the plate boundary that is a forerunner of the future great earthquake in the Shumagin region.

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3. The level lines vary in length between 600 and 1000 m and are oriented approximately in the direction of plate convergence. In the leveling we have used first-order procedures. The average sight length has been reduced from ≈ 35 to ≤ 30 m over the years, and the equalization of backsight and foresight lengths has been controlled more carefully. These improvements in our procedures show no correlation with the observed signals, except by a trend toward smaller errors. The cool, overcast, and moderately windy weather conditions in the Shumagins are favorable to leveling. We are able to further reduce refraction effects by measuring along beaches where the total elevation change along the line is less than a few meters. Errors due to ocean loading are random from year to year and are less than ±0.5 mm in a 1-km line. The tilt (as in Fig. 2a) is the height difference between the ends of the line divided by the line length and is referred to an arbitrary datum. The two data points plotted for each year are the results of the forward and backward runs of leveling. The closure error between these is the best check on human errors or blunders in measuring the line. The 1 σ error (where σ is the standard deviation) on each tilt datum is calculated from the four foresight and four backsight readings of the stadia rods taken at each tripod position.
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Sulfuric Acid Droplet Formation and Growth in the Stratosphere After the 1982 Eruption of El Chichón

Abstract. *The eruption of El Chichón Volcano in March and April 1982 resulted in the nucleation of large numbers of new sulfuric acid droplets and an increase by nearly an order of magnitude in the size of the preexisting particles in the stratosphere. Nearly 10^7 metric tons of sulfuric acid remained in the stratosphere by the end of 1982, about 40 times as much as was deposited by Mount St. Helens in 1980.*

Instrumented balloons, capable of altitudes in excess of 30 km, have been used to study the formation and growth of H_2SO_4 droplets from sulfurous gases injected into the stratosphere during the 28 March and 3 and 4 April 1982 eruptions of El Chichón Volcano in southern Mexico. The optical particle counters used in this work cover the size range from 0.01 to 1.8 μm in radius (r) (*1, 2*). Studies of earlier eruptions (*2–4*) have revealed considerable information on the gas-to-particle process that occurs in the stratosphere after major volcanic eruptions. However, none of these eruptions injected nearly as much material to as high an altitude as the 1982 El Chichón eruption. This eruption appears to be a once-in-a-century event that has apparently already produced a 3° to 5°C heating in the equatorial stratosphere (*5*) and will probably cause a measurable climatic perturbation. Thus, measurements made during the formation of the global aerosol layer are of the utmost importance in understanding this phenomenon.

Figure 1 shows the average integral particle concentration versus size as measured by balloon-borne particle counters in the main stratospheric particle layer at an altitude of 25 ± 0.5 km over Laredo, Texas, in May 1982, about 1½ months after the eruption. We observed large excesses of particles in both the small (r = 0.01 μm) and the large (r = 1 μm) size ranges. The concentration at 0.01 μm (~ 200 cm^{-3}) represents an average of data with considerable fluctuation in the 1 km of altitude. Concentrations as high as 750 cm^{-3} were present.

The data in Fig. 1 have been fitted with normal distributions in the logarithm of r. Such distributions are thought to be representative of the physical processes occurring. Such a size distribution, in differential bimodal form, may be expressed as

$$n(r)dr = \sum_{i=0}^{1} \frac{N_i}{(2\pi)^{1/2}} \exp\left(-\frac{\alpha_i^2}{2}\right) d\alpha_i$$

where $n(r)$ is the number concentration of particles per dr at r, N_i is the total concentration of the ith mode, and

$$\alpha_i = \frac{\ln(r/r_i)}{\ln \sigma_i}$$

where r_i is the ith modal radius (the median radius) and σ_i is the ith modal width (dimensionless). The integral of $n(r)dr$ above a radius r gives $N(> r)$, the integral concentration of particles, which is the measured parameter.

Also indicated in Fig. 1 is the preeruption distribution (dotted curve) as measured at Laramie during February to April 1982. Although the aerosol concentrations were slightly disturbed in the 18-km region at this time as a result of a smaller unidentified volcanic eruption in early 1982, the aerosol concentrations at 25 km appeared normal and are considered representative of preeruption data for Texas as the latitudinal particle gradient in the stratosphere is small during undisturbed periods (*6*).

