Chapter 26

Emission of SO_2, CO_2, and H_2S from Augustine Volcano, 2002–2008

By Kenneth A. McGee[1], Michael P. Doukas[1], Robert G. McGimsey[2], Christina A. Neal[2], and Rick L. Wessels[2]

Abstract

Airborne surveillance of gas emissions from Augustine Volcano and other Cook Inlet volcanoes began in 1990 to identify baseline emission levels during noneruptive conditions. Gas measurements at Augustine for SO_2, CO_2, and H_2S showed essentially no evidence of anomalous degassing through spring 2005. Neither did a measurement on May 10, 2005, right after the onset of low level seismicity and inflation. The following measurement, on December 20, 2005, showed Augustine to be degassing about 600 metric tons per day (t/d) of SO_2, and by January 4, 2006, only 7 days before the first explosive event, SO_2 emissions had climbed to ten times that amount. Maximum emission rates measured during the subsequent eruption were: 8,930 t/d SO_2 (February 24, 2006), 1,800 t/d CO_2 (March 9, 2006), and 4.3 t/d H_2S (January 19, 2006). In total, 45 measurements for SO_2 were made from December 2005 through the end of 2008, with 19 each for CO_2 and H_2S during the same period. Molar CO_2/SO_2 ratios averaged about 1.6. In general, SO_2 emissions appeared to increase during inflation of the volcanic edifice, whereas CO_2 emissions were at their highest during the period of deflation associated with the vigorous effusive phase of the eruption in March. High SO_2 was probably associated with degassing of shallow magma, whereas high CO_2 likely reflected deep (>4 km) magma recharge of the sub-volcanic plumbing system, For the 2005–6 period, the volcano released a total of about 1.5×10^6 tons of CO_2 to the atmosphere, a level similar to the annual output of a medium-sized natural-gas-fired powerplant. Augustine also emitted about 8×10^5 tons of SO_2, similar to that produced by the 1976 and 1986 eruptions of the volcano.

[1]Cascades Volcano Observatory, U.S. Geological Survey, 1300 SE Cardinal Court, Vancouver, WA 98683.

[2]Alaska Volcano Observatory, U.S. Geological Survey, 4210 University Drive, Anchorage, AK 99508.

Introduction

Augustine Volcano is located on an uninhabited island in the lower Cook Inlet of Alaska (fig. 1). It lies about 100 km west of Homer and 280 km southwest of Anchorage. The site of frequent explosive eruptions, Augustine Volcano is a young 1,250-m-high convergent plate boundary stratovolcano, lying about 100 km above the Benioff zone in the eastern portion of the Aleutian arc. It has had at least four periods of significant activity in the twentieth century in 1935, 1964–65, 1976, and 1986 before the most recent eruption in 2006 (Miller and others, 1998) and erupts mostly andesitic and dacitic lavas (Kienle and Swanson, 1983). Augustine Volcano consists of a broad apron of pyroclastic and debris-avalanche deposits surrounding a central vent and dome complex (Swanson and Kienle, 1988; Waitt and and Begét, 2009). When Augustine erupts, a number of volcanic hazards have the potential to threaten communities in south central Alaska and aviation, industrial facilities, petroleum and natural gas production, shipping, and other activities (Waythomas and Waitt, 1998).

Airborne gas measurements at Augustine Volcano are part of a systematic program to monitor baseline gas emissions at Cook Inlet volcanoes in order to recognize the beginning of unrest and to identify baseline values of gas emissions to which future measurements could be compared in the event of unrest (Doukas, 1995). In 1990, 4 years after the 1986 eruption, annual measurements were begun and have continued through 2008. This paper reports gas measurements made from 2002 to 2008 with special emphasis on precursory and eruptive activity during 2005–6.

Data from two earlier eruptions of Augustine allow comparisons with peak SO_2 emission rates measured during 2006. From February 8 through 18 during the 1976 eruption, Stith and others (1978) made a series of measurements using a Meloy flame photometric detector to determine total gaseous sulfur, which was assumed, by smell, to be all SO_2. They

measured a peak value of 25,900 t/d of SO_2 on February 9, 1976, followed by 8,600 t/d on February 11, 13, and 18. Their lowest measured SO_2 emission rate was 173 t/d on February 12, 16, and 17. A little more than a year after the eruption, they returned to Augustine for an additional measurement and recorded a value of 26 t/d on April 22, 1977. Using a scrubber system attached to their instrument, they were also able to remove SO_2 and estimate an emission rate for H_2S of 3.5 t/d for the 1977 measurement. They estimated that Augustine emitted about 1×10^5 tons of SO_2 during the 1-year period surrounding the 1976 eruption. As this estimate neglects the paroxysmal emissions of April 1976, it is only a minimum value. They point out that a significant portion of the SO_2 emitted during the paroxysmal eruptions was attached to the surfaces of ash particles and fell out of the plume after a short time.

During the March–April 1986 eruption of Augustine, Rose and others (1988) successfully made airborne ultraviolet spectroscopic (COSPEC) plume measurements on April 3, 1986, and calculated a SO_2 emission rate of 24,000 t/d during active ash emission and under high wind conditions; gas emission rates were likely higher during the peak of the eruptive activity from March 27 to April 3. More than a year after the end of the eruption, additional measurements of 380 t/d (July 24, 1986) and 45 t/d (May 24, 1987) were made during a period of post-eruptive passive degassing (Symonds and others, 1990). Rose and others (1988) used ash leachate and emission data along with seismic information and other observations to scale up their SO_2 measurement of April 3, 1986, to an emission rate of 3.75×10^4 t/d that was likely achieved on more than one day during the peak phase of the eruption.

Before the 2005–6 eruption, fumarolic activity at Augustine was confined to scattered areas near the summit dome complex (fig. 2). As early as the summers of 1986 and 1987, Symonds and others (1990) observed that the 1986 lava dome produced >90 percent of the gas emitted from Augustine. Other sources were the solfataras located west of the 1986 dome along the high ridge between the remnants of the 1935 and 1964 lava domes and in unconsolidated pyroclastic flow deposits near the northern base of the volcano's dome complex. In 1987, at least one fumarole on the dome was as hot as 870°C, but by 1989 it
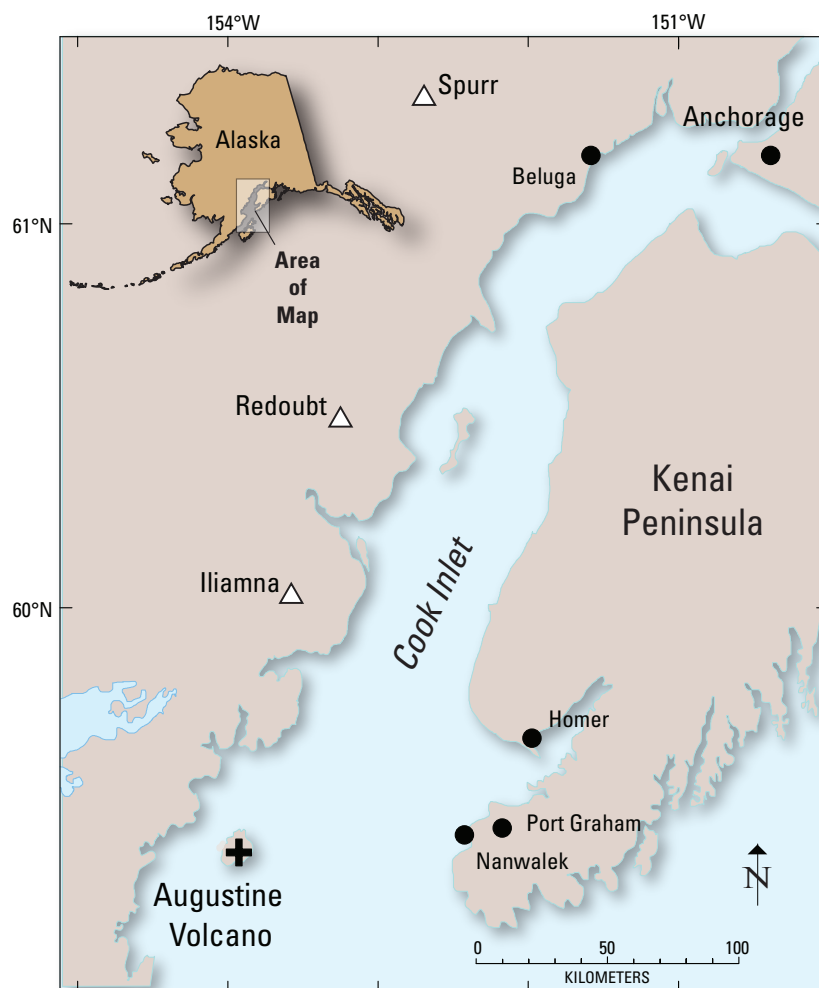

Figure 1. Location map for Augustine Volcano. Plus sign (+), Augustine Volcano; Open triangles, other volcanoes of Cook Inlet; Filled circles, cities and towns near Cook Inlet. Inset map of Alaska.

was only 640°C (Symonds and others, 1990). By 1992, fumarole temperatures had declined to about 97°C, boiling point for the summit elevation (Symonds and others, 2003).

Methods

Instrumentation

In this study, we used an instrument platform developed over the past 15 years at the Cascades Volcano Observatory (CVO). The platform is mounted on board an aircraft for transport to volcanic centers, usually in remote settings, and is capable of measuring volcanic CO$_2$, SO$_2$, and H$_2$S (Gerlach and others, 2008). For airborne emission measurements of the Augustine plume, a LI-COR Model LI-6252 nondispersive infrared analyzer and a Model LI-670 flow control unit were used to determine volcanic CO$_2$ (Gerlach and others, 1997; Gerlach and others, 1999). An Interscan Model 4170 analyzer with a 0 to 1 ppm range and an Interscan Model 4240 analyzer with a 0 to 2 ppm range were used for direct measurements of H$_2$S and SO$_2$ in the plume, respectively. These instruments consist of an electrochemical voltametric sensor coupled to a 1-liter-per-minute sample-draw pump. The calibrated analog output of the instruments record gas concentrations as described in detail by McGee and others (2001) and Werner and others (2006).

