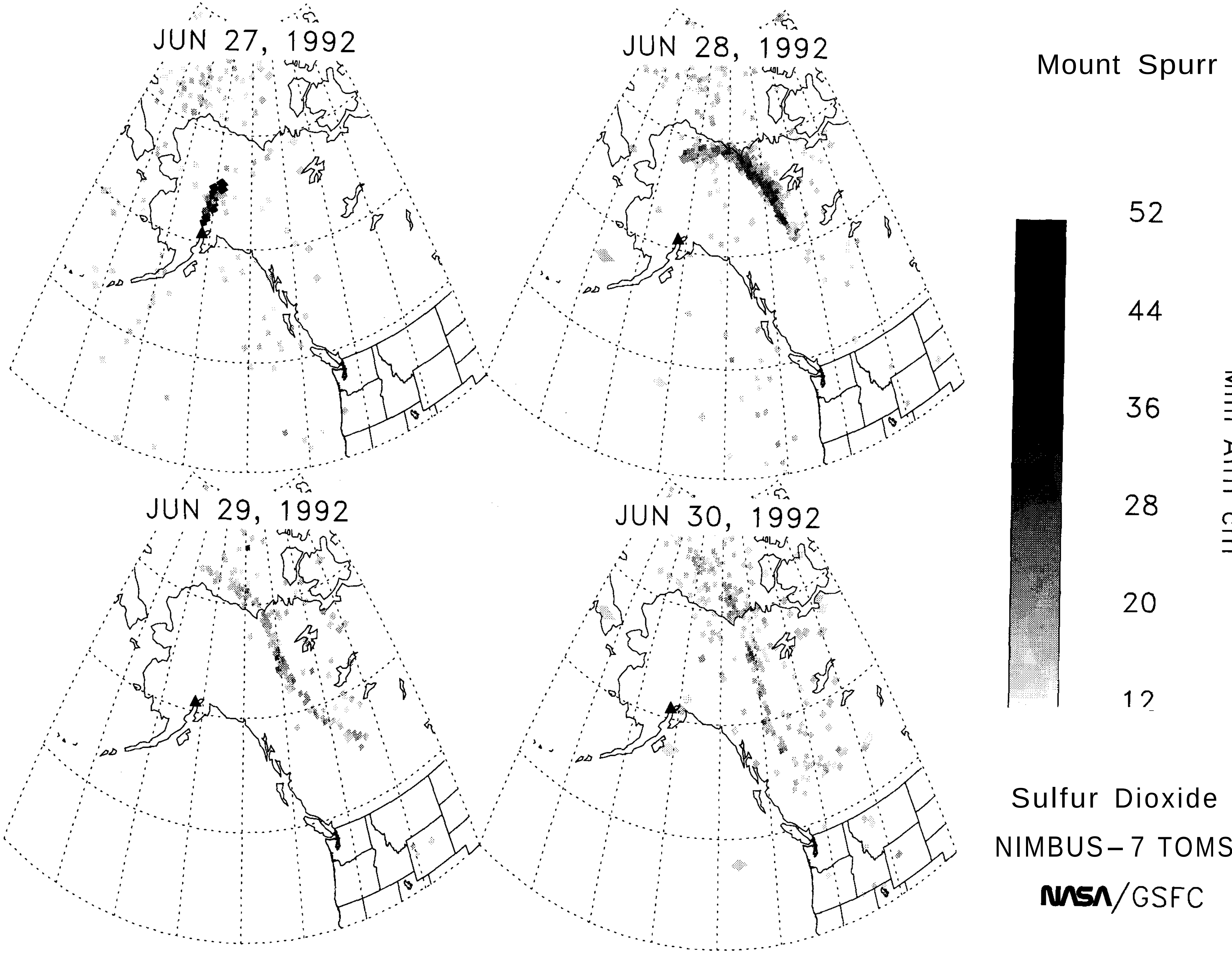

Figure 1. Total Ozone Mapping Spectrometer (TOMS) images of the SO_2 cloud for 4 days after the June 27, 1992, eruption of Crater Peak vent of Mount Spurr in Alaska. The SO_2 scale is in milli-atmosphere centimeters, a measure of the total SO_2 gas present in a column between the satellite and the reflecting surface (Earth). These measurements are then converted to a mass of SO_2. Approximate overpass times, in ADT, are: June 27: 10:49 a.m.; June 28: 9:25 a.m.; June 29: 9:41 a.m.; June 30: 9:58 a.m. (ADT = UT - 8 hours). Mount Spurr location is shown by a filled triangle.