Even though the log-normal fit to the data in Fig. 1 is not unique, the data could not be fitted with a single distribution of this type. The measured size distribution is clearly bimodal with mode radii at about 0.02 and 0.72 μm. These values could be varied slightly; however, a small- and a large-particle mode definitely appear to be present. The large-particle mode has nearly the same concentration as the preeruption mode; this result suggests that it has evolved through growth of the latter. The small-particle mode, which was not present prior to the eruption, is indicative of new particles. Since the coagulation time for the observed concentrations of 0.01-μm particles is of the order of a few days and the measurement was made 1½ months after the eruption, one must conclude that the small particles were not injected by the eruption itself but formed subsequently and probably continuously in the stratosphere.

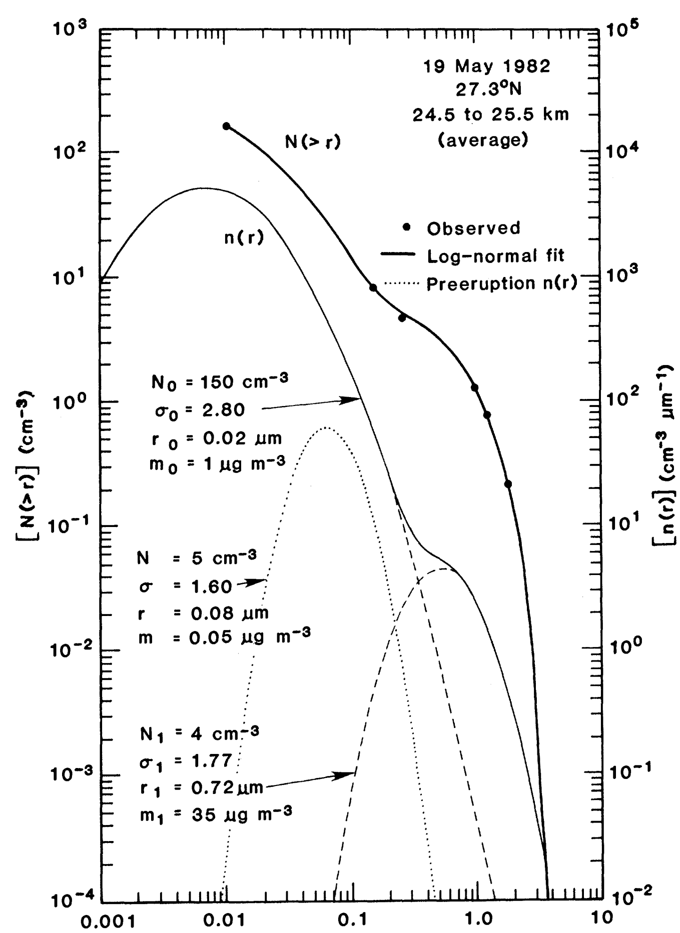
As indicated in Fig. 1, most of the particles are in the small-particle mode, but most of the mass m (35 as compared to 1 $\mu g\ m^{-3}$) is in the large-particle mode. It was these large particles that were primarily responsible for the unusual scattering of the visible solar light and large laser radar returns observed in Hawaii (*7*) and for the highly enhanced persistent twilight phenomena after the eruption.

Additional measurements were made in southern Texas in August and October 1982. They gave very similar results, shown in Fig. 2 in terms of the October balloon flight from Del Rio, Texas. There are several noticeable differences between these data and the May data (Fig. 1). (i) By October production of small ($r \sim 0.01$ μm) particles had ceased (the same was true in an August flight from Sinton, Texas), and they were totally depleted through coagulation and growth to give a small-particle mode at about 0.3 μm. (ii) The May large-particle mode at about 0.7 μm, although more difficult to measure, had apparently grown to about 1 μm and was considerably reduced in concentration (by a factor of 20), probably as a result of gravitational settling (a 1-μm particle will fall 1 km every 10 days at 25-km altitude). The mass concentration was reduced by about a factor of 8, and most of it now resided in the 0.3-μm mode.

Suggestions of a secondary 1-μm mode in the particle size distribution were also present 6 to 8 months after the eruptions of Mount St. Helens in 1980 and Alaid in 1981 (*2, 4*); however, the main mode in these eruptions was similar to the preeruption mode (~ 0.08 μm) rather than 0.3 μm as observed for El Chichón. Thus the 1982 El Chichón eruption stands out as one that produced higher concentrations of larger particles. The total mass has been estimated from these data to be about 10^7 metric tons about 6 months after the eruption and probably more than 2×10^7 tons initially (*8*). In contrast, the Mount St. Helens eruption of 1980 contributed about 0.25×10^6 tons to the stratosphere (*2*).