The airborne instrument package also included a COSPEC for measuring SO$_2$ column abundance (units of parts per million-meter, or ppm·m) and a type-T thermocouple shielded from wind and direct sunlight for measuring ambient air temperature. Atmospheric pressure was measured in the unpressurized aircraft cabin by a pressure transducer mounted within the LI-COR analyzer. A GPS receiver was used to tag the precise latitude, longitude, and altitude of each measurement. Data from all of the instruments were recorded on a common 1/s time base. All gas readings were corrected for the actual pressure and temperature at the altitude at which the measurements were taken.

Procedure

Two different instrument configurations were used for the airborne measurements between 1995 and 2006 owing to funding limitations and instrumentation availability. In one configuration (24 of the 45 campaigns reported in table 1), only a COSPEC V and a Model 60CSX GPS were used to determine SO$_2$ emission rates. Typically, four to six traverses were flown under the downwind plume perpendicular to the direction of plume travel with the upward-looking COSPEC to determine an average column abundance of SO$_2$. GPS-registered wind circles (positions logged once per second) at the elevation of the plume were then flown in order to calculate the velocity of plume travel so that a SO$_2$ emission rate could
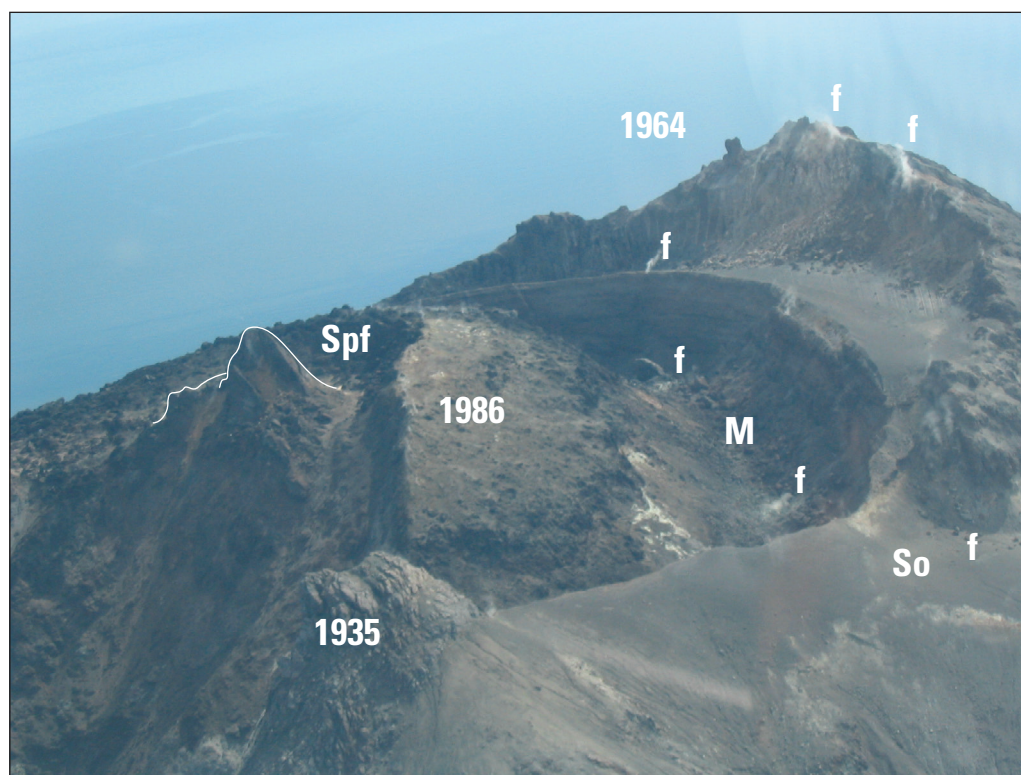

Figure 2. View of 2004 preeruptive summit of Augustine Volcano, as seen from the west. 1986, lava dome surrounded by moat (M) formed during the 1986 eruption. Spf, Spine fumarole located near base of spine (faint outline) (Symonds, and others, 1990). 1964, lava dome remnant forms collar on south summit. 1935, lava dome remnant lies north of the solfatara area (So). f, locations in 2004 wispy boiling-point fumaroles plumes (not sampled). Photo by M. Doukas.

be computed (Doukas, 2002). In the other configuration (21 of the 45 campaigns reported in table 1), the full instrument package for measuring CO_2, SO_2, and H_2S (LICOR, COSPEC, and Interscan) was mounted in a twin-engine aircraft configured for open-flow sampling of external air upstream of engine exhaust as described in Gerlach and others (1997) and Gerlach and others (1999). In addition to the traverses flown under the plume for the COSPEC measurements described above, a series of additional traverses were flown top to bottom through the plume at the same distance downwind of the vent in order to describe a vertical cross section of the plume.

To illustrate data collection techniques, figure 3 shows the reconstructed flight path from GPS data for a typical flight between 1400 and 1500 Alaska Standard Time (AKST) on January 19, 2006, with the full instrumentation package. Five traverses were made underneath the plume for the COSPEC measurements. Then, a series of 12 additional plume profile traverses were flown through the plume ranging from a top traverse at an altitude of 1,700 m above mean sea level (amsl) down to a bottom traverse of 780 m amsl based on aircraft altimeter readings and with an average vertical spacing of 80 m. Winds measured just after the flight by the wind circle method indicated winds out of the west-northwest at an average speed of 6.1 m/s. The plume from Augustine on this day was detected on all but the top and bottom traverses, and the characteristic smell of both H_2S and SO_2 was noticed by the aircrew on all of the traverses through the plume. Atmospheric pressure and temperature were nearly constant inside and

outside the plume on each traverse and averaged 88.04 kPa and −9.8°C. No temperature anomaly was detected in the volcanic plume on any of the traverses.

Two representative COSPEC traverses from the January 19, 2006, example are presented in figure 4. The COSPEC SO_2 signal is processed in Peakfit v. 4.0 (AISN Software, Inc.) to determine the area under the signal curve in kilometers×ppm·m. The average ppm·m is then determined by dividing the area by the width in kilometers. The average signal is then reduced by the ratio of the calibration cells used during the flight. The reduction equation gives the SO_2 emission rate (E) in units of t/d:

$$E_{cospec} = 0.00023(S_W \times Plume\ width \times Ave\ ppm \cdot m) \quad (1)$$

Where S_W is the average wind speed (m/s), Plume width in meters and *Ave ppm·m* is the resultant average ppm·m of the plume traverse. The constant reduces the concentration of the cross section to t/d.

Figure 5 shows a time-series plot of the January 19 CO_2, SO_2, and H_2S data series. The ambient CO_2 background measured on each traverse on either side of the CO_2 anomaly was fit using routines in PeakFit v. 4.0 (AISN Software, Inc.) and subtracted from each peak and zeroed to obtain the volcanic CO_2 gas signal. The resulting CO_2 plume anomaly on January 19, 2006, has a maximum concentration of nearly 5 ppm. A similar procedure was used for H_2S and SO_2 from the Interscan measurements, although no H_2S and SO_2 were present in the ambient
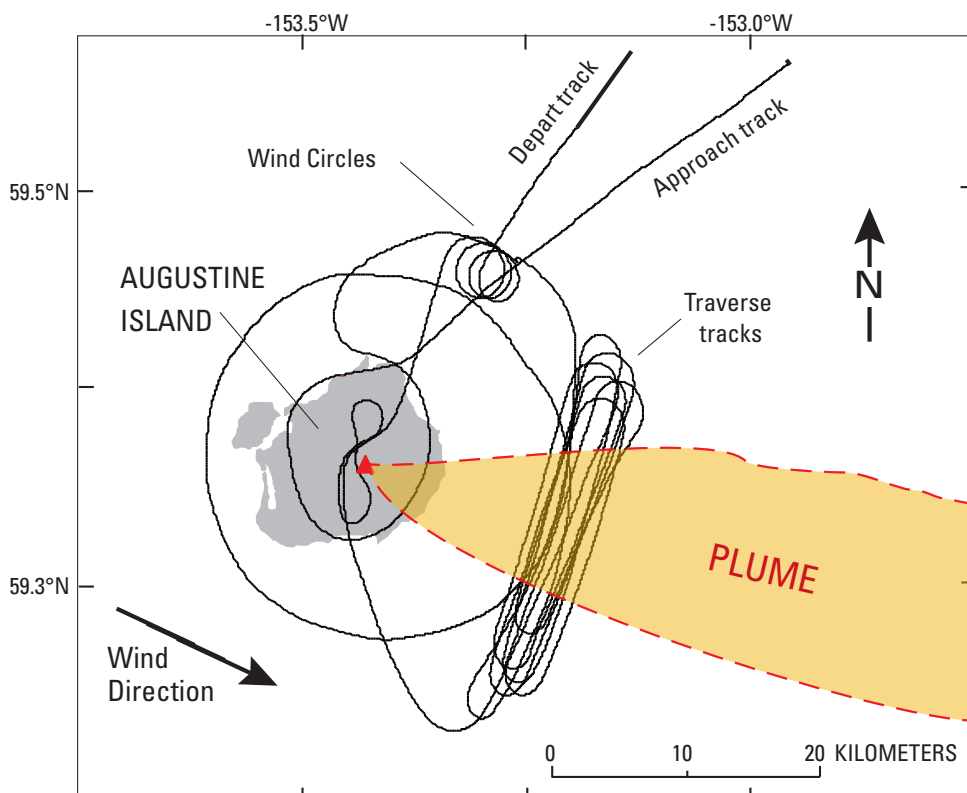

