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EMISSION RATES OF CO_2 FROM PLUME MEASUREMENTS

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ABSTRACT

Most of the CO_2 that emanated from Mount St. Helens became part of the gas plume as it moved away from the volcano. An airborne technique was developed for continuous sampling and infrared analysis for CO_2 in the plume. The CO_2-emission rates were determined by measuring the area, the horizontal velocity, and the CO_2 concentration anomaly in vertical cross sections of the plume. CO_2-emission rates were measured 55 times from July 6 to October 29, 1980. The precision of individual CO_2-emission rates is estimated to be ±10–40 percent. The emission rate varied from 2,100 t/day (metric tons per day; 2.1×10^9 g/day) to about 22,000 t/day (2.2×10^{10} g/day). Degassing of dacitic liquid is the most likely source of excess CO_2 in the gas plume. The total amount of CO_2 released to the atmosphere by volcanic activity during noneruptive periods at Mount St. Helens from the beginning of July 1980 to the end of October is about 910,000 t (9.1×10^{11} g). The contribution of CO_2 to the atmosphere exceeded that of SO_2. The monthly mean emission rate of CO_2 decreased significantly from 11,500 t/day (July 1980) to 5,300 t/day (October 1980). Significant changes in the emission rate of CO_2 may have occurred as a result of migration of CO_2 from deeper magma, intrusion of magma at a shallow level, change in the permeability of the vent, and change in the rate of crystallization of magmatic liquid. It is not possible at the present time to establish the actual cause or causes for changes in the CO_2-emission rate. Three Plinian eruptions (July 22, August 7, and October 16–18) of dacitic magma were preceded by significant decreases of CO_2-emission rates. The decreases, which occurred several days before eruptions, were useful for anticipating the August 7 and October 16–18 eruptions.

INTRODUCTION

The resumption of volcanic activity at Mount St. Helens in March 1980, and potential hazards from eruptions, prompted studies of the gaseous emissions and their discharge rates. The objectives of these studies are to provide information about the degassing of the subsurface magma body and to provide advance warning of volcanic eruptions. This report describes an airborne method for determination of the CO_2-emission rate and the results obtained at Mount St. Helens from July 6 to November 1, 1980.

ACKNOWLEDGMENTS

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DETERMINATION OF CO_2-EMISSION RATES

Most of the CO_2 that emanated from the volcano moved away in the gas plume. Hence, the CO_2-emission rate could be determined by measuring the area, the horizontal velocity, and the CO_2 concentration anomaly in a vertical cross section of the plume. Because the plume consisted of volcanic gases greatly diluted by atmospheric air, and because both contain CO_2, only the "excess" CO_2 concentration (that amount above the concentration normally found in the atmosphere) can be attributed to the volcanic source. CO_2-emission rates reported herein refer to the excess CO_2 present in the plume.

PROCEDURE FOR MEASURING EXCESS CO_2 IN THE PLUME

The airborne method for determination of excess CO_2 in the plume utilized continuous airborne sampling and infrared analysis for CO_2 during flights through the plume. An air-sampling tube was attached to the fuselage of a twin-engine, propeller-driven aircraft. The sample inlet (open to the front) was placed in a position such that contamination from aircraft engine exhaust was avoided. Because of the speed of the aircraft (72 m/s), the air sample flowed continuously through the gas cell (5.64 L) of an infrared spectrophotometer (Miran 1A, Foxboro Analytics, Inc., Foxboro, Mass.) at a rate of 0.4 L/s. The gas in the cell was completely replaced about every 15 s. The variations in spectral transmission through the gas over a 6.75-m path length were continuously recorded at the 4.26 μm absorption band for CO_2 while the aircraft flew into and across the plume (that is, at right angles to the plume trajectory) at some constant altitude (±10 m) and the constant airspeed of 72±2 m/s. The transmission was constant for air from outside the plume, but it decreased within the plume due to increased absorption caused by elevated amounts of CO_2 (fig. 118). After a step increase or decrease of CO_2 concentration in ambient air along a flight path, about 15 s are required for the gas in the instrument to attain the new composition. For an aircraft speed about 72 m/s and the overall response time about 15 s, the distance traveled before attainment of the full analytical response is about 1.1 km. The slow response time causes the measured shape of the plume cross section to be distorted and limits the spatial resolution of CO_2-concentration variations. The apparent width of the plume, as defined by the width of the measured CO_2-concentration anomaly, should exceed the actual width of the plume by as much as 2.2 km. Step changes of CO_2 concentration should appear as gradual changes over a 1.1-km distance. The distortions of the apparent plume width and the concentration profiles do not affect the integral (along the flight path) of the excess CO_2 concentration, provided the actual plume width exceeds 1.1 km.

