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The Injection of Sulfuric Acid Aerosols in the Stratosphere by the El Chichón Volcano and its Related Hazards to the International Air Traffic

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Abstract. With respect to atmospheric impact, the 1982 eruption of the El Chichón volcano in Mexico is one of the most significant volcanic events of this century. The presence in the stratosphere, during several years, of an unusally high amount of sulfuric acid aerosols produced by this eruption is thought to be responsible for severe windshield damages on high-flying commercial jets. This problem took epidemic proportions in 1983–1984 and the cost to commercial aviation companies is estimated at several tens of millions of U.S. dollars.

Key words. El Chichón volcano, sulfuric acid aerosols, volcanic gases, aircraft windshield, stratosphere.

1. Introduction

Volcanic eruptions represent a significant hazard for civil air transport. Numerous encounters of aircraft flying in volcanic plumes have been reported during the past ten years (Le Guern and Reddan, 1982; Rose *et al.*, 1983; Blong, 1984; Rose, 1986). These incidents were sometimes serious, as in Indonesia in 1982 when two Boeing 747s flying through the eruptive plume of the Galunggung volcano at 11 km altitude, suffered severe engine damage resulting in emergency landings (Oake, 1983). Due to the increasing density of international air traffic, the problem of explosive volcanic eruptions is of major concern for the International Civil Aviation Organizations (ICAO). This situation has led to the constitution of a Volcanic Ash Warnings (VAW) study group to improve the communications between volcanologists and members of Air Civil Transport Organization (Smith, 1984). Research is currently underway to improve the detection capabilities of volcanic ash plumes by satellite images (*Aviation Week and Space Technology*, 1987; Rose and Holasek, 1988).

This paper describes another type of volcanic hazard, observed after the eruption of the El Chichón volcano in Mexico. Since it is related to the emission of gaseous components and not silicate ash, it is less conspicuous than the problems cited above.

Volcanic gas emissions are well known to be responsible for numerous hazards to human population (sometimes very serious, as was the case in Indonesia in 1979 or Lake Nyos in 1983), cattle, agriculture and buildings (Blong, 1984; Bolt *et al.*, 1975).

2. Characteristics of the El Chichón Eruption

It is now well recognized that the April 1982 eruption of the El Chichón volcano in Mexico was an unusual event. With a volume of ash produced of 0.5–0.6 km^3, the magnitude of the eruption was not exceptional, being comparable to that of Mt St Helens (0.4 km^3), but unusally large amounts of sulfur were injected into the atmosphere (Pollack *et al.*, 1983). This eruption injected a massive quantity of gaseous SO_2 up to 28 km altitude. Photolysis converted this SO_2 gas to an aerosol layer of sub-micron ($\approx 0.1\ \mu m$) sulfuric acid particles (Hofmann and Rosen, 1983a, b). The total mass of sulfuric acid aerosols remaining in the stratosphere $6\frac{1}{2}$ months after the eruption is estimated at about 8 Tg (1 Tg = 10^6 metric tons), but the equivalent of more than 20 Tg were probably initially injected in the stratosphere (Hofmann and Rosen, 1983b). In comparison, the 1980 eruption of Mt St Helens contributed only 0.20 Tg of H_2SO_4 aerosols and the 1974 Fuego eruption about 0.5 Tg (Table I) (Hofmann and Rosen, 1982).

Three weeks after the eruption, the volcanic aerosol layer circled the globe. During the summer of 1982, this cloud remained largely confined to tropical latitudes with only intermittent transport to northern mid-latitudes revealed by LIDAR (Adriani *et*

Table I. Estimates of H_2SO_4 and HCl contributions to the stratospheric burden by recent volcanic eruptions (1974–1986)

Date	Volcano	Lat. (N)	Alt. (km)	H_2SO_4 (Tg)	HCl (Tg)	Ref.
14 Oct 1974	Fuego	14.5°	22	0.5	–	1
23 Jan 1976	St Augustine	59°	11	m	(0.08–0.18)[b]	2,3
18 May 1980	Mt St Helens	46°	22–23	0.25[a]	0.05	1,4
28 Apr 1981	Alaid	51°	15	0.15	–	5
15 May 1981	Pagan	18°	13.5	m	–	5
Jan 1982	Mystery cloud	20°	17	5.6	–	6
4 Apr 1982	El Chichón	17°	27–28	20	0.04	7,8
Nov 1985	Ruiz	23°S	–	m	–	2
28 Mar 1986	St Augustine	59°	13	m	(0.07–0.9)	9,4

– no data: 1 Tg = 10^6 metric tons.