Figure 3.   Map showing recorded GPS flight-track positions during the airborne survey at Augustine Volcano, Alaska, on January 19, 2006. Arrow shows determined wind direction, and the cluster of flights lines to the east of Augustine shows the NNE-SSW gas measurement traverses under and intersecting the volcanic plume downwind of the volcano. Red triangle locates the summit of the volcano. Flight tracks for wind circles to determine wind speed are shown northeast of Augustine and were flown at the altitude of the plume core.
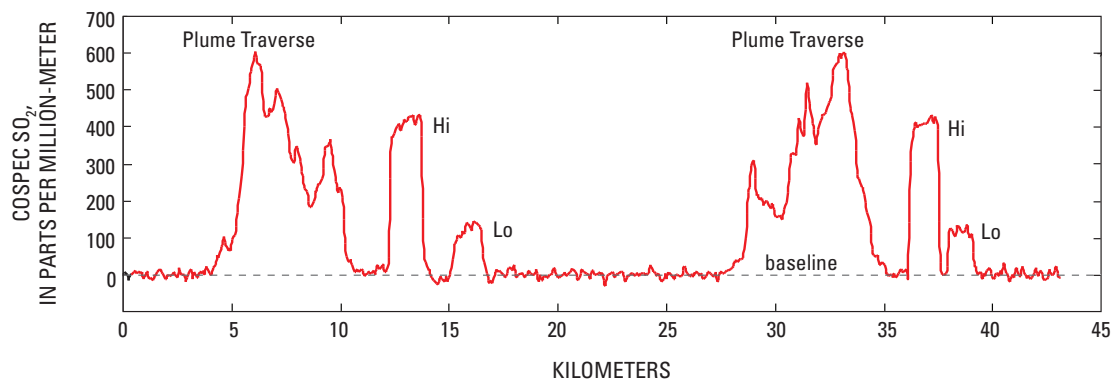
Figure 4. Data series from two of the five COSPEC traverses flown beneath the Augustine plume on January 19, 2006. High and low calibration-cell signals are labeled Hi and Lo and occur after the SO_2 peaks. The horizontal x-axis shows the cumulative flight distance for the two traverses in kilometers. Y-axis units are in parts per million-meter. Note the asymmetry of the SO_2 plume a result of flying in opposite directions.

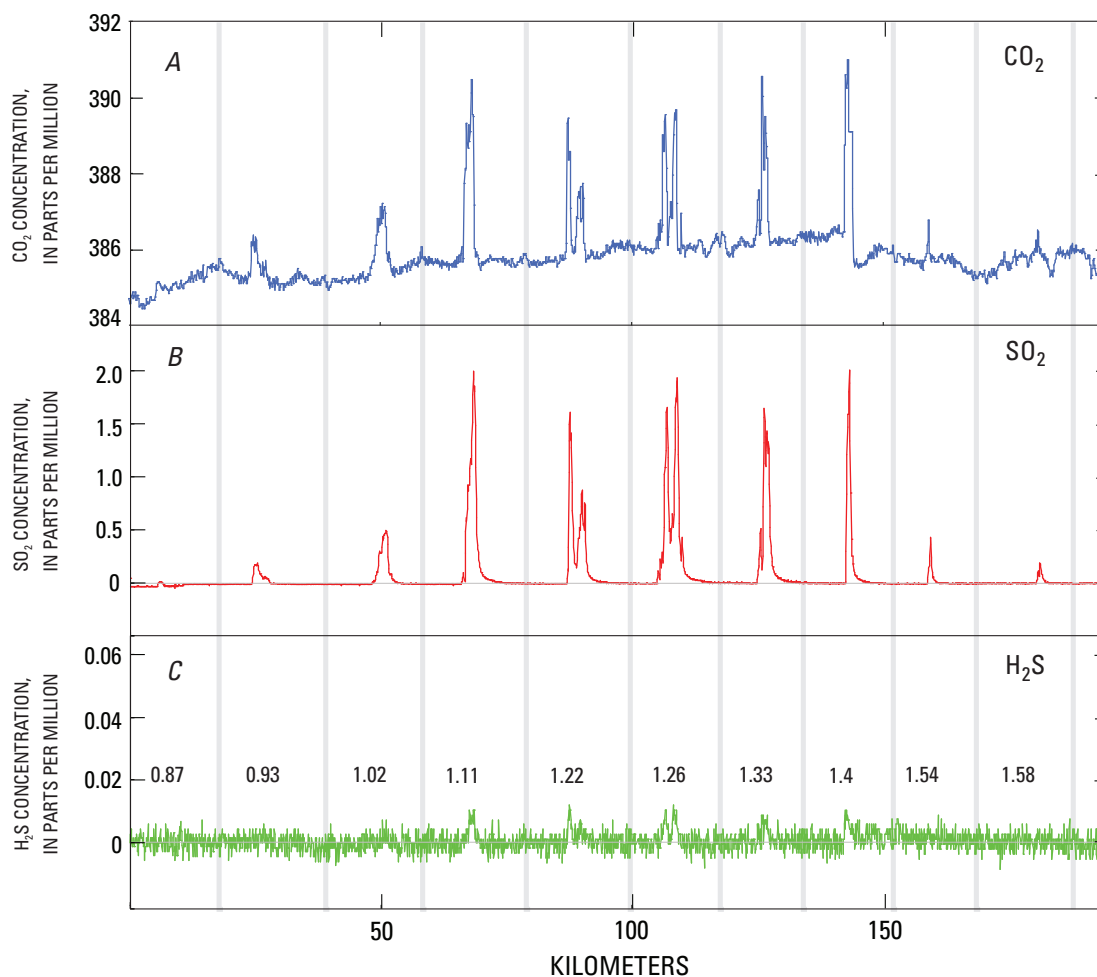**Figure 5.** Time-series plots of concentration data (in ppm) for CO_2 (blue), SO_2 (red), and H_2S (green) during the series of traverses flown through the plume at Augustine Volcano on January 19, 2006. The horizontal x-axis is the cumulative flight distance during the traverses (kilometers). Elevation of each traverse indicated in kilometers in the H_2S box. Vertical gray lines locate turn-around point during flight.

(background) air. For the example shown, the maximum plume concentration was about 2 ppm for SO_2 and 0.01 ppm for H_2S.

The conventional airborne method for measuring CO_2 emission rates from passively degassing volcanoes is based on analysis of air sampled through the volcanic plume normal to wind direction. The emission rate is then calculated from the average plume pressure and temperature, wind speed, and the volcanic CO_2 concentration anomaly in cross section (Gerlach and others, 1997). This method was adapted further by using the location of H_2S peaks, when present, as a guide to resolving the boundary between volcanic CO_2 and ambient CO_2 (McGee and others, 2001). Further, anomalous CO_2 signals appear during flying maneuvers (fig. 5, between altitudes 1.26 and 1.33 km, CO_2 time series), but the absence of SO_2 and H_2S peaks confirmed the nonvolcanic nature of the gas. Because the measurement traverses at Augustine were flown in a back-and-forth fashion through the plume, every other traverse was inverted before processing so that all traverses start from a common latitude and longitude and extend in the same direction across the plume. This eliminates introducing potential offsets between traverses due to the travel time of gas in the sample tubing from intake to analyzer when importing the data into contouring and mapping software.

Equation (1) from Gerlach and others (1997) gives the CO_2 emission rate (E) in units of t/d:

$$E = 0.457329\,(A \times S_W \times P_{CO_2})/T \qquad (2)$$

where A is the area of plume cross-section (m^2), S_W is the average wind speed (m/s), P_{CO_2} is the partial pressure of CO_2 (Pa) in the plume calculated from the product of average barometric pressure and the average molar concentration of CO_2 in the plume, and T is the average air temperature in the plume (K). The constant includes the formula weight of CO_2, the universal gas constant, and the number of seconds in a day. Average concentration of CO_2 in plume cross section was determined with kriging models for gridding and contouring the concentration measurements. A similar approach was used for computing emission rates for H_2S (constant = 0.354141) and SO_2 (constant = 0.665665).

Figure 6 shows resultant vertical plume cross sections for each of the three gases measured from the plume profile traverses on January 19, 2006, using contouring and mapping software (Surfer v. 8, Golden Software, Inc.). The cross-section for H_2S appears to show a smaller plume than those for CO_2 and SO_2 due to the very low concentration of H_2S and an Interscan detection limit of ~4 ppb for this type of measurement.

Standard deviation (s.d., table 1) for each day's COSPEC SO_2 emission rate calculation are based on the number of traverses flown and therefore represent the natural variation of the volcanic plume's SO_2. To decrease the standard deviation of the mean of our measurements by a factor of two would require that we acquire four times as many observations in our

daily measurements. The distance to and from the volcano and aircraft fuel capacity limits time at the volcano and thus the number of traverses made.

With the full instrument configuration, comparison of COSPEC results and Interscan SO_2 emission rates (table 1) were not always in agreement. Variability of environmental conditions during measurement was usually the cause. For example, clouds at the summit or opaque (perhaps ash bearing) plumes may prevent traverses through the whole plume, resulting in higher COSPEC SO_2 emissions compared with Interscan contoured results. A higher concentration section of a plume may lie between traverses. For internal consistency, only the COSPEC results are used in this report.

2005–2006 Eruption Chronology and Gas Data

Before the onset of volcanic unrest in 2005, airborne measurements were usually made once per year. Flight frequency increased once the unrest started but varied considerably over the course of the eruption. From July 2002 through the end of 2008, 45 successful COSPEC measurements of SO_2 and 21 measurements of CO_2 and H_2S were made using the full instrument package.

Emission rates from airborne measurements for CO_2, SO_2, and H_2S at Augustine Volcano from 2002 through 2008 are given in table 1 (Doukas and McGee, 2007) and are shown plotted with other eruption parameters and eruptive phases in figure 7. CO_2 or SO_2 were not detected at Augustine from 2002 through May 2005 with the exception of a very small amount of CO_2 in May 1997. H_2S measurements were not begun until 2001, and no H_2S was detected through 2005. Not until December 20, 2005, was SO_2 detected during a COSPEC flight. CO_2 measurements were not attempted until January 16, 2006. Note that some data from the 2006 time period have been revised from those published in McGee and others (2008), owing to reprocessing using the contouring technique.