Because the response of the instrument to changes in the mass of CO_2 per unit volume can be determined by calibrations, the excess CO_2 concentration in the

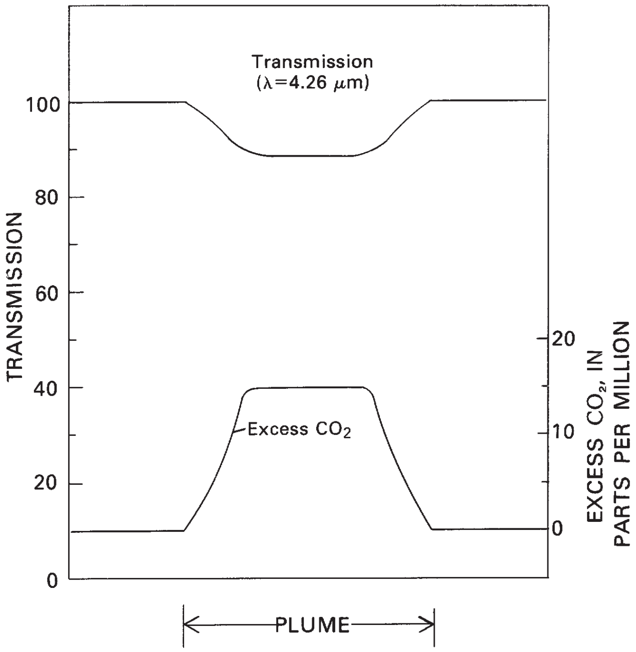

Figure 118.—Decrease of transmission at the 4.26-μm absorption band for CO_2 during flight through the plume at an altitude of 2,500 m.

plume can be calculated directly from the transmission measurements. Because pressure and temperature vary with altitude, and the total mass of CO_2 per unit volume can be calculated from the ideal gas law for a given composition of air, it is possible to calibrate the instrument response by varying altitude in air outside the plume and measuring the changes in transmission. We have assumed a CO_2 concentration of 330 ppm by volume in atmospheric air outside the plume, and have used the National Advisory Committee for Aeronautics formulas (Haltiner and Martin, 1957, p. 52) for pressure and temperature in the standard atmosphere (fig. 119). The logarithm of the transmission ratio varies inversely with the mass of CO_2 per unit volume. The excess CO_2 concentrations along flight paths through the plume have been calculated from the transmission measurements and include corrections for pressure and temperature.

Measurements along each flight path yield a line profile of the excess CO_2 concentrations in the plume at a particular altitude. A sequence of flight paths (often as many as eight) at various altitudes gives a sequence of CO_2-concentration profiles through an entire cross section of the plume. The results are used to construct a graph (for example, fig. 120) that shows the spatial dependence of excess CO_2 in a vertical cross section through the plume. As discussed above, the apparent plume cross section is as much as 2.2 km wider than the actual plume and the concentration gradients in the actual plume are greater than shown in figure 120. The CO_2-concentration anomaly is integrated (graphically) to obtain the product (ppm·m^2) of the mean CO_2 concentration (ppm) and the plume area (m^2).

