Atmospheric contribution of gas emissions from Augustine volcano, Alaska during the 2006 eruption

K. A. McGee,[1] M. P. Doukas,[1] R. G. McGimsey,[2] C. A. Neal,[2] and R. L. Wessels[2]

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[1] Airborne surveillance of gas emissions from Augustine for SO_2, CO_2 and H_2S showed no evidence of anomalous degassing from 1990 through May 2005. By December 20, 2005, Augustine was degassing 660 td^{-1} of SO_2, and ten times that by January 4, 2006. The highest SO_2 emission rate measured during the 2006 eruption was 8650 td^{-1} (March 1); for CO_2, 13000 td^{-1} (March 9), and H_2S, 8 td^{-1} (January 19). Thirty-four SO_2 measurements were made from December 2005 through 2006, with 9 each for CO_2 and H_2S. Augustine released 1×10^6 tonnes of CO_2 to the atmosphere during 2006, a level similar to the output of a medium-sized natural gas-fired power plant, and thus was not a significant contributor of greenhouse gas to the atmosphere compared to anthropogenic sources. Augustine released about 5×10^5 tonnes of SO_2 during 2006, similar to that released in 1976 and 1986. **Citation:** McGee, K. A., M. P. Doukas, R. G. McGimsey, C. A. Neal, and R. L. Wessels (2008), Atmospheric contribution of gas emissions from Augustine volcano, Alaska during the 2006 eruption, *Geophys. Res. Lett.*, *35*, L03306, doi:10.1029/2007GL032301.

1. Introduction

[2] Augustine, a young 1250-m-high convergent plate boundary stratovolcano about 100 km west of Homer, Alaska, has had four periods of significant activity in the twentieth century, 1935, 1964–65, 1976 and 1986, before the 2006 eruption [*Miller et al.*, 1998]. Typical eruptions at Augustine begin with an explosive phase that lasts from days to weeks followed by several months of effusive activity. Annual airborne gas measurements at Augustine volcano began in 1990 as part of a program to monitor gas emissions at Cook Inlet volcanoes to establish baselines to which future data could be compared in the event of unrest. No anomalous degassing was evident at Augustine until December 20, 2005 when a significant discharge of SO_2 was detected during a period of elevated seismicity, inflation of the volcanic edifice, and small phreatic explosions. In this study, we present the results of airborne plume measurements at Augustine from May 2005 to the end of 2006 to understand how degassing patterns relate to volcanic processes and to assess the total contribution of gases to the atmosphere.

2. Instrumentation

[3] Airborne emission measurements used a LI-COR LI-6252 nondispersive infrared analyzer to determine CO_2. This instrument and its use for measuring CO_2 in volcanic plumes have been described in detail elsewhere [*Gerlach et al.*, 1997, 1999]. Interscan 4170 and 4240 electrochemical analyzers were used for direct measurements of H_2S and SO_2 in the plume respectively, and their use is described in detail by *McGee et al.* [2001]. A correlation spectrometer (COSPEC) measured SO_2 column abundance and a type T thermocouple measured ambient air temperature. A pressure transducer mounted within the LI-COR analyzer recorded atmospheric pressure in the unpressurized aircraft and a GPS receiver marked the location of each measurement. All data were recorded on a 1-s time base and gas readings were corrected for pressure and temperature at the altitude where measured.

3. Procedure

[4] Two instrument configurations were utilized for airborne measurements. One employed a COSPEC and GPS receiver to determine SO_2 emission rates. Up to six traverses were flown beneath the downwind plume, perpendicular to the direction of plume travel. The other utilized the full instrument package for measuring CO_2, SO_2 and H_2S mounted in a twin-engine aircraft configured for open-flow sampling of external air upstream of engine exhaust [*Gerlach et al.*, 1997, 1999]. Besides COSPEC traverses, additional traverses were flown through the plume to record a vertical cross section of the plume. In both configurations, wind circles were flown nearby at plume altitude to determine plume velocity [*Doukas*, 2002]. Figure 1 shows the flight path for a typical flight with the full instrument package.