Precursory Phase (April 30, 2005–January 11, 2006)

The precursory phase (fig. 7) began with an increase in the number of microearthquakes in late April 2005 (fig. 8; Power and Lalla, this volume). The first airborne gas measurement during the unrest on May 10, 2005, detected no CO_2, SO_2, or H_2S. In mid-summer 2005, geodetic baselines began to lengthen suggesting inflation of the edifice throughout the last half of 2005 (Cervelli and others, this volume). The increasing seismicity continued until early December 2005 when a number of small phreatic explosions were recorded on seismometers (fig. 8; Power and Lalla, this volume). Sulfur smells had been reported in Nanwalek and Port Graham (fig. 1) on December 11,

2005, suggesting the arrival of significant sulfur-bearing gas at the surface at least by early December. On December 12, 2005, a vigorous gas and minor ash plume from the summit area was noted in MODIS satellite imagery and by observers, representing the most energetic of precursory phreatic explosions (fig. 9). The next measurement, for SO$_2$ only, was made on December 20, 2005, during the period of phreatic activity and showed a modest amount of SO$_2$ (660 t/d) in the plume. The emission rate was considered a minimum value owing to high wind speeds that pushed the plume to the ground, preventing the aircraft from flying below the plume (fig. 10). From early December 2005 through early January 2006, increased surface heating and snowmelt, phreatic explosions, and the energetic venting of gas and steam were recorded by the seismic network and observed on overflights (Power and Lalla, this volume; Power and others, 2006; Wessels and others, this volume). The following three measurements, taken on January 4, 9, and 10 near the end of the precursory phase, and just days prior to the first violent Vulcanian explosions, showed a significant rise in SO$_2$ emissions (6,700, 2,800, and 5,500 t/d, respectively; table 1; fig. 7).

Explosive Phase (January 11–28, 2006)

The explosive phase began with a vigorous swarm of volcano-tectonic (VT) earthquakes early on January 11, followed by two brief (1:18 and 3:18 minutes), ash-poor explosions (fig. 7; Power and Lalla, this volume). Additional explosions reamed a vent through the southern margin of the 1986 lava dome on January 13, 14, and 17. Ash clouds from these events deposited trace amounts of fine ash on communities to the northwest and east and disrupted air traffic (Wallace and others, this volume; Neal and others, this volume). Seismicity characteristic of lava effusion was recognized on January 12, 2006, (Power and others, 2006) and a small new lava dome was observed during a gas flight on January 16, 2006. Lava formed a second lava lobe between January 17 and 27, followed by more explosive events (Coombs and others, this volume).

Three gas-measurement flights with the full instrument package were conducted during the explosive phase (January 16, 19, and 24; table 1, fig. 7A). Sulfur dioxide emission rates were high (2,800, 3,000, and 730 t/d) but down somewhat
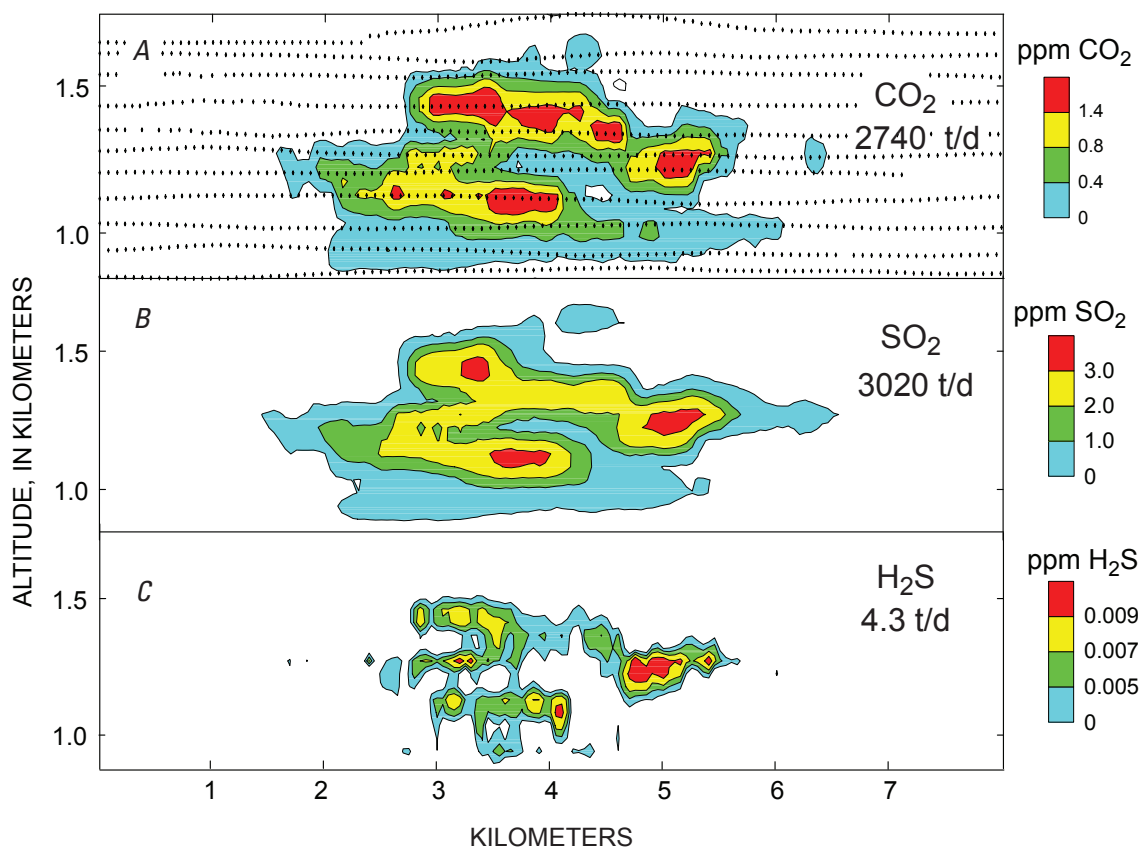

Figure 6. Concentration in a vertical cross-section for the CO$_2$ (A), SO$_2$ (B), and H$_2$S (C) components of the Augustine plume 5 km downwind from summit vent on January 19, 2006. View is upwind toward volcano. The x-axis is the flight distance during the traverses. Contours show concentration of each gas above background with color scale bars to the right. The CO$_2$ cross-section contains each data point of the traverses used to construct the contours (same points not shown in the SO$_2$ and H$_2$S contours). Cross-section of the 4 km-wide plume was constructed with contouring software (Surfer v.8) using exponential kriging models based on variograms fit to the concentration data for the plume. For the example shown, calculated emission rates are 2740 t/d of CO$_2$, 3,020 t/d of SO$_2$ and 4.3 t/d of H$_2$S.

Table 1.   Augustine volcanic gas emission rates 2002 to 2008 (data from Doukas and McGee, 2007 and this report).

[Dates of eruption phases separate dates of measurements. Uncertainty derived primarily from wind speed measurements is estimated at plus or minus 19 percent (Doukas, 2002).   n=number of traverses, s.d.=standard deviation, nm = not measured, tr = trace, below detection limit, nd = not determined m = minimum result]