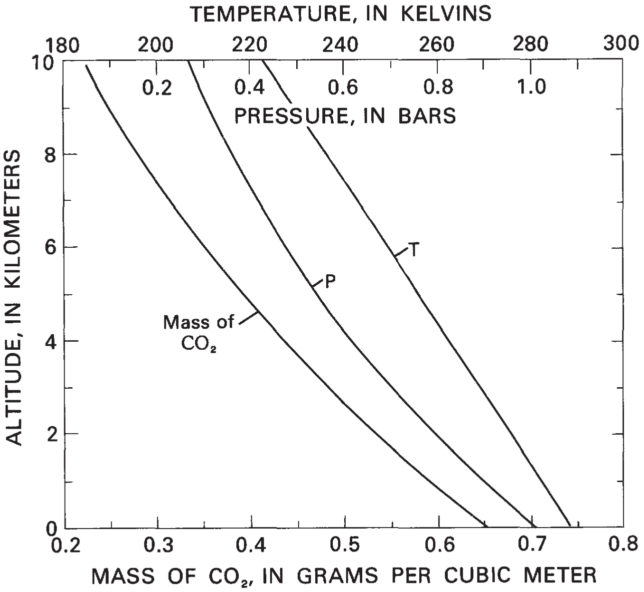

Figure 119.—Pressure, temperature, and mass of CO_2 per unit volume in the atmosphere. Pressure (P) and temperature (T) were calculated from National Advisory Committee for Aeronautics formulas for the standard atmosphere (Haltiner and Martin, 1957, p. 52). Mass of CO_2 per unit volume of air was calculated from the ideal gas law for 330 ppm CO_2 and pressures and temperatures used in formulas for the standard atmosphere.

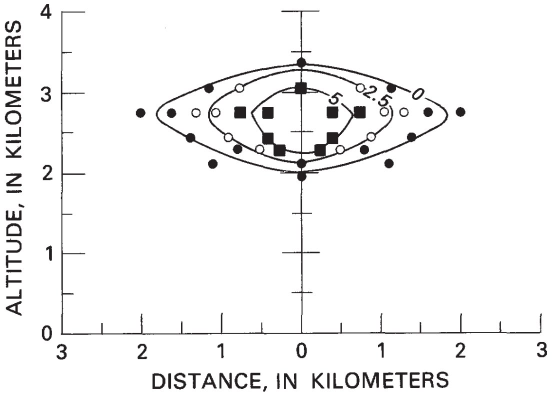

Figure 120.—Spatial distribution of excess CO_2 concentration in a cross section of plume on July 9, 1980. Solid circles, 0 ppm; open circles, 2.5 ppm; solid squares, 5 ppm CO_2 by volume in excess of the CO_2 concentration in the atmosphere distant from plume. The 0, 2.5, and 5 ppm contours are shown as solid lines.

MEASUREMENT OF THE WIND SPEED

The average horizontal velocity of the plume at the altitude and position of the CO_2-concentration anomaly must be known in order to calculate an emission rate for CO_2. Emission rates obtained through August 2 are based upon official National Weather Service forecasts of the winds aloft at altitudes appropriate for the plumes. Emission rates obtained after August 2 are more accurate because the wind speeds were actually determined from differences in the aircraft's true ground speeds for two flight paths parallel to the plume direction and in opposite directions, both flown at a constant air-speed.

True ground speeds were obtained by the pilot from Federal Aviation Administration radar measurements and (or) calculated from airborne radio navigation position measurements and elapsed time. Errors due to short-term fluctuations of the wind speed were reduced by flying in each direction for about 8 min, but changes in the average wind speed during the 2-hr measurement period may be significant.

CALCULATION OF THE CO_2-EMISSION RATE

The CO_2-emission rate is obtained from the product of the spatially averaged CO_2-concentration anomaly (ppm·m^2), the wind speed (m/s), and the density of CO_2 (g/m^3) at the pressure and temperature estimated for the mean altitude of the plume. Although the emission rates are reported in units of 10^9 g/day (10^3 t/day), each value represents about 2 hr of measurements.

ACCURACY AND PRECISION OF CO_2-EMISSION RATES

The accuracy and precision of individual measurements of the CO_2-emission rates are limited by the following sources of error:

1. The concentration of CO_2 in atmospheric air outside the plume is probably different from the assumed value of 330 ppm (volume). The CO_2 concentrations in air samples collected outside the plume in the vicinity of Mount St. Helens on October 22, 27, and 30, 1980, were determined by gas chromatography to be 351, 335, and 348 ppm, respectively (R. D. Cadle, written commun., 1980). Because the errors in emission rates are proportional to the errors in the assumed concentration of 330 ppm CO_2 in atmospheric air, the results determined in this study may be too small by 1-6 percent.