a given region is then obtained by multiplying the column amounts by their ground surface areas. Empirical corrections are used to offset the linear effects that variations in ozone and surface reflectance can impart on the SO_2 calculations. Eruption cloud tonnages are estimated from measurements of the SO_2 cloud compared to background measurements. Background data are taken adjacent to the SO_2 cloud to minimize latitudinal (such as, solar zenith angle and climatological variations) differences, and they are also taken in identical scan positions to avoid scan bias (such as, changes in instrument resolution from nadir to scan-edge positions).

The typical TOMS detection limit of a fresh, tightly constrained eruption cloud is roughly 5 to 10 kilotons (kt) SO_2. Older, more dispersed clouds are difficult to discern because of low signal-to-noise ratios. Uncertainties arising from background variations and theoretical limitations of the SO_2 algorithm combine to give a typical total error of approximately 30 percent in cloud tonnage, as calculated by Krueger and others (1990). The location of Mount Spurr in the northern latitudes makes TOMS data collected there more difficult to analyze owing to high solar zenith angles (the longer path lengths increase background noise), but it is also advantageous in that more observations are possible because of orbit overlap.

ACKNOWLEDGMENTS

This work was supported by funding from NASA Headquarters Solid Earth Program. Scott Doiron and Elizabeth Duncan provided technical and scientific support to the TOMS SO_2 research. This paper was improved by the helpful reviews of Terry Gerlach and Bill Rose.

JUNE 27 ERUPTION

This first violent eruption of Mount Spurr began at 7:04 a.m. Alaskan daylight time (ADT = UT - 8 hours), and it lasted over 4 hours (Power and others, 1992). A composite image of TOMS observations is shown in figure 1. The first TOMS overpass occurred 10:49 a.m. ADT, and it caught the SO_2 emission in progress. A second view of the erupting cloud was obtained in the subsequent, overlapping orbit, at approximately 12:23 p.m. ADT. The gas cloud was observed initially drifting northward and its movement was consistent with a 10-km altitude, as determined from wind data from the National Meteorological Center (NMC). By the next day the cloud was elongated and had begun to drift to the east and southeast. By June 29 the cloud became further elongated; it stretched from Point Barrow, Alaska, to Edmonton, Alberta, in Canada. However, on June 30 the cloud unexpectedly ceased its southeastward drift, and it rotated about 10° clockwise from its position on the previous day. The SO_2 cloud became more difficult to discern from background, but observations over the next 3 days indicated that the cloud continued its slow clockwise rotation. From NMC data, the shearing action on the 29 and 30 and subsequent cloud motions of the cloud suggested that the upper portion of the SO_2 cloud had reached altitudes of around 12 km. The last recognizable view of the cloud was obtained July 3 when it was oriented along 140°W longitude and stretched from Dawson in the Yukon province to the Gulf of Alaska.

AUGUST 18 ERUPTION

The Crater Peak vent of Mount Spurr erupted again at 4:42 p.m. ADT on August 18 for approximately 3.5 hours (McGimsey and Dorava, 1992). The SO_2 cloud emitted from this eruption drifted southeast, and it was observed by the TOMS instrument at 10:51 a.m. ADT on August 19 as a discrete mass over the Gulf of Alaska (fig. 2). By the next day the cloud had begun to spread and show evidence of shearing on both southern and northeastern fronts. On the August 21 TOMS image, the SO_2 cloud consisted of a main portion located off the coast of Oregon, and an elongated section that extended over 3,000 km to the east over Lake Winnipeg, Canada. The western edge of the cloud could not be delineated because of TOMS data losses during that particular overpass (for comparison with the extent of the ash component of the cloud on this day, see Schneider and others, this volume). By August 22, the elongated eastern section had separated from the main cloud mass, and it was barely detectable near Hudson Bay. NMC data suggest that this part of the cloud had been sheared away by winds at an approximately 14-km altitude. The main cloud was located over Oregon and showed an eastward drift that indicated an altitude of about 12 km. On subsequent days this main cloud mass elongated and followed a tortuous route along the jet stream northeast over Hudson Bay, south of Greenland, then across the Atlantic. The last remnant of the cloud visible to TOMS was observed over England on August 26.