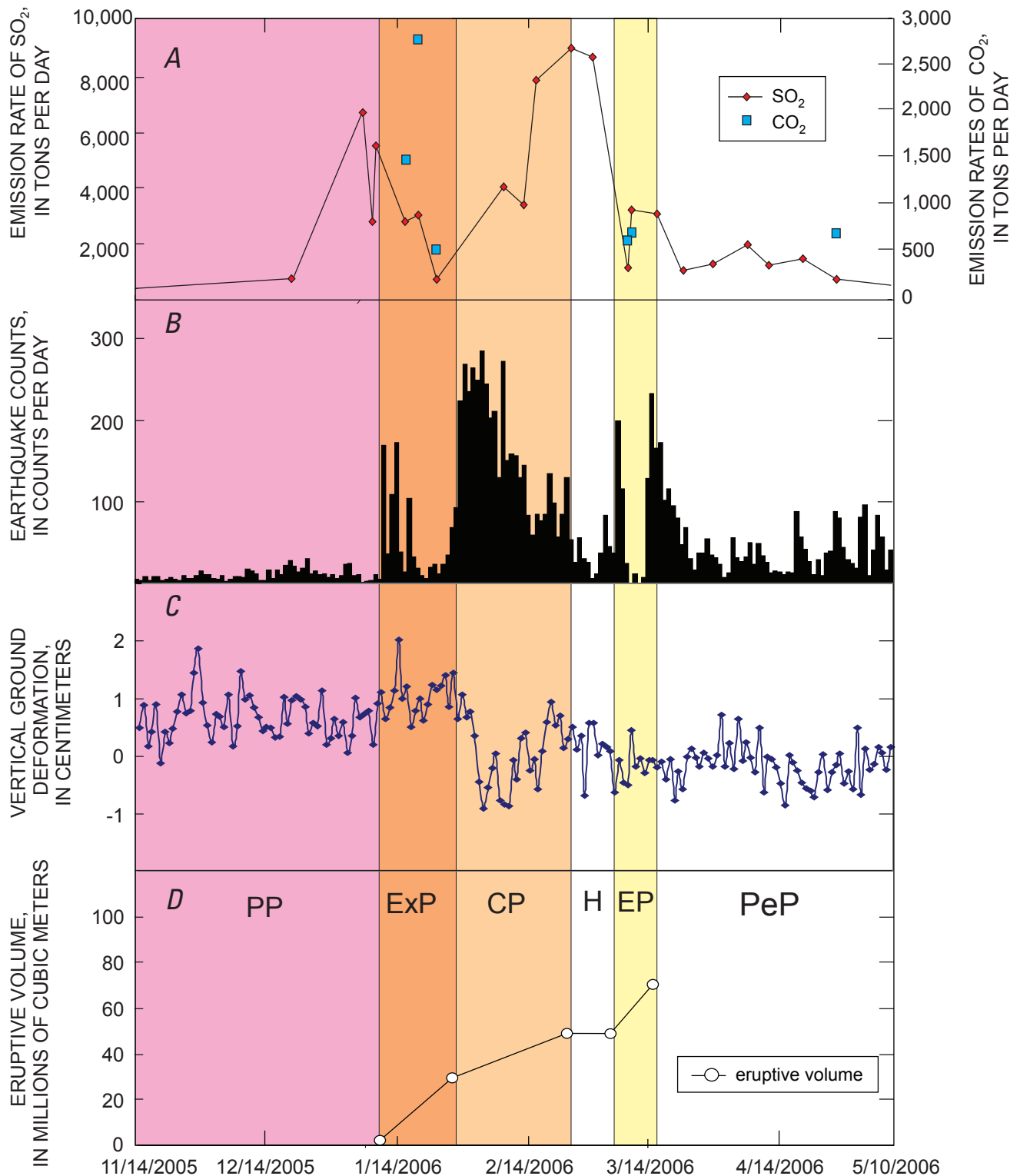| Date	COSEC SO_2 t/d	n	s.d.	Interscan SO_2 t/d	LiCor CO_2 t/d	Interscan H_2S t/d	Molar ratio CO_2/SO_2	Distance Downwind km	Wind Speed m/s	Wind Error %	Wind Direction Degrees	T °C	P kpa	Plume Width km
07-01-02	0	5	0	0	0	0	0.0	3	8.8	6%	220	10.2	89.22	0
07-02-02	0	2	0	0	0	0	0.0	2	6.2	x	270	11.5	87.88	0
09-10-02	0	1	0	0	0	nm	0.0	2	nm	nd	180/270	1.4	85.64	0
09-10-02	0	7	0	0	0	nm	0.0	2	nm	nd		3.4	87.21	0
08-03-03	0	4	0	0	0	0	0.0	2	2.7	10%	270	7	88.02	0
08-07-04	0	2	0	0	0	0	0.0	2	3.4	38%	170	16.6	89.82	0
April 30, 2005		**Precursory Phase**												
05-10-05	0	5	0	0	0	0	0.0	1.5	4.6	26%	120	1.7	87.7	0
12-20-05[m]	660	4	190	nm	nm	nm	nd	4.5	8.7	nd	90	nm	nm	2.1
01-04-06	6,700	4	790	nm	nm	nm	nd	4.5	13.4	nd	100	nm	nm	9.6
01-09-06	2,800	7	520	nm	nm	nm	nd	1.6	6.2	nd	90	nm	nm	3
01-10-06	5,500	2	200	nm	nm	nm	nd	13	10	19%	60	nm	nm	22
January 11, 2006		**Explosive Phase**												
01-16-06	2,800	4	500	836	1,470	tr	0.8	7	14.5	10%	0	0.9	96.08	2.6
01-19-06	3,000	5	620	1,516	2,700	4.3	1.3	15	6.1	31%	250	-9.8	88.04	7.5
01-24-06	730	5	80	280	500	1	1.0	15	2	80%	300	-21	80.1	8
January 28, 2006		**Continuous Phase**												
02-08-06	4,000	3	820	nm	nm	nm	nd	7	16.5	19%	110	nm	nm	10
02-13-06	3,400	3	700	nm	nm	nm	nd	8	5.3	28%	300	nm	nm	13.5
02-16-06	7,800	5	990	nm	nm	nm	nd	7	13	nd	230	nm	nm	4.1
February 24, 2006		**Hiatus**												
02-24-06	8,930	5	630	nm	nm	nm	nd	4.5	6.5	15%	320	nm	nm	2.3
03-01-06	8,650	8	1,130	nm	nm	nm	nd	4.5	5.6	18%	310	nm	nm	2
March 3, 2006		**Effusive Phase**												
03-09-06	1,130	4	200	340	1,800	0	2.3	13	17.3	4%	350	-12	89.78	2.8
03-10-06	3,200	4	430	390	1,200	0	0.5	10	7	.17%	30	-7.5	82.64	5.1
03-16-06	3,050	5	400	nm	nm	nm	nd	8	9.6	42%	80	nm	nm	8.2
March 16, 2006		**Post-eruption Phase**												
03-22-06	1,070	6	190	nm	nm	nm	nd	6.3	5.6	nd	50	nm	nm	2.5
03-29-06	1,270	6	190	nm	nm	nm	nd	10	5.5	11%	320	nm	nm	3.2
04-06-06	1,970	6	160	nm	nm	nm	nd	8	6	nd	45	nm	nm	3.9
04-11-06	1,220	5	90	nm	nm	nm	nd	5.8	7.7	13.7%	140	nm	nm	3
04-19-06	1,440	5	180	nm	nm	nm	nd	3.4	3.6	nd	220	nm	nm	5.2
04-27-06	750	5	210	860	660	1.3	1.3	10	18.6	2%	20	1.4	95.28	2.4
05-12-06	400	7	50	nm	nm	nm	nd	6	2.6	nd	40	nm	nm	6.3
05-23-06	230	5	30	nm	nm	nm	nd	11	7	21%	45	nm	nm	3.3
06-02-06	430	6	80	nm	nm	nm	nd	2.6	4.6	**14%**	330	nm	nm	1.8
07-12-06	500	7	90	nm	nm	nm	nd	4	7.3	3%	25	nm	nm	1.9
08-23-06	530	6	30	nm	nm	nm	nd	3.6	3.3	15%	330	nm	nm	5.4
09-24-06	250	3	56	180	280	1.3	1.6	6.5	4	13%	330	1.25	86.55	5.3
09-25-06	280	5	50	nd	nd	0	nd	7.1	7.8	12%	110	6.54	95.8	5
10-12-06	1,100	2	56	nm	nm	nm	nd	5	10.6	5%	120	nm	nm	7.65
10-23-06	100	2	3	nm	nm	nm	nd	4	16	nd	280	nm	nm	3.6
11-04-06	190	2	15	nm	nm	nm	nd	7.2	4.1	7%	280	nm	nm	4
11-16-06	170	2	43	0	0	0	nd	6.3	13	7%	45	-15.7	80.15	1.8
11-17-06	100	1	0	0	0	0	nd	5	4.3	6%	40	-9.3	84.5	2.8
11-18-06	220	1	0	0	0	0	nd	3	7.3	9%	40	-7.4	88.83	1.5
02-22-07	50	4	8	nm	nm	nm	**nd**	1.3	4.8	15%	280	nm	nm	1.3
05-18-07	30	4	6	80	94	0.0	4.3	2.8	3.7	8%	90	-4.9	85.88	2
03-14-08	Tr	4	14	nm	180	0		3	3.8	2%	270	-7	88.79	4.2
07-17-08	120	3	17	tr	tr	0	nd	2	5.4	18%	280	9.8	94.1	2.3

Figure 7. Time series from November 14, 2005, through May 10, 2006, showing: *A*, the measured SO$_2$ and CO$_2$ emission rates in tons per day, red diamonds are SO$_2$ and blue squares are CO$_2$; *B*, located earthquake counts per day (Power and others, this volume); *C*, the displacement in centimeters measured between CGPS stations A59 and AV02 (Cervelli and others, this volume), *D*, the erupted volume as determined by Coombs and others (this volume). Vertical colored segments in figure represent phases of the 2006 eruption (pre-November data not included). PP, precursory phase beginning April 30, 2005, to January 11, 2006; ExP, explosive phase January 11–28, 2006; CP, continuous phase January 28 to February 10, 2006; H, hiatus February 10 to March 3, 2006; EP, effusive phase March 3–16, 2006; PeP, post-eruption phase March 16, 2006 to July 17, 2008.

from the levels recorded during the precursory phase. CO_2 was measured for the first time since the beginning of the unrest (1,466, 2,740, and 500 t/d). The highest emission rate of H_2S during the eruption, 4.3 t/d, was recorded on January 19. We have no measurements of gas emissions during any of the 13 explosions that occurred between January 11 and 28.

Radar data and pilot reports suggest Augustine injected gases and ash into the stratosphere on as many as four different days during this period (January 11, 13, 17, and 27 (Collins, and others, 2007; Schneider and others, 2006). We estimate from meteorological data (NOAA, Air Resources Laboratory, www.arl.noaa.gov/ready.php, last accessed April 1, 2010) that the tropopause was at about 8.5 to 9.0 km asl above Augustine during this time period.

Infrared based Atmospheric Infrared Sounder (AIRS) satellite detected the SO_2 clouds during January 28 and 29, 2006. Prada (2006) reported that .0025 to .0041 Tg (2,500–4,100 t/d) were ejected into the atmosphere during the explosive events on these days. Early satellite measurements showed SO_2 eruption clouds represented equal to or above quiescent SO_2 emission rates (fig. 11). The AIRS satellite detected SO_2 in the stratosphere, so the values reported are probably minimums due to the missed SO_2 below 8 to 9 km. The first satellite measurements suggest measurements of the quiescent plumes with emission near 3,000 t/d (fig. 11). Later, measurements may represent syneruptive SO_2 plumes. These clouds did not contain the syneruptive amounts of SO_2 typical of explosive eruptions.

Ozone Monitoring Instrument (OMI) satellite determinations of SO_2 were unavailable during this time interval (Simon Carn, oral communication, 2008) owing to low winter UV levels. Not until March and at lower latitudes (Nevada) were OMI satellite results available.

Continuous Phase (January 28–February 10, 2006)

A continuous eruption phase began on January 28 and was characterized by nearly constant, low-altitude tephra emission and rapid andesitic dome extrusion, high rates of shallow seismicity, and steady deflation of the edifice. Repeated collapses of the growing dome and overlapping lobes of lava extending to the north beyond the margin of the 1986 lava dome produced block-and-ash flows intermittently through February 10, 2006 (Vallance and others, this volume; Coombs and others, this volume). Gas and ash plumes during this phase penetrated the tropopause on at least two days (January 28 and 29; Bailey and others, this volume); however, most ash plumes remained below 6,000 m asl. A gas measurement on February 8 (table 1, fig. 7A) during the continuous phase yielded an emission of 3,960 t/d SO_2, a value similar to those calculated during the late precursory and early explosive phases. SO_2 was detected (but no value derived) in the eruption cloud from January 29–30 by satellite (Dean and others, 2006). We have no CO_2 data from the continuous phase.