[a] total of the 3 major eruptions: 18 May, 7 Aug, and 18 Oct 1980.

[b] numbers in parentheses represent total atmospheric input.

m: no or very weak aerosol enhancement.

1. Hofmann and Rosen (1982); 2. Hofmann and Rosen (1987); 3. Johnston (1980); 4. Symonds *et al.* (1988); 5. Hofmann and Rosen (1981); 6. Evans and Kerr, (1983); 7. Hofmann and Rosen (1983b); 8. Mankin and Coffey (1984); 9. Rose *et al.* (1988).

al., 1983; D'Altorio and Visconti, 1983; Reiter *et al.*, 1983). During this period, the stratospheric cloud was observed in two distinct layers: a lower layer extending from the tropopause (12–16 km) to about 21 km and an upper layer at 23–28 km. The average proportion of sulfuric acid to H_2O in the cloud was 75% H_2SO_4/25% H_2O (Hofmann and Rosen, 1983b).

It is only after October 1982 that the major aerosol mass moved to high latitudes due to the poleward drift in the stratospheric wind circulation at the end of the summer. By the end of 1982, the two stratospheric clouds mixed producing one layer, reached high latitudes in polar regions, while its peak concentration descended to 21 km due to particle sedimentation (Hofmann and Rosen, 1983b; McCormick *et al.*, 1983b; Pollack *et al.*, 1983).

This eruption also injected a significant amount of HCl into the stratosphere. Mankin and Coffey (1984) report a 40% increase of the HCl content in the stratospheric volcanic cloud in the months following the eruption. The total mass of stratospheric HCl produced is estimated at 0.04 Tg, which represents 9% of the global HCl burden of the stratosphere. A significant part of this HCl could have been produced by the reaction of NaCl particles with the H_2SO_4 aerosol droplets, as suggested by Woods *et al.*, 1985.

The silicate ash component was a significant fraction of the stratospheric cloud in May through July 1982 (Mackinnon *et al.*, 1984). However, due to higher sedimentation rates, it rapidly became a minor component, even in the coarser fraction ($> 1\ \mu m$) of the cloud (Gooding *et al.*, 1983; Woods and Chuan, 1983). By October 1982, the high altitude (20 km) stratospheric cloud was almost entirely composed of H_2SO_4 droplets. The total ash load of the stratosphere was estimated at 8400–32000 metric tons. This corresponds to an average ash/H_2SO_4 ratio of 10^{-4} (Gooding *et al.*, 1983).

The unusually large quantity of sulfuric acid aerosols significantly modified the solar backscattering properties of the upper atmosphere for a large part of the Northern Hemisphere, resulting in an increase in the monthly mean stratospheric temperatures from July to October 1982 well above those shown for the previous 18 years (Labitzke *et al.*, 1983; Parker and Browscombe, 1983).

3. The Aircraft's Windshield Problem

In early 1983, aircraft manufacturers recieved complaints from some airline companies about cockpit windows which suffered severe crazing damage after a very small number of flight hours. The crazing of cockpit windows consist of the appearance of a network of tiny fissures in the surface of the window. When severe, this crazing obscures pilot vision with direct sunlight and requires replacement (Rogers, 1983). The progressive crazing of acrylic-made windows is a routine problem on a commercial jet. It is usually caused by mechanical stress (depressurization) or chemical attack (de-icing fluids, cleaning solvent) and normally limits the working life of these windows to 10 000–20 000 flight hours.

During the first months of 1983, an abnormally high rate of crazing of these cockpit windows was suddenly observed, requiring very frequent replacements. The problem became epidemic in 1983 and 1984. Figure 1 shows that in the past Japan Airlines (JAL) experienced less than one window removal/month but in May 1983, this company experienced as high as 42 removals/month. The origin of this crazing was not easily found because not all airlines suffered from this problem. The problem was restricted to long-range, high-flying aircraft (B747, DC10, L1011) crossing the North Atlantic and polar areas. Aircraft used only in Europe or in Japan did not have this problem. And all the manufacturers of acrylic windows were concerned (Rogers, 1983).