SEPTEMBER 16–17 ERUPTION

At 12:03 a.m. ADT (September 17), the third major eruption of Mount Spurr began, and it also lasted for approximately 3.5 hours (Alaska Volcano Obser-

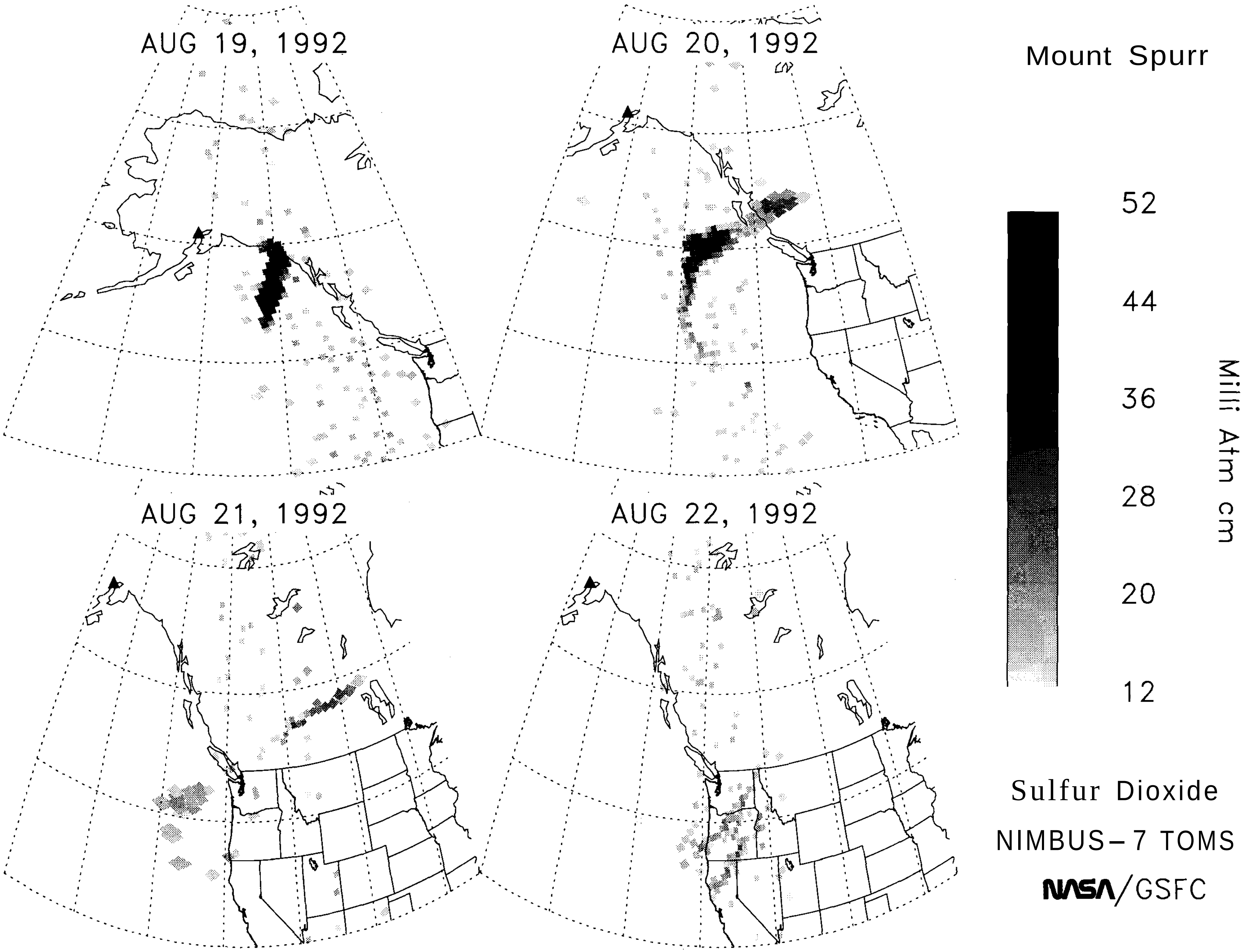

Figure 2. SO_2 cloud progression from the August 18, 1992, eruption of Crater Peak vent of Mount Spurr in Alaska. Approximate overpass times, in ADT: August 19: 10:51 a.m.; August 20: 11:07 a.m.; August 21: 9:41 a.m.; August 22: 9:57 a.m. This cloud was tracked for several more days as it crossed the Atlantic and reached England on August 26. Mount Spurr location is shown by a filled triangle.