Hiatus (February 10–March 3, 2006)

Careful analysis of photography and other observations reveal no evidence of significant additional accumulation of lava in the summit crater from February 10 through March 3 (Coombs and others, this volume). Low levels of seismicity also suggest that the eruption was in a pause during this interval (Power and Lalla, this volume). Interestingly, of the four gas measurements made during the hiatus, three recorded the highest SO_2 emission rates of the eruption (7,800, 7,930, and 8,650 t/d; table 1; fig. 7A).
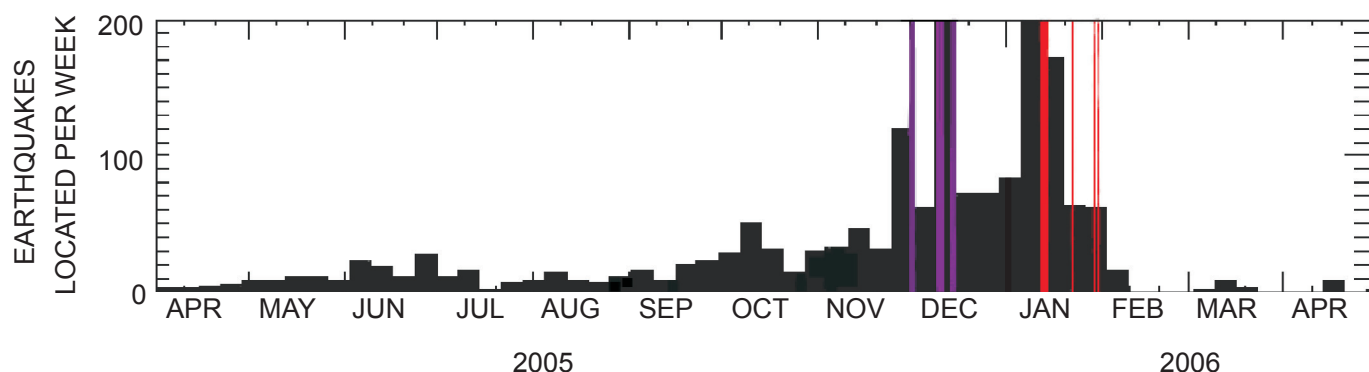

Figure 8.   Earthquake counts from April 2005 through April 2006 showing the gradual increase of located earthquakes during 2005 (from Power and Lalla, this volume). Purple and red lines correspond to approximate times of phreatic and magmatic explosions, respectively (Power and Lalla, this volume).

Effusive Phase (March 3–16, 2006)

On March 3, increasingly frequent rockfall signals on seismometers suggested a return to active lava effusion and resulting instability of the dome as new material was added to the surface and lava flow fronts advanced. Over the next 2 weeks, more or less continuous eruption of lava from a single vent in the summit dome marked the final activity of the effusive phase of the eruption (EP, fig. 7D). The top of the growing dome eventually reached an elevation more than 100 m higher than the preeruption summit of the 1986 lava dome. Collapse of the fronts of two primary lava flow lobes produced block-and-ash flows down the north and northeast flank of Augustine especially during the early portion of the effusive phase. The end of the phase coincided with cessation of drumbeat earthquakes, which were recorded from March 7 to March 16 (Power and Lalla, this volume). Three SO$_2$ emission measurements during this period range from 1,130 t/d to 3,050 t/d, values in the low to moderate range for the eruption. Two emission rates for CO$_2$, however, were showing decline in the eruption sequence—590 and 680 t/d.

Post-eruption Phase (March 16, 2006–July 17, 2007)

Twenty-one additional gas measurement flights made from April 2006 to July 2008 show SO$_2$ emission rates declining from more 1000 t/d to less than or equal to 120 t/d (table 1). We define the end of the post-eruption phase as the date when SO$_2$ emissions reached levels of 50 t/d. A single helicopter-borne flight in July 2008 measured 120 t/d, revealing latent degassing was still possible at the volcano. These final low values of SO$_2$ emission are similar to those observed following the 1986 eruption of Augustine when, within 8 months of the end of the eruption, 45 t/d was measured (Symonds and others, 1990). Similarly, emission rates for CO$_2$ went from 660 t/d on April 27, 2006, to 94 t/d in May 2007. H$_2$S levels were typically very low (1.3 t/d) or not quantifiable through the last measurement in July 2008.

Discussion

Changing SO$_2$, CO$_2$, and H$_2$S emissions pre-, syn-, and post-eruption can be interpreted in the context of other monitoring and observational data to infer characteristics of changing magma supply and residence at shallow levels beneath and within the volcano (fig. 7). The following discussion is limited somewhat by the lack of equivalently detailed time series data for all three gas species, in addition to a paucity of gas output measurements by satellite or other means during individual explosive events.

Sulfur dioxide largely disappeared from the plume and fumarole gases of Augustine in the months following the 1986 eruption, indicating no further influx of fresh magma
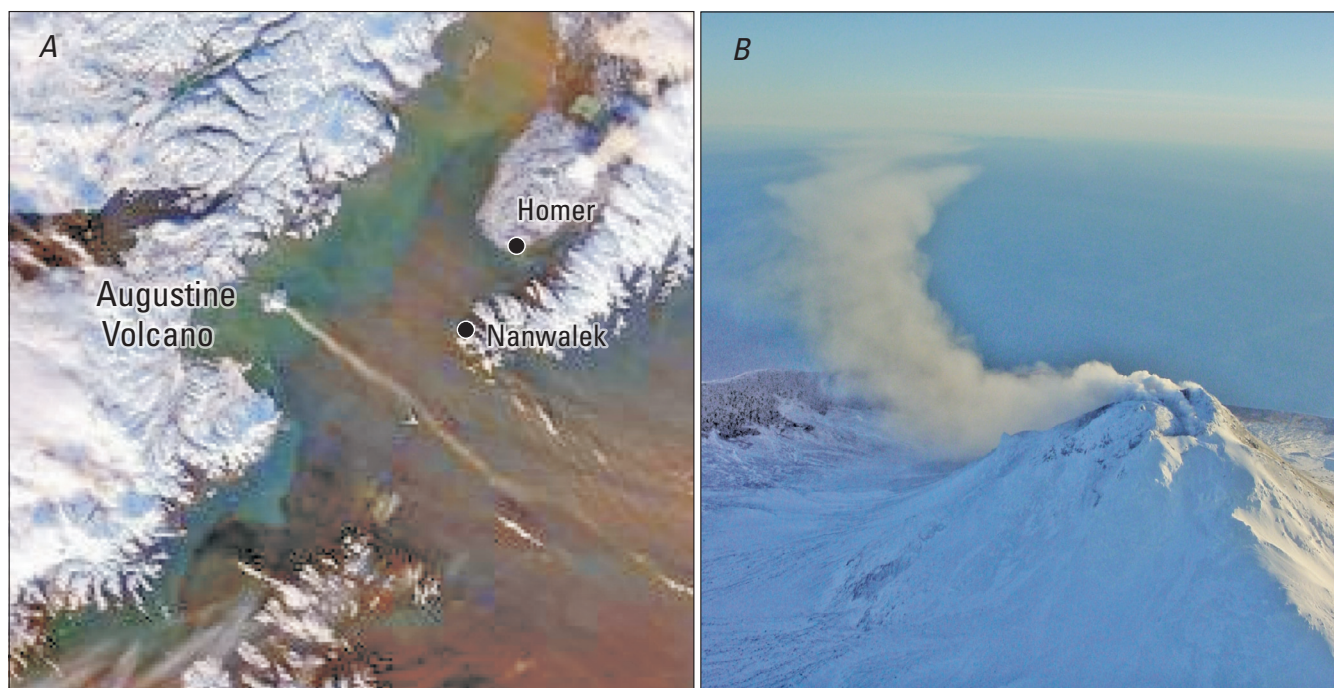

Figure 9. *A*, December 12, 2005, MODIS satellite view of lower Cook Inlet, Alaska, showing Augustine Volcano, as the source of a long narrow plume extending Southeast towards the southern portion of the Kenai Peninsula (image courtesy of the Geographic Information Network of Alaska (GINA)). *B*, December 12, 2005, photograph of an ashy plume extending from summit fumaroles to the southeast. Photo by R.G. McGimsey.

shallower than about 4 km below the summit (Doukas, 1995; Symonds and others, 1990; Symonds and others, 2003). Influx of water (both meteoric and seawater; Symonds and others, 1990) into the lower edifice likely consumed any residual SO_2 from the cooling 1986 magma by hydrolysis reactions. Indeed, annual airborne measurements at Augustine detected no SO_2 until December 2005, when precursory activity at Augustine was well advanced. It is notable that neither SO_2 nor CO_2 (CO_2 is a gas not easily scrubbed by water) were detected on a May 2005 flight during the earliest stage of the recent unrest. Cervelli and others (2006) suggest that a sea-level pressure source might have been present under the volcano by May 2005. If so, the lack of detected CO_2, which would have been significantly oversaturated in the magma at that shallow depth, suggests that the pressure source was not magmatic in origin but more likely resulted from an invigorated, expanding hydrothermal system being heated from below. Cervelli and others (this volume) conclude that this early deformation signal was not from a magma body. The corresponding lack of SO_2 is also consistent with no significant shallow (<4 km, sea level is approx 1.5 km) magma body at that time.