When the crazing problem was at its peak in 1983–84, two different theories were suggested to explain its origin: (1) a decrease in the quality standards during the manufacturing processes of these windows (Ewald, 1984), or (2) an acid attack of the acrylic windows resulting from the presence of H_2SO_4 aerosols injected into the stratosphere by the El Chichón eruption (Rogers, 1984, 1985).

A decrease in the quality of acrylic windows was suspected essentially because laboratory attempts to reproduce the exact crazing patterns were not successful, although H_2SO_4 is known to be an effective crazing agent for an acrylic window (Ewald, 1984). The exact mechanism of crazing is certainly not resolved, but additional effects of minor components such as HCl or silicate ash were never tested. Furthermore, it is difficult to explain a simultaneous decrease in the quality

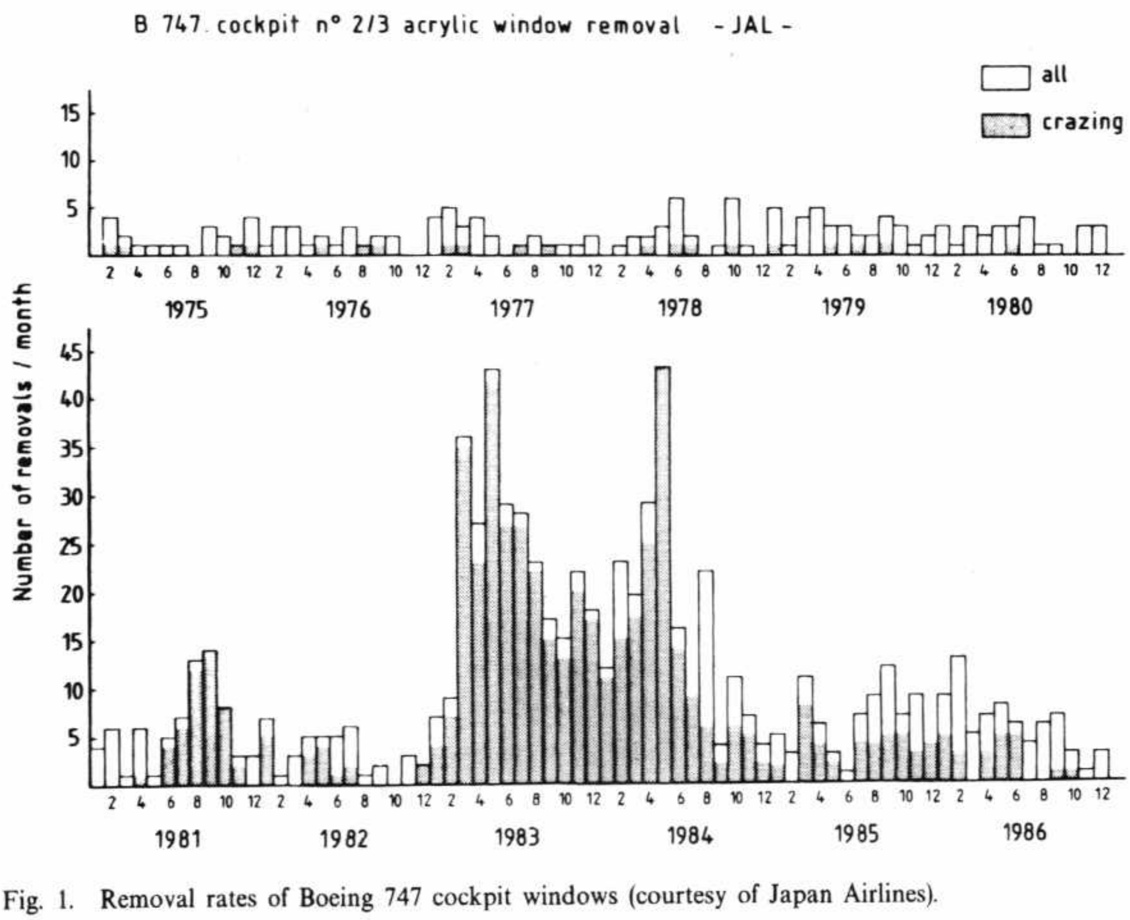

Fig. 1. Removal rates of Boeing 747 cockpit windows (courtesy of Japan Airlines).

standards from all the manufacturers and the fact that older windows suffered the same problem (Martens, 1985).