vatory, 1993). The SO_2 cloud drifted eastward into Canada, then southward over the United States at a remarkable rate; it reached North Dakota (nearly 3,700 km away) approximately 34 hours after the eruption began (fig. 3). The cloud remained fairly compact during this time, and its behavior was consistent with NMC wind patterns over a range from 12 to 16 km. NMC data located the SO_2 cloud on a high-pressure ridge during the first 2 days after the eruption. However, by the following day the cloud was drawn into a region of high vertical shear, the steep wind gradient between high- and low- pressure systems over the Great Lakes area on the 19th. Accordingly, in the September 19 image the cloud changed drastically; it formed a 2,000-km-long arc from Detroit to northern Quebec. The extent of shearing observed was consistent with the SO_2 cloud extending from 12 to 16 km in altitude. The following day's image showed the shearing had abated, but the cloud continued its northeasterly drift over the Labrador Sea. The last day the SO_2 cloud could be discerned was on September 21 as a small mass off the east coast of Greenland.

DISCUSSION

Relations of cloud tonnage and area as a function of time can be useful in monitoring the physical and chemical processes that affect an erupted SO_2 cloud. The amount of TOMS-observed SO_2 generally decreases because of both chemical conversion of SO_2 to H_2SO_4 and physical dissipation of SO_2 at cloud margins to below the TOMS detection limits. The (chemical) decay rate of SO_2 gas can ideally be described by an exponential decay function, with an el2 or e-folding time. For large eruption clouds emplaced in the stratosphere, in which chemical processes dominate physical effects, the TOMS measurements can be used to derive an e-folding time for the cloud (for example, approximately 35 days for the 1991 Mount Pinatubo SO_2 cloud; Bluth and others, 1992). However, the dispersion rate of SO_2 is altitude dependent; it is typically more persistent if emplaced in the relatively drier, less turbulent, and less reactive stratosphere rather than in the troposphere. Sulfur dioxide dispersion is also dependent on cloud size and shape; the larger the surface area to mass ratio, the greater the effects of dissipation and chemical reaction at cloud boundaries.

Because TOMS observes volcanic SO_2 clouds for only a short period of their total lifetimes in the atmosphere, the clouds' dispersion rates within this time can be approximated by a linear daily decrease. Empirically, SO_2 clouds emplaced in the stratosphere generally decrease in mass by about 10 percent per day (Doiron and others, 1991; Bluth and others, 1992), whereas tropospheric clouds can decrease by up to 50 percent per day (Bluth and others, 1994). In contrast, cloud area typically increases for the first few days, reflecting expansion of the gas cloud. As dispersion processes become more prevalent, the areal extent of SO_2 observable by TOMS then decreases owing to chemical conversion and physical dissipation. Rapid changes in area and (or) SO_2 amount generally indicate that the clouds have undergone physical changes as a result of wind shear and other turbulence. The daily tonnages and areal extents of the SO_2 clouds for the three Crater Peak eruptions are shown as a function of time in figure 4.

The eruption of June 26 was in progress when initially observed by TOMS, and the first two SO_2 and area values in figure 4A show that the eruption cloud was still developing. Two more observations were made on June 27, but the second orbit missed approximately 5 to 10 areal percent of the cloud's leading edge, as reflected by the small drop in SO_2 amounts determined from one orbit to the next. Both the SO_2 mass and area of the June cloud decreased at fairly constant rates; these decreases, along with the NMC wind data and relatively minor amount of observed drift, suggest that the local meteorological conditions were fairly stable at that time.

Both the August and September eruption clouds showed marked variations in area as they underwent fairly drastic changes as a result of wind shear (figs. 4B and 4C). But the most remarkable pattern observed for these two eruptions is in the daily SO_2 tonnages. After both eruptions, measured SO_2 increased from the first to second day, followed by gradual cloud dispersion. In contrast to the June eruption, both eruption clouds were observed after complete separation from the volcano—accordingly, there was no possibility that the increase could have occurred from additional outgassing after the TOMS overpass. Nor was there evidence of severe physical disturbance during this time.

We can offer several reasons why measured SO_2 may have increased in the clouds. First, the data variation falls within our stated accuracy of cloud tonnage estimations (±30 percent; however, we do not believe the pattern is an artifact of the uncertainty in TOMS data or analysis. When analyzing cloud tonnages on successive days, the relative precision of the TOMS on these daily measurements of an SO_2 cloud is approximately 10 percent. Thus, the SO_2 increases observed for these eruption clouds are probably well above uncertainty levels.