During the October flight, the intake tube to one of the particle counters was heated during a slow balloon descent through the 25-km particle layer. Nearly all the particles present had $r \geq 0.15$ μm, and 99 percent of these were observed to vaporize at a temperature of 104° ± 3°C. At 25 km (pressure = 18.5 mmHg), water boils at about 20°C and pure H_2SO_4 at about 220°C. The measured boiling point is consistent with an aerosol composition of 80 percent H_2SO_4 and 20 percent H_2O droplets. Thus it is reasonable to assume that the observations in Figs. 1 and 2 represent the nucleation and growth of H_2SO_4–H_2O droplets in the stratosphere.

Only recently has the stratospheric concentration of H_2SO_4 vapor been esti-



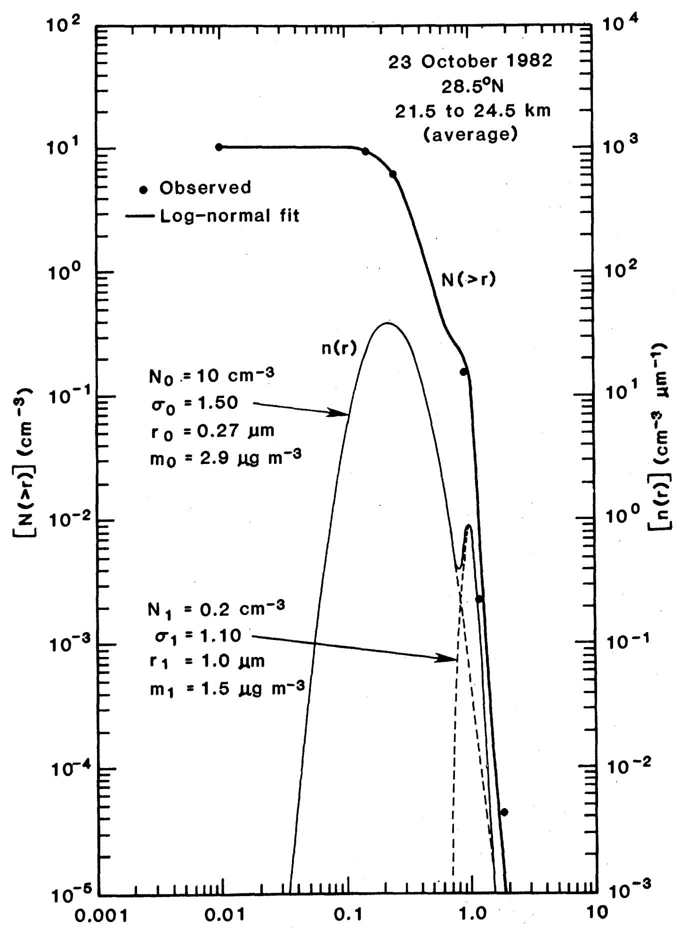


Fig. 1 (left). Results of optical particle counter measurements at 25 km, about 1½ months after the 1982 eruption of El Chichón. These measurements (large dots) are fitted with a bimodal log-normal particle size distribution (see text for explanation) which suggests modal radii at about 0.02 and 0.72 μm. The dotted distribution is typical of preeruption conditions. Fig. 2 (right). Same as Fig. 1, but about 7½ months after the eruption.

mated from models (*9*) and measured directly (*10*). These measurements indicate that the altitude region from 25 to 30 km is nearly saturated with a vapor concentration of 10^5 to 10^6 molecules per cubic centimeter. Thus, after a major volcanic eruption, which injects large amounts of sulfurous gases to the 25-km region (as El Chichón apparently did), a high degree of H_2SO_4 supersaturation can evolve in this region. Under such conditions two things, important for particle formation in the stratosphere, can happen. (i) If the supersaturation is high enough (H_2SO_4 concentration exceeds $\sim 10^7$ molecules per cubic centimeter at 25 km), H_2SO_4–H_2O droplets will form homogeneously from the gas phase (*11*), that is, do not require a condensation center. (ii) Accretion of the vapor and the newly formed droplets on existing particles will cause substantial growth of the preexisting distribution of particles.