[5] Ambient atmospheric CO_2 measured on each traverse was fit using PeakFit v. 4.0 (Systat Software, Inc.) and subtracted from each CO_2 anomaly then zeroed to obtain CO_2 due only to the volcanic source. A similar procedure was used for H_2S. Traverse data were then imported into contouring and mapping software (Surfer v. 8, Golden Software, Inc.). Emission rates were calculated from average plume pressure and temperature, plume velocity, and volcanic gas concentration anomaly in cross-section using a procedure explained in detail by *Gerlach et al.* [1997] and *McGee et al.* [2001]. Figure 2 shows vertical plume cross-sections for the example plume. All SO_2 emission rates reported here were determined by COSPEC traverses.

4. Eruptive Sequence

[6] *Power et al.* [2006] divide the 2005–2006 eruption of Augustine into four phases based on the character of unrest and style of activity. The precursory phase began with an increase in microearthquakes in May 2005 and continued to

[1] U. S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington, USA.
[2] U. S. Geological Survey, Alaska Science Center, Alaska Volcano Observatory, Anchorage, Alaska, USA.

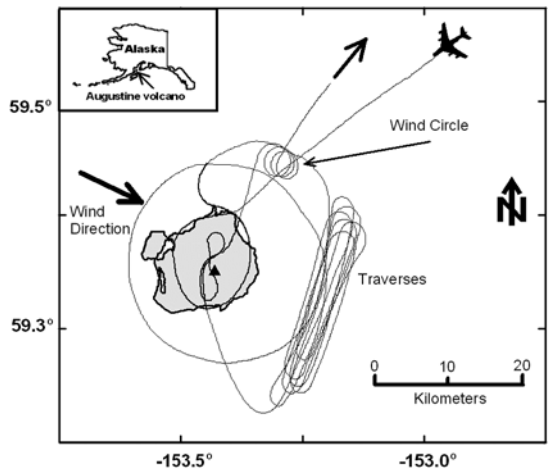

Figure 1. GPS flight path for the airborne survey at Augustine volcano, Alaska on January 19, 2006. Shaded area represents Augustine Island, darkened arrow shows wind direction, and the cluster of flight lines to the east of Augustine shows the NNE-SSW gas measurement traverses made downwind of the volcano. Traverses through the plume were flown from 780 m ASL to 1700 m ASL with an 80 m average vertical spacing. Average flight speed was 75 ms^{-1}. Flight tracks for wind circles to determine wind speed are shown NE of Augustine and were flown at the altitude of the core of the plume.

early December 2005 with several small phreatic explosions. Geodetic baselines began to lengthen in mid-summer 2005 suggesting inflation of the edifice through the latter half of 2005 [*Cervelli et al.*, 2006]. On December 12, 2005, observers noted a vigorous plume degassing from the summit area. Beginning in early December 2005 through early January 2006, phreatic explosions and energetic venting of gas and steam were observed [*Cervelli et al.*, 2006]. The first gas measurement during the unrest was May 10, 2005 at the beginning of the precursory phase and detected no CO_2, SO_2 or H_2S. The next measurement, for SO_2 only on December 20, 2005, showed a modest 660 td^{-1} SO_2 in the Augustine plume (Figure 3). The next three measurements, January 4, 9 and 10 near the end of the precursory phase, showed a marked jump in SO_2 emissions (6600, 2800 and 5500 td^{-1} respectively). Tabulated emission rates for Augustine are by *Doukas and McGee* [2007].

[7] January 11, 2006 marked the beginning of an explosive phase lasting until January 28, 2006. This phase started with a vigorous swarm of volcano-tectonic earthquakes followed by two brief ash-producing eruptions [*Power et al.*, 2006]. More explosive eruptions followed over several days. A small summit lava dome was sighted on January 16 although seismicity indicative of effusion was recognized several days earlier [*Power et al.*, 2006]. Three full instrument package measurements were made during the explosive phase (January 16, 19 and 24); SO_2 emission rates were down slightly from levels recorded during the precursory phase (2800, 3000 and 910 td^{-1}) and CO_2 was measured for the first time (5000, 6000 and 1500 td^{-1}). The highest H_2S emission rate of the eruption was recorded during this phase, 8 td^{-1} on January 19. From radar data and pilot reports, Augustine injected gases and ash into the stratosphere on at least four days during this phase (January 11, 13, 17 and 27).