Second, the SO_2 retrieval on the first day may have been incomplete because of interference from co-erupted ash. Data from the Advanced Very High

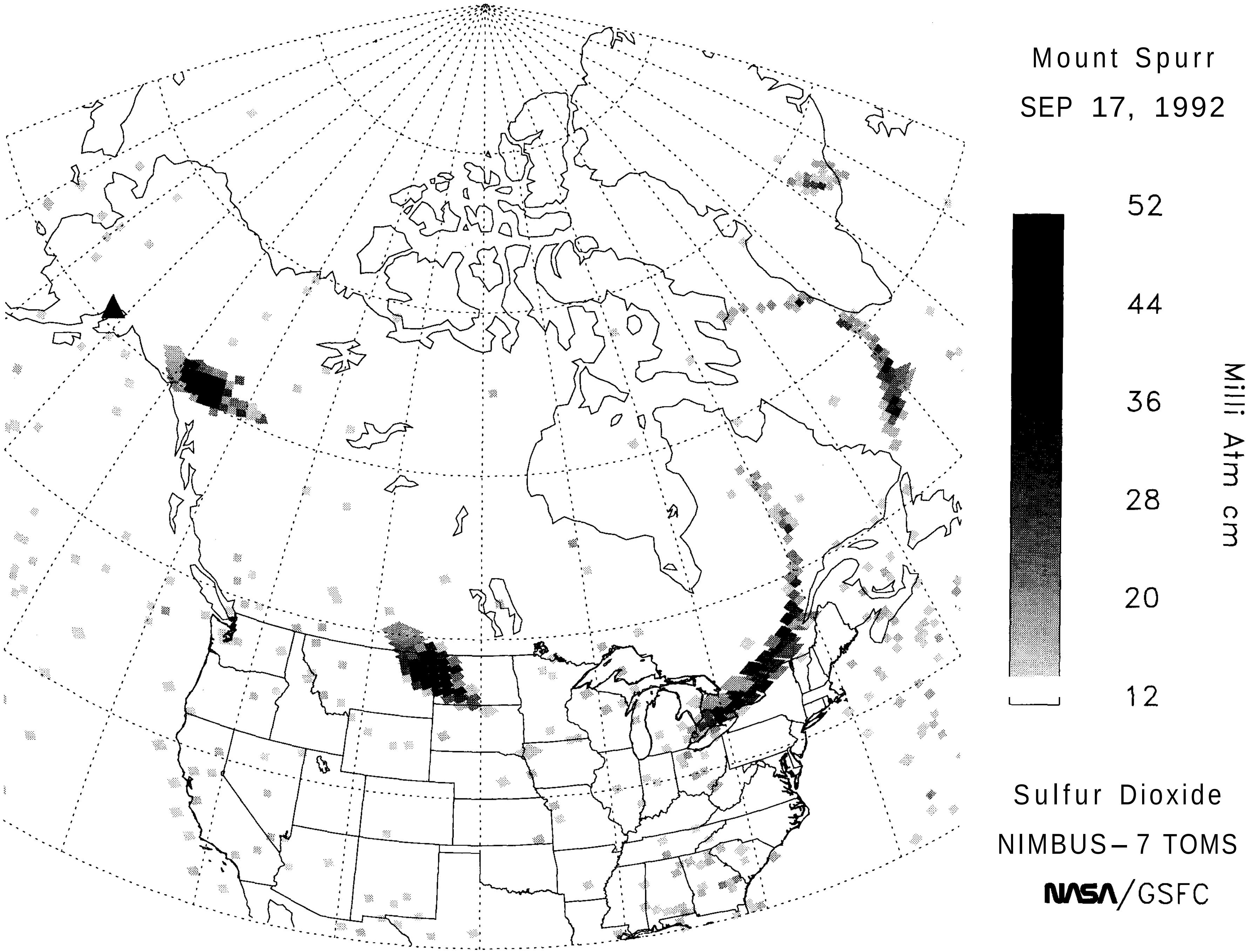

Figure 3. Composite image of the September **16-17, 1992,** SO_2 cloud, observed for 5 days after the eruption of Crater Peak vent of Mount **Spurr** in Alaska. Approximate overpass times for each cloud observation, in ADT: September **17:** 10:47 a.m.; September **18:** 9:16 a.m.; September **19:** 6:07 a.m.; September **20:** 4:45 a.m.; and September **21:** 3:20 a.m. Mount **Spurr** location is shown by a filled triangle.