Creation of new droplets under supersaturated conditions is a very rapid and copious process, resulting in high particle concentrations ($\gtrsim 10^3$ cm^{-3}) initially. However, since the coagulation rate depends on the square of the concentration, the coagulation of droplets takes place very rapidly. As the size of the coagulating droplets increases, the concentration decreases rapidly and the lifetime increases. Under such conditions the smallest particles are rapidly depleted; this results in a maximum in the particle size distribution. The distribution so formed approximates a log-normal distribution (*12*), as we have observed. Thus our interpretation of the observed bimodal distribution as representing new droplet nucleation on the one hand and growth of the preexisting distribution on the other is consistent with what is known about such stratospheric processes.

The fact that the August and October 1-μm particle concentrations observed over Texas at 25 km were very similar and that the total mass was relatively constant indicates that, although no new particles were being created during this period, particles lost as a result of gravitational settling were replaced through growth of smaller particles. Since particles with $r \lesssim 0.05$ μm had essentially disappeared as a result of coagulation by August, replenishment of the 1-μm droplets probably occurred primarily through molecular accretion on particles in the 0.3-μm mode. With this assumption, one can estimate the H_2SO_4 concentration. For kinetically limited growth in the low-pressure limit, one may obtain the rate of change of the droplet radius by equating the molecular mass flux on a particle's surface with the rate of change of mass of the particle

$$\frac{dr}{dt} = \frac{1}{4} v V n_a$$

where v is the molecular thermal velocity, V is the molecular volume, and n_a is the H_2SO_4 molecular concentration in excess of the saturation concentration. Growth from 0.3 to 1 μm in 100 days (the time required for a 1-μm particle to fall from 25 to 18 km) gives an H_2SO_4 concentration of about 10^7 molecules per cubic centimeter.

The loss rate of vapor to a distribution of particles is given by the molecular flux on a surface multiplied by the total particle surface area

$$\frac{dn_a}{dt} = -\frac{1}{4} v n_a \int_0^\infty 4\pi r^2 n(r) dr$$

Thus the exponential time constant for vapor loss is given by

$$\tau = \left[\pi v \int_0^\infty r^2 n(r) dr\right]^{-1}$$

For the size distribution observed in May, τ had a value of only about 5 minutes, whereas in August and October it had lengthened somewhat to 15 to 20 minutes. This result suggests that the vapor would be rapidly used up (would be down by a factor of 100 in 4.6 time constants) by the particles if it were not replenished. Thus the conversion from volcanic sulfurous gas to H_2SO_4 must have taken place continuously.

Measurements at Laramie through December 1982 indicate a continual growth of the total mass in the stratosphere. Thus the normal "decay" of the event, which for past eruptions had an exponential time constant of about 10 months (*3*), had not yet begun. The El Chichón eruption of 1982 is the largest such event, in terms of lasting effects on the stratosphere, since the advent of stratospheric measurements and probably will prove to be the largest in at least the past century.

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Zonal Winds in the Central Equatorial Pacific and El Niño

Abstract. *Easterly trade winds from near-equatorial islands in the central Pacific weakened before each El Niño between 1950 and 1978, except for the 1963 El Niño. The weakening of the easterlies and their later collapse did not occur uniformly over several months, but rather through a series of strong westerly wind bursts lasting 1 to 3 weeks. The bursts may force equatorial Kelvin waves in the ocean that can both initiate and sustain the sea surface warming characteristics of El Niño events.*

The term El Niño commonly refers to the occurrence of unusually warm surface water near the coast of South America just south of the equator (*1, 2*). As part of the southern oscillation (*2*), El Niño precedes or coincides with anomalous oceanographic (*3*) and meteorological (*2*) conditions throughout the tropical Pacific, and has been related to mid-latitude weather (*4*). The exact sequence of events and the physical mechanisms of their interaction are subjects of increasing research and debate. We examine here some newly acquired time series of wind data from central Pacific islands and relate the zonal wind fluctuations to El Niño events.

Wyrtki (*3*) suggested that El Niño events follow a strengthening and subsequent weakening of the trade winds over the central equatorial Pacific. Theoretically, the effect of these wind changes on the ocean can be quickly propagated eastward by equatorial waves (*5, 6*). The connection between the propagation of these waves and changes in sea surface temperature (SST) is not completely understood, but SST anomalies can be