By late November 2005, magma likely rose to within several kilometers of the surface; shallow enough to degas SO_2 to the atmosphere and drive phreatic explosions. An airborne

Figure 10. Wind-depressed plume during the gas flight of December 20, 2005. Plumes from fumaroles were pushed down to the ground making COSPEC measurements difficult and minimizing the emission rate for that day. Photo by R.G. McGimsey.
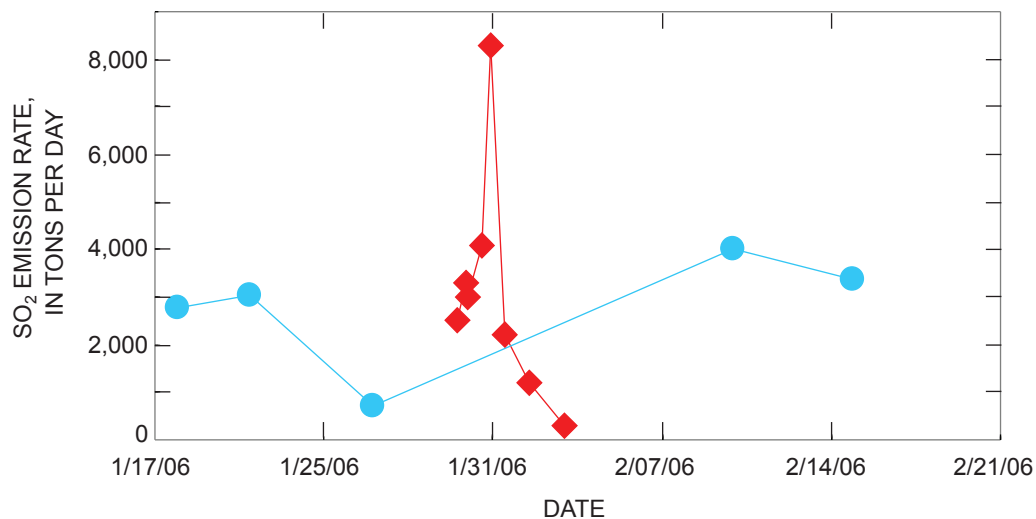

Figure 11. Airborne COSPEC emission rates (blue circles) and infrared AIRS satellite SO_2 determinations (red diamonds; F. Prada, written commun., 2009) during January 2006. AIRS satellite results are measurements of SO_2 in the stratosphere.

measurement on December 20, 2005, detected SO$_2$ at Augustine for the first time since 1987. A minimum emission rate of 660 t/d was measured on that flight (fig. 10, table 1; wind conditions prevented traverses completely beneath the plume, resulting in a minimum emission rate.). During December, observers also noted large white plumes that suggested the release of large amounts of water vapor from the volcano as it continued to heat up. ASTER thermal infrared (TIR) images of Augustine taken on December 20 showed a broad area of new snow-free ground and fumaroles at the summit, and forward-looking infrared (FLIR) surface-temperature measurements on December 22 indicated the temperature of a fumarole on the south flank was 210°C and the summit moat area at 80°C (Wessels and others, this volume). By January 4, 2006, the surface temperature of the moat area had increased to 390°C. Based on reports from residents in the village of Nanwalek on the lower Kenai Peninsula of strong "rotten egg" odors, it is likely that a significant portion of sulfur emissions from Augustine during the precursory stage were in the form of H$_2$S, consistent with earlier scrubbing of SO$_2$ by water and subsequent boiling of the fluid to create H$_2$S (Symonds and others, 2001). Further, during a FLIR flight on December 22, 2006, observers noted that fume emitted from a fumarole on the southeast base of the 1986 Augustine dome was distinctly pale yellow-green in color. We believe this was likely due to the transient presence of native sulfur in the plume produced by the reaction of H$_2$S and SO$_2$ (Symonds and others, 1994; Kodosky and others, 1991). Based on GPS measurements, dike propagation into the edifice started on November 17, 2005, a month earlier, and Cervelli and others (2006) conclude that magma was shallow enough by the time of the December 20, 2005, gas measurement to allow CO$_2$ and H$_2$S to escape, along with SO$_2$, and become incorporated into the plume. It is not possible, however, to confirm this because CO$_2$ and H$_2$S measurements were not made during this period.

By early January 2006, continued heating of the Augustine summit by the shallow magma had dried out the shallow hydrothermal system thereby limiting scrubbing effectiveness. The volcano was emitting SO$_2$ in large amounts with emission rates reaching 6,700 t/d (table 1; fig. 7A). On January 11, 2006, either the gas-filled dike tip arrived at the surface or a highly pressurized shallow hydrothermal system was breached, resulting in a series of explosions with little, if any, juvenile material ejected (Coombs and others, this volume; Wallace and others, this volume). SO$_2$ emission rates began to drop by more than half and finally to below 1,000 t/d near the end of the explosive period on January 28. This drop could reflect relative depletion in the volume of near-surface, SO$_2$-charged magma along with a temporary lack of replenishment. Similarly, CO$_2$ measurements during the explosive phase showed high CO$_2$ at the beginning (1,400–2,700 t/d) but dropping to 500 t/d by the end of the period. The continuing trend of inflation of the edifice throughout the explosive period (fig. 7C), however, suggests a net mass or pressure increase. An alternative explanation for the relatively low gas values during this time is a repetitive sealing of the shallow conduit system that prevented complete gas escape to the surface but contributed to pressurization seen as inflation.

Interestingly, on the gas-measurement flight of January 16, 2006, observers noticed a yellow-orange plume in the largely white vapor cloud enveloping the new lava dome within the summit crater (fig. 12). As noted earlier, the highest H$_2$S emission rate of the eruption was measured during this time (table 1). We believe the yellow-orange plume, like the colored plume observed on December 22, 2005, was native sulfur, produced at a single vent under just the right conditions of temperature and concentrations of gas streams rich in SO$_2$ and H$_2$S. This reaction possibly could reduce H$_2$S as seen in the trace amount measured that day. Production of native sulfur is achieved in industry using the Claus process (2H$_2$S + O$_2$ → S$_2$ + 2H$_2$O) where gases rich in H$_2$S (>25%) at high temperatures burn to produce sulfur and water. An accompanying process with H$_2$S and SO$_2$ reacting together can reduce H$_2$S to native sulfur (2H$_2$S + SO$_2$ → 3S + 2H$_2$O). The high-temperature fumarole at the base of the 1986 dome probably was a

Figure 12.   Yellow plume venting from summit of Augustine Volcano. View to the southwest. Dark mass below and left of yellow plume is first sighting of a lava dome mass (January 16, 2006). Dashed line outlines yellow part of plume. Photo by R.G. McGimsey.

source for this plume (Wessels and others, this volume). After January 19, 2006, H_2S emission rates declined and no further yellow plumes were observed during the eruption.

Moderate to high SO_2 emissions—similar in magnitude to those measured during the explosive phase—persisted during the continuous phase of the eruption and into the very early days of the hiatus as reflected in two airborne measurements on February 8 and 13 (table 1; fig. 7A). During the continuous phase, intense seismicity due to rapid extrusion and explosive disruption of blocky andesitic lava was accompanied by marked deflation of the volcano as magma was withdrawn to feed surface activity (Power and others, 2006; Coombs and others, this volume; Cervelli and others, this volume).

The onset of a hiatus in extrusion and a return to a very weak inflationary signal (Cervelli and others, this volume) on February 10 at first saw no significant change in SO_2 emission (fig. 7). However, SO_2 emission rates more than doubled on February 16 and remained high until the onset of rapid effusion (Coombs and others, this volume) and weak shallow deflation in early March (Cervelli and others, this volume). In fact, the highest SO_2 emission rates measured during the entire eruption occurred during this 3-week pause in extrusion, accompanied by low rates of seismicity and an overall weak inflationary trend (fig. 7). Several factors may have

contributed to the high SO_2 during the hiatus. The high eruption rates and conduit drawdown of the continuous phase (fig. 7; Coombs and others, this volume) may have resulted in an open, hot, and dry pathway in the upper few kilometers of the conduit facilitating degassing of residual melt. Alternatively (or in addition), the inflationary signal during the hiatus may reflect recharge of the shallow conduit system with fresh, gas-rich melt that lacked sufficient time to reach the surface but was able to degas freely. Unfortunately, we have no CO_2 emission rate data for the hiatus.

The hiatus ceased on March 6 marked by the return of strong shallow seismicity and a deflationary signal as seen on GPS (fig. 7C). March 9 and 10 had relatively high CO_2 emission rates; at the same time, SO_2 emission rates were near the lower end of their range during the eruption. The plume was visually dramatic on these days (fig. 13). The high CO_2 probably reflected deep recharge of magma (see below) at depths below the SO_2 exsolution level. High CO_2 and heat flux could have been the response of the rapid extrusion of largely degassed lava in early March feeding the north and northeast lava flow lobes and associated block-and-ash flows (Coombs and others, this volume). The next measurement of CO_2 was at the end of April, by which time it had dropped to about 600 t/d, confirming that the influx of new magma had stopped.

Figure 13.   Gas plume from Augustine Volcano. White condensate plume is short lived, while gases and aerosols continue down wind. View to the east. Photo by R.G. McGimsey.

Evaluating CO$_2$/SO$_2$ Ratios

Seven instances of simultaneous airborne plume measurements of CO$_2$ and SO$_2$ during 2006 provide the opportunity to compute a CO$_2$/SO$_2$ ratio for those days (fig. 14). The mean molar ratio is 1.1 with a standard error of ±0.4.

The CO$_2$/SO$_2$ measured on March 9, 2006, (0.8 under a mean of 1.1) occurred during the effusive phase (EP), a period of intense seismicity that began in early March, increased to a nearly continuous signal by March 8, and lasted until March 14 (Power and others, this volume). This was also a period of weak deflation of the edifice (Cervelli and others, this volume) and partly reflects no new CO$_2$ or additional magma rising from depths up towards the surface to feed the eruption, and SO$_2$ being depleted from a shallower magma source. By May 2007 the molar ratio had climbed to 4.3, higher than the eruptive values (not used in the mean ratio calculation). Melting of the snow pack of winter 2006–7 added water to the shallow hydrothermal system in the summit, thus aiding in the scrubbing of residual sulfur gases and raising the ratio.