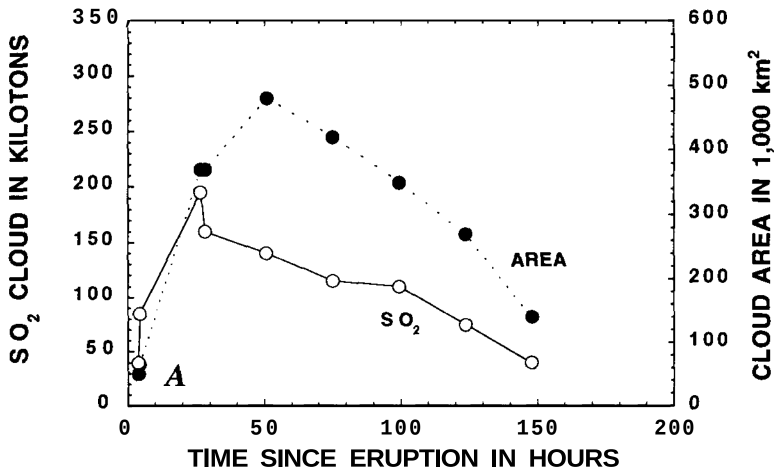

Figure 4. Comparisons of cloud sulfur dioxide mass (open circles) and area (filled circles) as a function of time after 1992 eruptions of Crater Peak vent of Mount Spurr in Alaska. A, June 27 eruption.

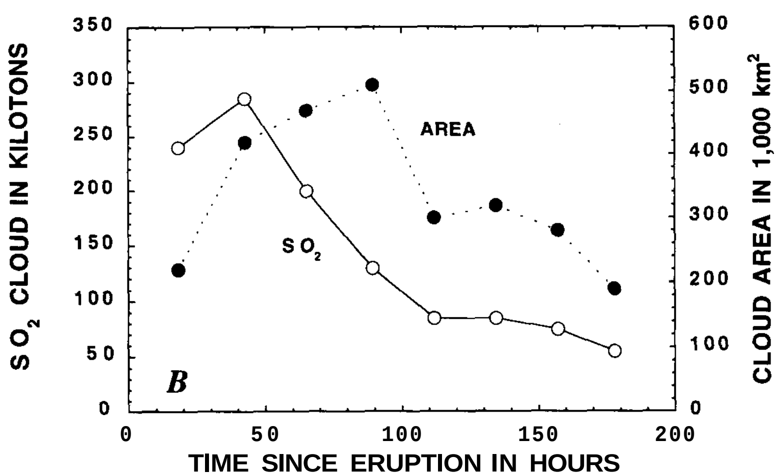

Figure 4. Continued. **B.** August 18 eruption.

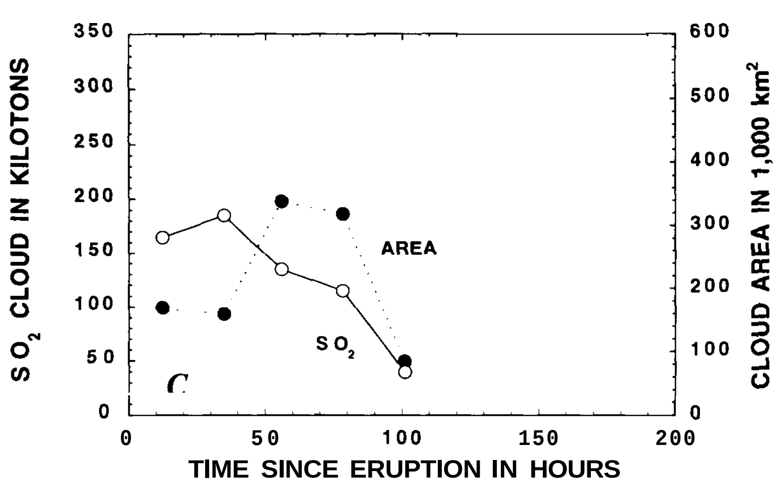

Figure 4. Continued. ***C*,** September 16–17 eruption.