[8] The third phase, a short episode beginning on January 28 with four explosive eruptions, was characterized by

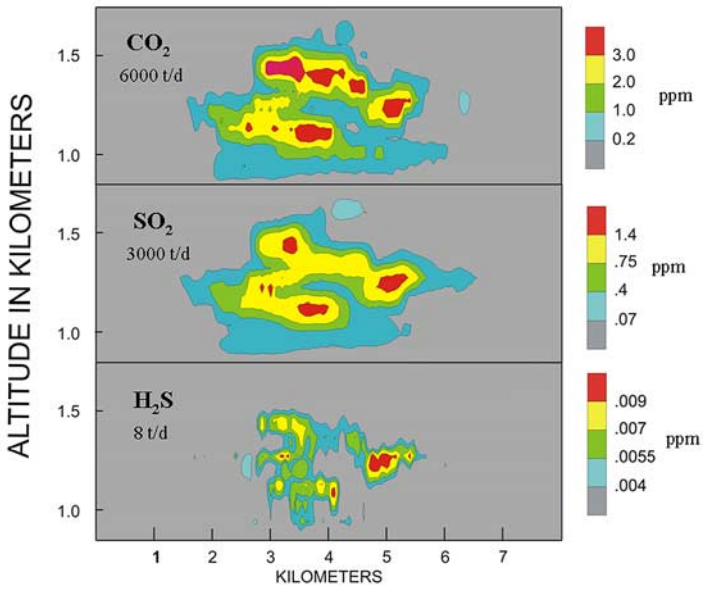

Figure 2. Cross-section of the CO_2, SO_2 and H_2S anomalies 5 km downwind from Augustine volcano from plume profile measurements on January 19, 2006. View is upwind toward volcano. Altitude scale to the left shows the distance above sea level. Contours show concentration of each gas above background with ppm color scale bars to the right. Cross-section of the 4 km-wideplume was constructed with contouring software (Surfer v.8) using exponential kriging models based on variograms fit to the concentration data for the plume. For this example, Augustine was degassing 6000 td^{-1} of CO_2, 3000 td^{-1} of SO_2 and 5 td^{-1} of H_2S. Variations in gas concentration across the plume cross-section primarily reflect the contribution of multiple vents.

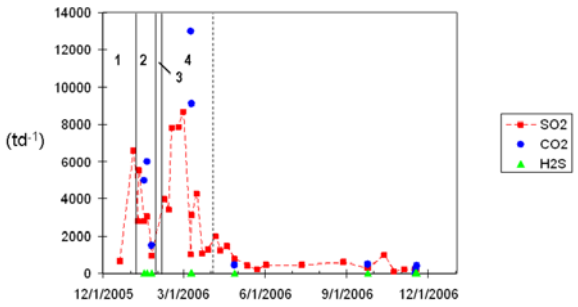

Figure 3. Emission rate time series for CO_2 (blue dots), SO_2 (red squares) and H_2S (green triangles) at Augustine from December 2005 through 2006. Emission rate uncertainty nominally reflects the uncertainty in the wind speed measurement, estimated to be ±5% for these measurements. Numeral 1 marks the precursory phase of the eruption; 2 marks the explosive phase; 3 marks the continuous phase; and 4 marks the effusive phase. The vertical dashed line shows the approximate end of the eruption.

nearly continuous ash emission and rapid dome extrusion. Repeated collapses of the dome produced large block and ash flows lasting until February 2, 2006 [*Bull et al.*, 2006]. Gas and ash plumes from Augustine briefly penetrated the tropopause on two days during this phase (January 28 & 29). Unfortunately, no gas measurement flights were made during this phase although SO_2 was detected by satellite in the eruption cloud from January 29–30 [*Dean et al.*, 2006].