The mean molar CO$_2$/SO$_2$ value of 1.1 for Augustine during the eruption is not out of line with that of other active Cook Inlet volcanoes. Casadevall and others (1994) report an average CO$_2$/SO$_2$ of about 2 for the 1989–90 eruption of Redoubt Volcano. Molar CO$_2$/SO$_2$ values of 10 ranging to as great as 100 were noted for the gases produced by the 1992 eruption of Crater Peak, although the higher ratios were almost certainly due to the masking of SO$_2$ emissions by aqueous scrubbing (Doukas and Gerlach, 1995). During 1980–81 when CO$_2$ was measured at Mount St. Helens, CO$_2$/SO$_2$ ratios averaged about 8, while during 2004–5 the median CO$_2$/SO$_2$ was about 11; this difference was also attributed to scrubbing (Gerlach and others, 2008). In general, unless the magma is degassing through liquid or boiling water, it

appears that CO$_2$/SO$_2$ values for convergent-plate volcanoes typically fall in the range 1 to 12 (Doukas and Gerlach, 1995; Marty and Le Cloarec, 1992; Williams and others, 1992).

SO$_2$ Emission Rates in Previous Augustine Eruptions

Two earlier eruptions of Augustine allow comparisons with peak SO$_2$ emission rates measured during 2006. Although the peak emission rates measured during the last three eruptions are different, other evidence suggests that the total SO$_2$ output for the Augustine eruptions in 1976, 1986, and 2006 were likely similar in magnitude.

During the 2006 unrest, the highest measured SO$_2$ emission rate was 8,930 t/d, only about one-third the peak values reported in 1976 and 1986. This could imply that the earlier eruptions were larger or more gas-rich events or simply reflect that during 2006 a measurement was not made on a day when SO$_2$ emissions were at their highest levels. Regardless, we believe total SO$_2$ emissions for the past three eruptions of Augustine are roughly similar. Eruptive volume estimates for the 1976, 1986, and 2005–6 eruptions of 0.39, 0.26, and 0.12×10^6 m^3, respectively (bulk volumes; Coombs and others, this volume) suggest that the recent event was smaller; however, limited gas data do not permit an in-depth comparison of total gas emissions from the three eruptions.

Comparison to Anthropogenic Emissions

Without quantitative emissions data it would be difficult to evaluate the volcanic contribution of greenhouse gases, such as CO$_2$, to the atmosphere. Augustine, even with its characteristically short interval between eruptions, illustrates that the volcanic contribution is likely not significant over time.
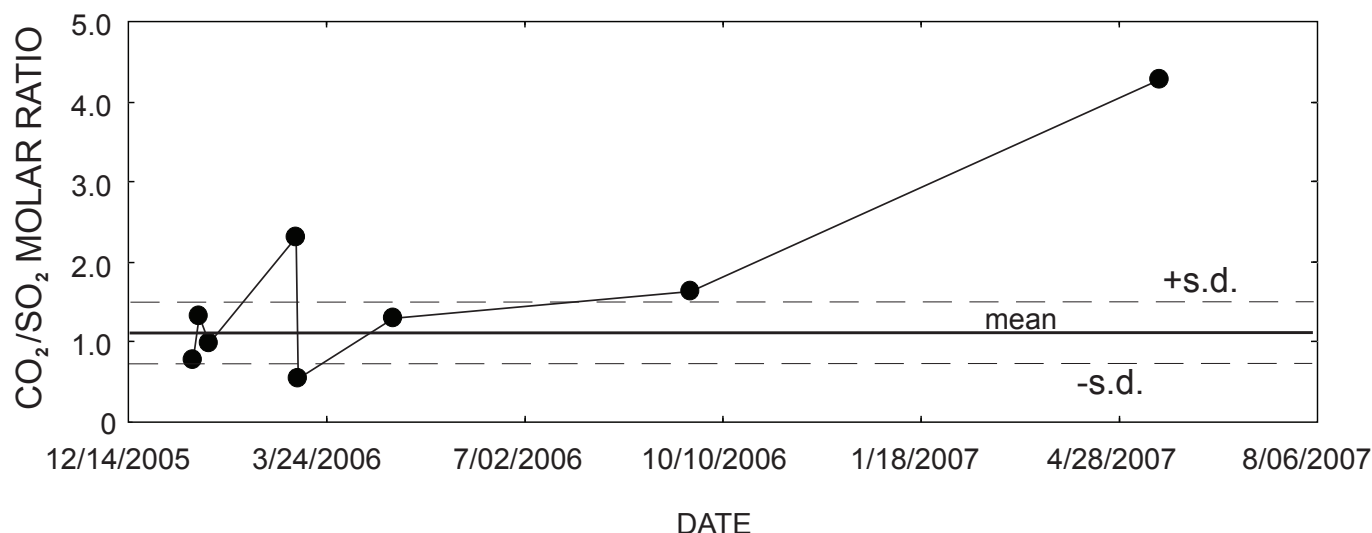
Figure 14. Molar CO$_2$/SO$_2$ for all the days when CO$_2$ and SO$_2$ were measured simultaneously. The mean molar ratio of the points (not counting the 4.3 ratio measured in 2007) is 1.3 (middle horizontal line) with a standard deviation of ±0.69.

Some volcanoes passively emit low levels of gases for decades or more (McGee, 2001). Others, like Augustine, become restless and emit gases for a few months and then become quiet again. In the case of Augustine, the repose periods between the five eruptions since the beginning of the twentieth century are 29, 11, 10, and 20 years. On the basis of CO_2 measurements reported here and using linear extrapolating to a full year, we estimate a total CO_2 output of 1.96×10^5 tons of CO_2 for Augustine in 2006, the year encompassing the majority of the most recent eruption. This is similar to the 1.2×10^6 tons of CO_2 emitted by the Beluga natural gas-fired powerplant on the west side of the Cook Inlet near Tyonek in 2004 (fig. 1) and significantly less than the output of most of the U.S. coal-fired power generation plants, some of which produce more than 20×10^6 million tons of CO_2 per year (U.S. Environmental Protection Agency, 2007). No CO_2 data exist for the earlier eruptions of Augustine. Even though Augustine erupts frequently, every 17.5 years on average since the beginning of the last century, it is clear that the greenhouse gas output of Augustine is negligible compared to the several hundred power plants of all fossil fuel types currently operating in the United States. Augustine's 2006 eruption might be considered a typical size for an average eruption worldwide (for example, volcanic explosivity index = 3, 0.01–0.1 km^3 of eruptive products; Simkin and Siebert, 1994). Using estimates from Casadevall and others (1994) for the total emission rate of SO_2 (1×10^6 tons) and the molar CO_2/SO_2 (~2) for the 1989–90 eruption of Redoubt Volcano, we can compute a total CO_2 emission rate of 1.4×10^6 tons for a similar-sized eruption of another Cook Inlet volcano.

From these data it is clear that even if several volcanoes like Augustine erupted continuously for a decade or even a century, they would still be negligible greenhouse gas contributors to the atmosphere compared to current anthropogenic sources of CO_2 emission. One of the largest continuous volcanic carbon dioxide sources on Earth is Kilauea Volcano, which emits about 9,000 tons of CO_2 a day (Gerlach and others, 2002). This amounts to 3.3×10^6 tons of CO_2 annually, still considerably less than the yearly output of a single large coal-fired powerplant (U.S. Environmental Protection Agency, 2007). Thus it appears that volcanoes are currently not significant contributors of greenhouse gases to the atmosphere compared to power generation plants.

We also estimate that Augustine emitted about 6.3×10^5 tons of SO_2 during 2006, slightly more than half the amount of CO_2 produced. Although not a greenhouse gas, SO_2 combines readily with water droplets to form aerosols and can fall as acid rain or cause cooling if injected into the upper atmosphere. The SO_2 output of Augustine during 2006 is equivalent to several coal-fired powerplants, but the short duration of the eruption insures that any impact from acid rain or acid-coated ash particles will be comparatively small. Further, given Augustine Volcano's island location and relatively low elevation, much of the gas from Augustine during 2006, with the exception of several days in January, was discharged at low elevation into the troposphere, and most of any resulting acid rain likely fell into the ocean or on sparsely inhabited land areas downwind. From early 2007 through the summer of 2008, the SO_2 output of Augustine was about 100 t/d and is expected to fall to near zero within several years as it has following the previous two eruptions.

Conclusions

1. The similar nature of recent Augustine eruptions points to generalizations regarding the timing and eruptive behavior of the volcano as well as to generalizations about the nature and magnitude of its gas emissions.

2. Geochemical surveillance of Augustine since the 1986 eruption indicates that degassing declines essentially to nil within 1 to 2 years after an eruption and does not resume to a measurable level until magma once again ascends toward the surface. This is likely due to abundant ground and hydrothermal waters available to scrub any acid gases released from remnant magma once the system cools down.

3. Although the number of plume measurements for SO_2 during the eruption is not large, the available evidence suggests that, in general, once magma is within hundreds of meters of the surface and an open pathway exists between magma and the surface, SO_2 emissions will increase. The measured SO_2 output decreased during the explosive and continuous phases but increased again during the hiatus phase of the activity prior to the final rapid effusion phase. The highest SO_2 emission rates were achieved during the early part of the hiatus, whereas the highest measured CO_2 emission rates were measured about 1 month earlier during inflation and explosive activity in January. This is in line with the idea that more SO_2 will be released as magma intrudes to shallow levels and lower pressures. High emission rates for CO_2 should be detected as deeper CO_2-rich magma moves toward the surface and discharges its load of CO_2 while still deep enough to inhibit SO_2 outgassing, although the scant CO_2 measurements do not conclusively illustrate this.

4. Emissions measurements yield an average molar CO_2/SO_2 value of about 1.3±0.7 for the 2006 eruption of Augustine, similar to typical values of 1 to 12 reported for other convergent plate boundary volcanoes.

5. Augustine is not a significant contributor to the atmospheric load of greenhouse gases compared to anthropogenic sources. In 2006, Augustine released about 1.9×10^5 tons of CO_2, a level similar to the output of a medium-sized natural-gas-fired powerplant. Augustine also released about 8×10^5 tons of SO_2 during the 2006 eruption. Evidence from other investigators suggests that the sulfur dioxide output in the 1976 and 1986 eruptions was of similar magnitude to that measured in 2006.

Acknowledgments

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