Resolution Radiometer (AVHRR; Schneider and others, this volume) show that the geographic positions and dimensions of the ash clouds were remarkably similar to the gas clouds. Because of the coincidence of the two, ultraviolet (UV) light scattering by the ash may have partially masked detection of SO_2. However, TOMS reflectivity data (taken at two wavelengths where ozone and SO_2 are nonabsorbing) showed no evidence of UV attenuation from ash particles. The fact that only the first TOMS observations were affected, 18 hours (August) and 12 hours (September) after eruption, may also provide some constraints based on the fallout rates of the tephra. For instance, the slow fallout rate of micron-sized particles in the cloud (Rose, 1993) suggests that their effect on TOMS measurements should have lasted for weeks, rather than only a single day. One of the keys to understanding the effect of ash on SO_2 detection is determining the UV absorption by the variously sized particles in the cloud.

A third possibility is that significant amounts of H_2S gas were emitted, along with sulfur dioxide, from the Crater Peak eruptions. Doukas and Gerlach (this volume) report on evidence and a possible mechanism for H_2S emissions from the volcano, and Graedel (1977) calculated that H_2S in the atmosphere, derived from oxidation reactions, has a lifetime of approximately 1 day. If significant quantities of H_2S were emitted, the oxidation of this species to SO_2 subsequent to the first day could explain the tonnage increases. The amount of H_2S required to produce the SO_2 pattern observed in the TOMS data is roughly 75 kt H_2S for the August eruption (a 3:1 SO_2-H_2S ratio), and 25 kt H_2S for the September eruption (a 6:1 SO_2-H_2S ratio).

This pattern of SO_2 signals from an eruption cloud was observed previously in the TOMS data after the eruption of Mount St. Helens in 1980. The TOMS SO_2 data for this eruption showed an increase of about 10 percent from the first to the second day of observation, then decreasing tonnage measurements on the following days (unpub. data). On May 18, only hours after the major eruption, Hobbs and others (1981) Sampled the eruption cloud and reported high concentrations of H_2S. However, we do not have enough data to make definitive conclusions regarding TOMS detection of H_2S gas emissions from either the Mount St. Helens or the Crater Peak eruptions.

The characteristics of the three eruptions of Mount Spurr are summarized in table 1. The emitted SO_2 is calculated from the TOMS data, assuming a linear daily loss of SO_2. Data from each day were used until cloud losses through shearing were evident. A best-fit line was determined using 7 days after the June eruption, days 2 through 4 for each of the August and September eruptions, and projected back to the approximate end point of the eruption.

The August eruption was calculated from the TOMS data to have produced the greatest amount of SO_2, at 400±120 kt. The September eruption produced 230±70 kt, and the June eruption emitted 200±60 kt SO_2. There was no apparent correlation of gas production with tephra emission that the Alaskan Volcano Observatory estimated for the June, August, and September eruptions. These estimates were 12, 14, and 15 million m3, respectively (W. Rose, oral commun., 1993).

The Mount Spurr SO_2 tonnage data corresponded to a 20 to 30 percent daily loss of SO_2 for each of the three eruptions; this loss suggests the clouds were injected at middle altitudes between purely stratospheric and purely tropospheric layers. At the latitudes of Alaska and southern Canada, the summertime tropopause height fluctuates but is generally around 12 km altitude. The maximum injection altitudes of the June,

Table 1. Observations of SO, clouds produced by the **1992** eruptions of Crater Peak vent, Mount Spurr, Alaska.

Eruption	TOMS data Days observed	TOMS data Maximum areal extent	Estimated SO_2 emitted	SO_2 cloud altitude[1]	Max ash altitude[2]	Emitted tephra[3]
June 27	7	480,000 km^2	200 ±60 kt	10-12km	14.5 km	12 x10^6 m^3
August 18	8	510,000	400 ±120	12-14	13.7	14
September 16-17	5	340,000	230 ±70	12-16	13.9	15

[1]Calculated from NMC wind data and actual cloud positions from TOMS data

[2]Rose and others (this volume)

[3]Alaska Volcano Observatory (1993)

August, and September ash clouds ranged from 13.7 to 14.5 km (table 1, modified from Rose and others, this volume). Each of these eruptions should therefore have reached the lower stratosphere; however, comparisons of daily wind data to actual cloud positions indicate the SO_2 clouds are most accurately considered to extend several kilometers vertically. The June SO_2 cloud corresponded to the lowest altitude (10–12 km) on the basis of its drift speed and directions, and most of this cloud probably remained in the troposphere. In contrast, most of the September cloud (ranging from 12–16 km by our calculations) was in the lower stratosphere. A large part of the August cloud (12–14 km) also appears to have reached the stratosphere. From the available data we therefore estimate that at least half of the SO_2 emitted by the three Crater Peak eruptions was emplaced in the stratosphere.