The volcanic theory explains the erratic distribution of the crazing problem between the different airline companies or even within the same company. Commercial jet aircraft normally cruise at altitudes of 26 000–38 000 ft. At low latitude, this corresponds to the upper troposphere. At high latitudes, however, the tropopause is much lower (Figure 2) and the aircraft cruising altitude is stratospheric. Because of this, polar routes would be most likely to encounter long-lived stratospheric volcanic aerosols.

Moreover, the delay observed between the 4 April eruption of the El Chichón volcano and the sudden increase in the crazing of windows (9–10 months (Figure 1)) corresponds well with the time elapsed before the main mass of the cloud reached high latitudes (>45°N). The significant migration of the cloud to northern latitudes started only after October 1982 (Pollack *et al.*, 1983). Lidar and radiometric observations at 46–47°N show that the maximum stratospheric perturbation resulting from the eruption was recorded 10 months after the eruption (Jäger and Carnuth, 1987: Pearson *et al.*, 1987). A secondary maximum in the window removal rates is observed in early 1984 and small maxima are again observed in early 1985 and early 1986 (Figure 1). These maxima can be correlated with the seasonal increases in the stratospheric optical depth recorded by radiometric measurements (Jäger and

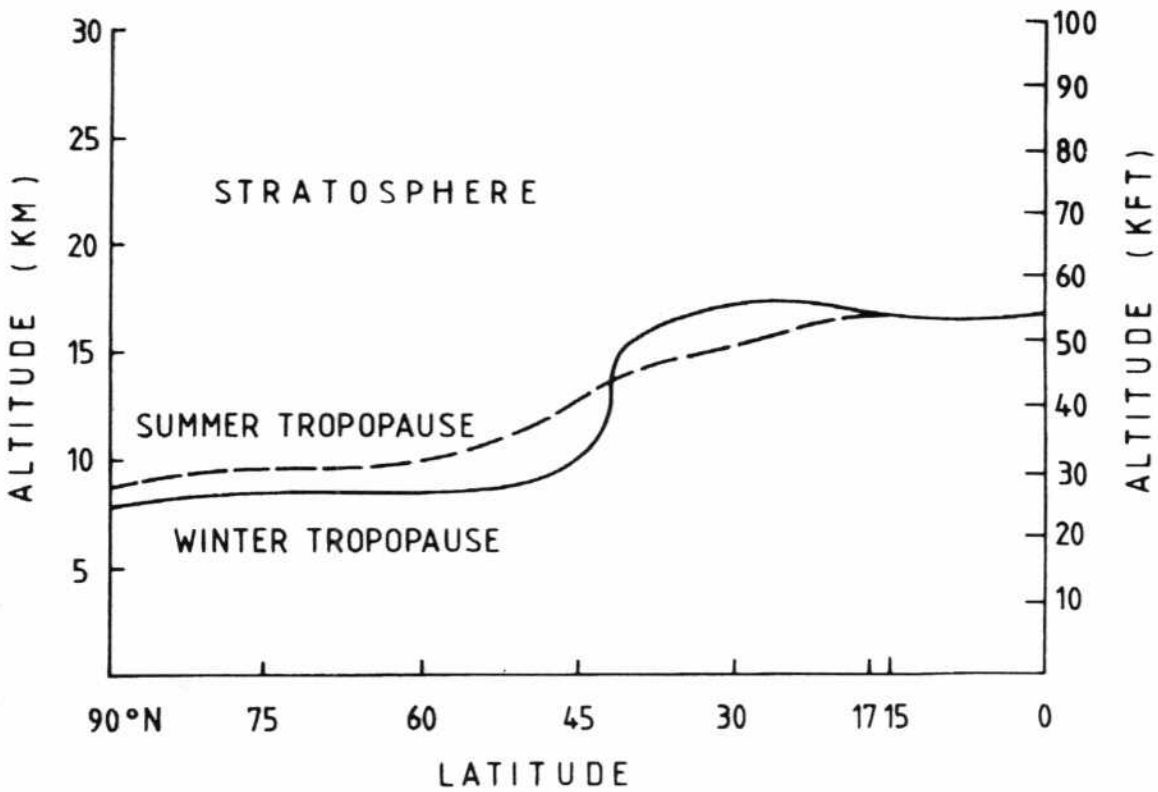

Fig. 2. Variation of tropopause altitude as a function of the latitude and seasonal effect (adapted from Feagle and Businger (1980) and Rogers (1983)).