2. The CO_2 concentrations may be in error due to instrument calibration and (or) reading errors. Excess CO_2 concentrations determined in this study may be compared with those determined by R. D. Cadle, who collected gas samples in the plume at the same time our continuous measurements were made. On October 22, a flight through the plume at an altitude of 2,530 m gave a peak excess CO_2 concentration of 9 ppm in the plume, whereas Cadle's result for a bulk sample, based on the difference of two analytical results, was 11 ppm. Similar measurements on October 30 showed values of 2 ppm excess CO_2 for our technique and 2-3 ppm excess CO_2 by Cadle's methods. Results obtained by the two methods on October 27 showed large discrepancies, which might be due to an analytical error in the background value (335 ppm) for CO_2 in atmospheric air outside the plume on that day. Two measurements of CO_2 concentrations in atmospheric air on October 22 and 30 gave values of 351 and 348 ppm, respectively. If 350 ppm CO_2 is assumed for the atmospheric air on October 27, then the excess CO_2 concentrations obtained by the two methods are in much better agreement.

3. Graphical integration of the CO_2-concentration profile is subject to error and requires careful judgment and experience in order to obtain the best precision. Each plume cross section requires reading 100-200 points from the continuous chart recording of the infrared transmission, although only about 30 measurements of the apparent plume widths at various excess-CO_2 concentrations are shown in figure 120. The errors made at this stage are estimated to be about ±10 percent.

4. The actual wind speed is probably known to about ±25 percent for speeds between 10 and 20 knots, and to ±10 percent for speeds larger than 20 knots. At wind speeds of 3-5 knots, which are uncommon, the uncertainty is about ±40 percent.

5. The actual flight speeds and altitudes may be incorrect by ±5 percent.

The overall precision of the individual emission rates is estimated to range from ±10 to ±40 percent of the amount. Because the precision is so poor, it is necessary to obtain redundancy in order to demonstrate trends or changes in emission rates. Errors in the wind speed contribute large errors to individual measurements, but, because the errors should be random, the mean values of the emission rates have smaller errors.

RESULTS

The CO_2-emission rate was measured 34 times during the 55-day period from July 6 to August 29, 1980, and 20 times during the 44-day period from September 17 to October 29, 1980. The intervals between measurements averaged 1.6 and 2.2 days for the two periods, respectively. During these two periods, the plume was being sampled about 5 percent of the time.

The emission rates of CO_2 are plotted chronologically in figure 121. The emission rates of SO_2 (Casadevall and others, this volume) and the CO_2:SO_2 mass ratio are shown for comparison.

Table 10 lists the monthly variations of emission rates of CO_2 and SO_2. During each month, the CO_2-emission rate varied over a large range. From July to October, the monthly mean CO_2-emission rate *decreased* by a factor of two. However, from September 15 to October 9 there was a gradual *increase* in the CO_2-emission rate from 2,100 t/day to 5,400 t/day, except for a much larger rate (17,000 t/day) on September 27. Between October 9 and the October 16 eruption, the rate decreased to about 3,500 t/day.

Table 11 shows that the CO_2-emission rate decreased before the July 22, August 7, and October 16–18 Plinian eruptions. The preeruption decreases in the CO_2-emission rates are sufficiently large to be beyond the estimated errors of individual measurements. Because several measurements were taken in each time span, there is redundancy within each sequence of measurements.

The total amount of CO_2 emitted by Mount St. Helens from the beginning of July through the end of October is estimated to be about 910,000 t (9.1×10^{11} g). The relative amounts of magmatic and nonmagmatic CO_2 in this total are not known, but possible sources of the CO_2 will be considered.

DISCUSSION

The origin of CO_2 in the plume is not known at the present time. The geologic environment of the magma body within the active crater suggests two sources of CO_2 to be considered: (1) heating of ground water containing dissolved CO_2 and HCO_3^-, and (2) degassing of CO_2 from silicate liquids of dacitic composition.

The amount of ground water that circulates near the magma body in a given period of time is not known. However, if we assume that all of the excess CO_2 in the plume owes its origin to the heating of ground water and release of the dissolved CO_2 near the magma body, then we can estimate the rate at which water would have to be supplied. For a CO_2-emission