SUMMARY

During the summer of 1992, Mount Spurr ended a 39-year period of quiescence and emitted large clouds of gas and ash during three separate eruptions within a 3-month period. The TOMS data suggest that the August 18 eruption was the largest of the three with 400±120 kt SO_2 emitted, followed by the September 16–17 (230±70 kt) and June 27 eruptions (200±60 kt). Data for the August and September eruptions suggest that either co-emitted ash affected the TOMS measurements, or that significant quantities of H_2S (25–75 kt), in addition to SO_2, may have been explosively outgassed by these two eruptions. However, TOMS does not measure H_2S, and thus we can only, at this time, infer this possibility from SO_2 data. Based on the maximum injection altitudes of the ash clouds, matching of ash and gas cloud positions to known wind conditions, and the dispersion rates of the gas clouds, the explosive eruptions of Crater Peak vent of Mount Spurr injected at least 50 percent of their SO_2 into the lower stratosphere.

REFERENCES CITED

Alaska Volcano Observatory, 1993, Mt. Spurr's 1992 eruptions: Eos, Transactions of the American Geophysical Union, v. 74, p. 217–222.

Bluth, G.J.S., Casadevall, T.J., Schnetzler. C.C., Doiron, S.D., Walter, L.S., Krueger, A.J., and Badruddin, M., 1994, Evaluation of sulfur dioxide emissions from explosive volcanism: the 1982–1983 eruptions of Galunggung, Java, Indonesia: Journal of Volcanology and Geothermal Research, v. 63, p. 243–256.

Bluth, G.J.S., Doiron, S.D., Schnetzler, C.C., Krueger, A.J., and Walter, L.S., 1992, Global tracking of the SO_2 clouds from the June, 1991 Mount Pinatubo eruptions: Geophysical Research Letters, v. 19, p. 151–154.

Doiron, S.D., Bluth, G.J.S., Schnetzler, C.C., Krueger, A.J., and Walter, L.S., 1991, Transport of Cerro Hudson SO_2 clouds: Eos, Transactions of the American Geophysical Union, v. 72, p. 489–498.

Graedel, T.E., 1977, The homogeneous chemistry of atmospheric sulfur: Reviews of Geophysics and Space Physics, v. 15, p. 421–428.

Hobbs, P.V., Radke, L.F., Eltgroth, M.W., and Hegg, D.A., 1981, Airborne studies of the emissions from the volcanic eruptions of Mount St. Helens: Science, v. 211, p. 816–818.

Krueger, A.J., 1983, Sighting of El Chichón sulfur dioxide clouds with the Nimbus 7 Total Ozone Mapping Spectrometer: Science, v. 220, p. 1377–1379.

Krueger, A.J., Walter, L.S., Schnetzler, C.C., and Doiron, S.D., 1990, TOMS measurement of the sulfur dioxide emitted during the 1985 Nevado del Ruiz eruptions: Journal of Volcanology and Geothermal Research, v. 41, p. 7–15.

McGimsey, R.G., and Dorava, J.M., 1992, Eruption of Mount Spurr volcano, Alaska, August 18, 1992: video footage: Eos, Transactions of the American Geophysical Union, v. 73, p. 345–346.

Power, J.A., Page, R.A., Lahr, J.C., Stephens, C.D., Chouet, B.A., McNutt, S.R., Davies, J.N., and March, G.D., 1992, Precursory seismicity and forecasting of the 1992 eruptions of Mount Spurr, Alaska: Eos, Transactions of the American Geophysical Union, v. 73, p. 342.

Rose, W.I., 1993, Comment on "another look at the calculation of fallout tephra volumes" by Judy Fierstein and Manuel Nathenson: Bulletin of Volcanology, v. 55, p. 372–374.

Schoeberl, M.R., Doiron, S.D., Lait, L.R., Newman, PA., and Krueger, A.J., 1993, A simulation of the Cerro Hudson SO_2 cloud: Journal of Geophysical Research, v. 98, p. 2949–2955.