Carnuth, 1987; Pearson *et al.*, 1987). These seasonal oscillations are interpreted as a signature of the annual transport of aerosols into the polar stratosphere from lower latitudes. The Ruiz eruption in November 1985, although very weak (Table I), could have been the source of some of the crazing observed during early 1986, since a short stratospheric perturbation was recorded (Hofmann and Rosen, 1987).

The short and relatively small increase in the crazing observed in 1981 (Figure 1) is possibly correlated to the cumulative effects of the Mt St Helens and Alaid eruptions (Table I). Although minor in comparison with El Chichón, these eruptions produced a significant stratospheric perturbation (Hofmann and Rosen, 1981). Radiometric optical depth measurements at mid-latitudes, show a peak value centered in mid-1981 (Pearson *et al.*, 1987). The 1974 Fuego eruption was somewhat larger than that of MSH and Alaid combined (Table I) and produced a more significant stratospheric perturbation (Hofmann and Rosen, 1987). However, JAL data (Figure 1) show no increase in the rate of window crazing for the period following the eruption (1975–1976). We were unable to obtain from Japan Airlines their flight records on polar routes for the period 1975–1976 and no conclusive evidence (for example, less air traffic in the polar regions) is found to explain this absence of window crazing. Data from Lufthansa show, however, a small increase in late 1975 and early 1976 in the rate of window crazing.

The presence of acids in the stratosphere was confirmed by observations of low pH readings on the outer surface of aircraft (as low as pH = 1). Most of these low pH readings were found on the acrylic windows and sometimes on the paints. In each case, the pH was neutralized by simply rinsing the surface with water at high pressure. This suggests the presence of small acid particles on the surface of the windows (Martens, 1985).

Finally, recent data from JAL (Figure 1) show that the crazing problem has now disappeared, just as the situation in the stratosphere is back to near-normal conditions.

A direct relationship between window crazing and volcanic clouds has also been observed during special scientific flights by an NCAR Queen Air aircraft in Guatemala in 1978 (Rose *et al.*, 1980). After a total of about 25 h of volcano flights, including about 2–3 h of flying within various types of volcanic clouds near active volcanoes, windshield replacement was necessary. In this case, other than exposure to the volcanic clouds, there was no explanation for the rapid crazing. In a subsequent series of volcano flights by the same aircraft in 1980, crazing was prevented by applying temporary polyethylene cover sheets (MYLAR) to the windshield before each volcano cloud flight.

4. Conclusions

The 4 April El Chichón eruption was only moderately explosive in comparison with cataclysmic eruptions such as those of Santa Maria (1902) which produced 10 km^3 of ash or Krakatau in 1883 (20 km^3) and Tambora in 1815 (180 km^3). But the injection of unusually large volumes of gaseous sulfur compounds (SO_2/H_2S) into the stratosphere characterized by a long residence time, caused a long-term and widespread occurrence of aircraft window crazing in the Northern Hemisphere, and particularly on polar routes.

The crazing problems are due to the unusually sulfur-rich nature of the El Chichón magma. The cause of this sulfur enrichment is not yet clearly understood. Although this enrichment was present in past eruptions of the El Chichón volcano (Rose *et al.*, 1984), it seems that, based on abundant geochemical data available, such enrichment occurs in only a small proportion of volcanic eruptions.

Although short-term corrective actions (use of glass windows or protective coatings) were undertaken in 1983–1984, no real technological solutions were found to counter future problems.

The cost of the window crazing problem for one company, Japan Airlines, is estimated at U.S. $6.8 million. This amount represents the cost of the cockpit windows replaced during the years 1983–1984. Since the charges for the labor or resulting from the immobilization of the aircraft or from the research involved to find the origin and a solution to the problem, are not taken into account, this represents only a fraction of the total cost.

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References

Adriani, A., Congeduti, F., Fiocco, G., and Gobbi, G. P.: 1983. One-year LIDAR observations of the stratospheric aerosol at Frascati, March 82 – March 83, *Geophys. Res. Lett.* **10**, 1005–1008.