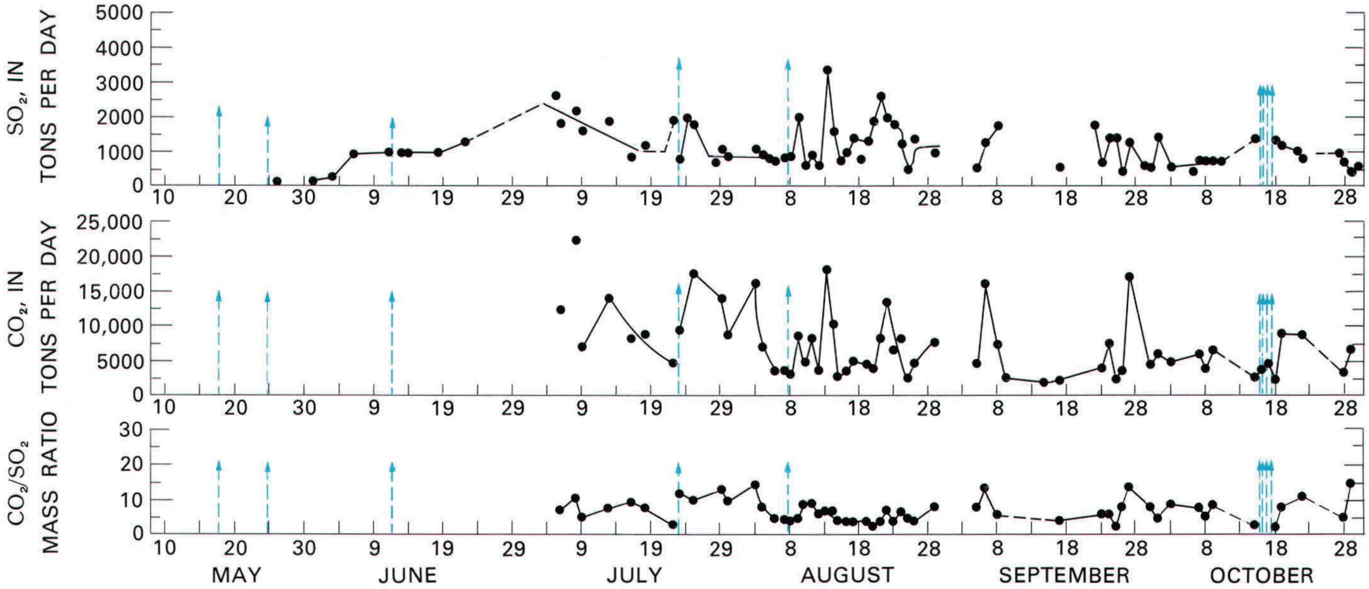

Figure 121.—Chronological variations in CO_2- and SO_2-emission rates and the CO_2/SO_2 mass ratio. The SO_2-emission rates are from Casadevall and others (this volume). Blue lines with arrows represent Plinian eruptions of dacitic magma. Dashed lines represent extrapolations.

Table 10.—Monthly variations of CO_2- and SO_2-emission rates, June to October 1980

[Leaders (---) indicate no data; SO_2 data from Casadevall and others, this volume]

	June	July	August	September	October
		CO_2			
Number of measurements---	0	11	23	12	11
Monthly mean (t/day)-----	---	11,500	7,100	6,000	5,300
Minimum----------------	---	4,800	2,500	1,500	2,400
Maximum----------------	---	22,000	16,000	17,000	8,900
		SO_2			
Number of measurements---	8	14	25	15	16
Monthly mean (t/day)-----	900	1,500	1,300	950	880
Minimum----------------	260	700	530	430	470
Maximum----------------	1,300	2,200	3,400	1,800	1,400
$\frac{\text{Monthly mean } CO_2}{\text{Monthly mean } SO_2}$	---	7.7	5.5	6.3	6.0

Table 11.—Changes in mean CO_2-emission rates before eruptions

[Number in parentheses is number of measurements in the mean]

Number of days before eruption	CO_2 emission rate (t/day)			
	July 22	August 7	October 16	Average
9 to 16--------	14,000 (4)	13,700 (5)	5,400 (4)	11,000
3 to 8---------	8,600 (2)	10,600 (3)	5,200 (2)	8,100
Less than 2----	4,800 (1)	3,700 (2)	3,200 (2)	3,900

rate of 10,000 t/day and assumed concentrations of 100-500 ppm (by weight) CO_2 dissolved in the ground water (see for instance, Davis and DeWiest, 1966, p. 106), the flow rate of water toward the magma body would have to be about 0.02-0.1 km^3 H_2O/day ($0.24–1.2\times10^9$ g H_2O/s). The volume of water required each day is equivalent to a layer with an area of 400 km^2 and a thickness of 5-25 cm. The required flow appears to be much too large for ground water to be the dominant source for the CO_2 emissions. Isotopic data also suggest that both the carbon and water in fumarolic gases are not meteoric (Evans and others, this volume).