Aviation Week and Space Technology, July 6 1987 **127**:1, 30–31.

Blong, R. J.: 1984, *Volcanic Hazards. A Source Book of the Effects of Eruptions*, Academic Press, New York.

Bolt, B. A., Horn, W. L., MacDonald, G. A., and Scott, R. F.: 1975; *Geological Hazards.*, Springer-Verlag, New York.

D'Altorio, A. and Visconti, G.: 1983, Lidar observations of dust layers transience in the stratosphere following the El Chichón eruption, *Geophys. Res. Lett.* **10**, 27–30.

Evans, W. F. and Kerr, J. B.: 1983, Estimates of the amount of sulphur dioxide injected into the stratosphere by the explosive volcanic eruptions: El Chichón, Mystery volcano, Mt. St. Helens, *Geophys. Res. Lett* **10**, 1049–1051.

Ewald, K.: 1984, Acrylic window crazing, unpublished report. ASTM subcommittee meeting, 23–25 October, 1984. Hilton Head, South Carolina.

Fleagle, R. G. and Businger, J. A.: 1980, *An Introduction to Atmospheric Physics* vol. 25, Academic Press, New York.

Gooding, J. L., Clanton, U. S., Gabel, E. M., and Warren, J. L.: El Chichón volcanic ash in the stratosphere: particle abundances and size distributions after the 1982 eruption, *Geophys. Res. Lett* **10**, 1033–1036.

Hofmann, D. J. and Rosen, J. M.: 1981, Stratospheric aerosol and condensation nuclei enhancements following the eruption of Alaid in April 1981, *Geophys. Res. Lett.* **8**, 1231–1234.

Hofmann, D. J. and Rosen, J. M.: 1982, Balloon-borne observations of stratospheric aerosol and condensation nuclei during the year following the Mt. St. Helens eruption, *J. Geophys. Res.* **87**, 11039–11061.

Hofmann, D. J. and Rosen, J. M.: 1983a, Sulfuric acid droplets formation and growth in the stratosphere after the 1982 eruption of El Chichón, *Science* **222**, 325–327.

Hofmann, D. J. and Rosen, J. M.: 1983b, Stratospheric sulfuric acid fraction and mass estimate for the 1982 volcanic eruption of El Chichón, *Geophys. Res. Lett.* **10**, 313–316.

Hofmann, D. J. and Rosen, J. M.: 1984, On the temporal variation of stratospheric aerosol size and mass during the first 18 months following the 1982 eruptions of El Chichón, *J. Geophys. Res.* **89**, 4883–4890.

Hofmann, D. J. and Rosen, J. M.: 1987, On the prolonged lifetime of the El Chichón sulfuric acid aerosol cloud, *J. Geophys. Res.* **92**, 9825–9830.

Jäger, H. and Carnuth, W.: 1987, The decay of the El Chichón stratospheric perturbation observed by Lidar at northern midlatitudes, *Geophys. Res. Lett.* **14**, 696–699.

Johnston, D. A.: 1980, Volcanic contribution of chlorine to the stratosphere: more significant to ozone than previously estimated? *Science* **209**, 491–493.

Labitzke, K. Naujokat, B., and McCormick, M. P.: 1983, Temperature effects on the stratosphere of the April 4, 1982 eruption of El Chichón, Mexico, *Geophys. Res. Lett.* **10**, 24–26.

Lazrus, A. L., Cadle, R. D., Gandrud, B. W., Greenberg, J. P., Huebert, B. J. and Rose W. I.: 1979, Sulfur and halogen chemistry of the stratosphere and of volcanic eruptions plumes, *J. Geophys. Res.* **84**, 7869–7875.

Le Guern, F. and Reddan, M.: 1982, Les panaches volcaniques et l'aviation commerciale, *INTRADO, Air France* **42**, 1–8. Ed. Air France, Paris.

McCormick, M. P. and Swissler, T. J.: 1983a, Stratospheric aerosol mass and latitudinal distribution of the El Chichón eruption cloud for October 1982, *Geophys. Res. Lett.* **10**, 377–880.

McCormick, M. P., Trepte, C. R., and Kent, G. S.: 1983b, Spatial changes in the stratospheric aerosol associated with the North Polar vortex, *Geophys. Res. Lett.* **10** 941–944.

Mackinnon, I. D. R., Gooding, J. L., McKay, D. S., and Clanton, U.S.; 1984, The El Chichón stratospheric cloud: solid particulates and settling rates, *J. Volcanol. Geotherm. Res.* **23**, 125–146.

Mankin, W. G. and Coffey, M. T.: 1984, Increased stratospheric hydrogen chloride in the El Chichón cloud. *Science* **226**, 170–172.

Martens, J.: 1985, Crazing of acrylic windows, unpub. report, 18th General EACMT meeting, Montreux, 19–20 June 1985.

Oake, P. J.: 1983, Technical report in *British Airways Air Safety Review*, October 1983, pp. 14–19.

Parker, D. E. and Brownscombe, J. L.: 1983, Stratospheric warming following the El Chichón volcanic eruption, *Nature* **301**, 406–408.

Pearson, E. W., LeBaron, B. A., and Michalsky, J. J.: 1987, Decay of the El Chichón perturbation to the stratospheric aerosol layer: multispectral ground-based radiometric observations, *Geophys. Res. Lett.* **15**, 24–27.

Pollack, J. B., Toon, O. B., Danielsen, E. F., Hofmann, D. J. and Rosen, J. M.: 1983, The El Chichón volcanic cloud: an introduction, *Geophys. Res. Lett.* **10**, 989–992.

Reiter, R., Jäger, H., Carnuth, W., and Funk, W.: 1983, The El Chichón cloud over Central Europe, observed by LIDAR at Garmisch-Partenkirchen during 1982, *Geophys. Res. Lett.* **10**, 1001–1004.

Rogers, J. T.: 1983, Acrylic window crazing problem. Aircraft manufacturers review, unpub. report ATA meeting, Phoenix AZ, 16 July 1983.

Rogers, J. T.: 1984, Results of El Chichón, *Boeing Airliner*, April–June 1984, 19–25, Ed. Boeing Seattle.

Rogers, J. T.: 1985, Results of El Chichón – Part II. Premature acrylic window crazing report. *BOEING Airline*, April–June 1985, 1–5, Ed. Boeing, Seattle.

Rose, W. I., Chuan, R. L., Cadle, R. D. and Woods, D. C.: 1980, Small particles in volcanic eruption clouds, *Amer. J. Sci.* **280**, 671–696.

Rose, W. I., Wunderman, R. L., Hoffman, M. F., and Gate, L.: 1983, A volcanologist's review of atmospheric hazards of volcanic activity: Fuego and Mt St Helens, *J. Volcanol. Geotherm. Res.* **17**, 133–157.

Rose, W. I., Bornhorst, T. J., Halsor, S. P., Capaul, W. A., Plumley, P. S., De La Cruz-Reyna, S., Mena, M., and Mota, R.: 1984, Volcán El Chichón, Mexico: pre-1982 S-rich eruptive activity, *J. Volcanol, Geotherm. Res.* **23**, 147–167.

Rose, W. I.: 1986, Interaction of aircraft and explosive eruption clouds: a volcanologist's perspective, *AIAA J.* **25**, 52–58.

Rose, W. I. and Holasek, R. E.: 1988, Anatomy of 1986 Augustine volcano eruption as recorded by digital AVHRR weather satellite data, *EOS*, **69**, 529.

Rose, W. I., Heiken, G., Wohletz, K., Eppler, D., Barr, S., Miller, T., Chuan, R. L., and Symonds, R. B.: 1988, Direct rate measurements of eruption plumes at Augustine volcano: a problem of scaling and uncontrolled variables, *J. Geophys. Res.* **93**, 4485–4499.

Smith, W.: 1984, The effects of volcanic ash on air operations, International Civil Aviation Organization (ICAO), Volcanic Ash Warning study group memorandum.

Symonds, R. B., Rose, W. I., and Reed, M. H.: 1988, Contribution of Cl- and F- bearing gases to the atmosphere by volcanoes, *Nature* **334**, 415–418.

Woods, D. C. and Chuan, R. L.: 1983, Size-specific composition of aerosols in the El Chichón volcanic cloud, *Geophys. Res. Lett.* **10**, 1041–1044.

Woods, D. C., Chuan, R. L., and Rose, W. I.: 1985, Halite particles injected into the stratosphere by the 1982 El Chichón eruption, *Science* **230**, 170–172.