Another possible source for the CO_2 is the degassing of the dacitic magma. The gas occluded in vesicles of pumice erupted in June 1980 includes CO_2 as an abundant species (Gary Olhoeft, oral commun., 1980). Also, CO_2 is an abundant component of the fumarole gases sampled at the crater in September 1980 (Casadevall and Greenland, this volume). The minimum amount of silicate liquid required to explain the CO_2 gas emissions could be estimated if the initial (preintrusion) CO_2 concentration of the liquid were known. Unfortunately, the initial CO_2 concentration of the liquid has not yet been determined. However, in order to consider the dacitic magma as a source for the CO_2, we might assume that the liquid phase of the dacite contained 0.13 weight percent CO_2 before degassing. (CO_2 was determined to be 0.13 weight percent in melt inclusions in olivine crystals in a subduction zone basalt studied by Harris, 1979.) Complete degassing of 0.77×10^{12} g of dacitic liquid per day could supply 10,000 t/day CO_2. The volume of completely degassed liquid required would be about 3×10^5 m^3/day.

For the period July through October 1980, a 0.26 km^3 volume of dacitic liquid would be required to supply the 910,000 t (9.1×10^{11} g) of CO_2 emitted over this period of time. This amount is about five times the total volume (0.053 km^3 of magma; Lipman and others, this volume) of dacite, including air-fall ash, pyroclastic flows, and dome, erupted during the May 25, June 12, July 22, August 7, and October 16-18 eruptions. If intrusion and degassing of magma released more than 0.13 weight percent CO_2 from the dacitic liquid (possibly due to initial vapor saturation of CO_2 at a confining pressure of 5 kbar or more), then the volume of intruded liquid that is required would be less than 0.26 km^3.

Emission rates of CO_2 may change as a result of migration of CO_2 from deeper magma, intrusion of magma at a shallow level, change in the permeability of the vent, and change in the rate of crystallization of liquid. It is not possible at the present time to establish the actual cause or causes for observed changes in the CO_2-emission rate.

The results in figure 121 show that the CO_2- and SO_2-emission rates often show similar changes. However, the emission rates of the two gases appear to have varied independently at certain times (especially on July 9, July 22, August 4 to 7, October 15, and October 18). The CO_2/SO_2 ratio was not constant but varied over a large range. Although the correlation coefficient for the CO_2- and SO_2-emission rates is 0.57, the emission rates of the two gases were not correlated in a simple way.

Each of the three eruptions (July 22, August 7, and October 16–18) of dacitic magma during the time interval of this study was preceded by a significant decrease of the CO_2-emission rate. The decreases occurred several days before each eruption. Because the large decrease of the CO_2-emission rate from July 14 to July 22 was followed by an eruption and the pattern was repeated (August 3–6), the August 7 eruption was anticipated. Finally, the much lower emission rate of CO_2 on October 15, as compared to the September 15 to October 9 trend of increasing CO_2-emission rate, suggested that an eruption might be imminent; several Plinian columns were erupted from October 16 to 18.

Forecasting of volcanic eruptions by geochemical techniques may be possible, but a quantitative understanding of the behavior of volatile elements during magmatic processes is required in order to make better forecasts. For example, on August 20, on the basis of changes of the CO_2- and SO_2-emission rates, another eruption was anticipated to occur between August 20 and August 23, but no eruption occurred. Because the principal propellant in the explosive eruptions at Mount St. Helens is probably H_2O vapor, its role in the mechanisms of eruption and degassing of magma should be thoroughly investigated.

CONCLUSIONS

1. Degassing of dacitic liquid is the most likely source of excess CO_2 in the gas plume.
2. The total amount of CO_2 released to the atmosphere by volcanic activity at Mount St. Helens during noneruptive periods from the beginning of July to the end of October is about 910,000 t (9.1×10^{11} g). Since the CO_2:SO_2 mass ratio of the emissions is greater than unity, the contribution of CO_2 to the atmosphere exceeded that of SO_2.
3. The monthly mean emission rate of CO_2 has decreased significantly from 11,500 t/day (July 1980) to 5,300 t/day (October 1980).
4. Three Plinian eruptions of dacitic magma (July 22, August 7, and October 16–18, 1980) were preceded by significant decreases of CO_2-emission rates up to several days before the eruptions. These changes may be useful for anticipating eruptions.

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