[9] February 2, 2006 marked the beginning of the final phase of the eruption, a phase defined by continuous effusive activity in the summit crater. Block and ash flows from collapse of the lava dome continued during the early portion of the effusive phase. Effusive activity fed two lobes of lava that advanced down the north and northeast flanks of the cone. Effusion ended in late March [*Power et al.*, 2006]. Ten gas measurement flights were made during this phase and recorded the highest emission rates of the eruption (March 1, 8650 td^{-1} SO_2) and (March 9, 13000 td^{-1} CO_2), but by the end of March, SO_2 emission rates had declined substantially.

[10] Seventeen additional gas measurements were made from April through the end of 2006 with most SO_2 emission rates below 500 td^{-1} and the final five measurements in the 100–200 td^{-1} range. Emission rates for CO_2 during this period were similarly low, below 500 td^{-1}; H_2S levels were also very low and typically not quantifiable from March through the end of the year.

5. Discussion

[11] Following the March 1986 eruption, SO_2 had disappeared from the plume and fumarole gases of Augustine by the end of 1987 [*Doukas*, 1995; *Symonds et al.*, 1990]. Declining gas production from the cooling 1986 magma coupled with gradual influx of water into the lower edifice consumed any residual SO_2 in hydrolysis reactions resulting in SO_2, relatively unstable at low temperatures, being extinguished in the Augustine plume. Annual airborne measurements from 1990 until December 2005 detected no SO_2 in the Augustine plume. Neither SO_2 nor CO_2, a gas not well scrubbed by water, were detected during a May 2005 flight during the earliest stage of unrest. Data from *Cervelli et al.* [2006] suggest that a sea-level pressure source may have been in place under the summit by May 2005, but the lack of CO_2 would argue that this pressure source was not magma but perhaps instead simply an expanding hydrothermal system.

[12] Although visible plumes were first noticed at Augustine in early December [*Power et al.*, 2006] and sulfur smells were reported on the Kenai in mid-December, the next gas measurement, for SO_2 only, was on December 20, 2005 and detected SO_2 at Augustine for the first time in eighteen years. That measurement, a modest but elevated emission rate of 660 td^{-1}, is a minimum owing to wind conditions that prevented traverses completely beneath the plume. White billowy plumes characteristic of this period suggest large amounts of water vapor being degassed from the volcano as the edifice began heating up and expelling water. Thermal infrared (TIR) images of Augustine from ASTER on December 20 showed a broad area of new snow-free ground and fumaroles at the summit [*Wessels et al.*, 2006]. Forward looking infrared (FLIR) temperature measurements on December 22 show the temperature of a south flank fumarole to be 210°C with the summit moat area just below boiling at 80°C; by January 4, 2006, the surface temperature of the moat area was 390°C [*Wessels et al.*, 2006]. Reports from residents of Nanwalek on the lower Kenai Peninsula of strong "rotten egg" odors suggest significant sulfur emissions in the form of H_2S, consistent with earlier scrubbing by water. When SO_2 undergoes hydrolysis reactions, a portion of it is converted to H_2S which can be subsequently released as fluid temperature rises and boiling begins, while the original SO_2 remains dissolved in the water [*Symonds et al.*, 2001].

[13] By the end of the precursory phase in early January 2006, Augustine was vigorously degassing SO_2 at rates exceeding 6000 td^{-1}. Much of the water near the top of the edifice had been expelled or boiled off by then and magma had intruded to a shallow level, allowing SO_2 to degas in large amounts from the magma. Indeed, *Cervelli et al.* [2006] showed convincing evidence from GPS data for a dike intrusion beginning in mid-November and ascending toward the surface through December and early January.

[14] On January 11, 2006, the inferred dike, or highly pressurized hydrothermal system, broke the surface signaling the beginning of a series of explosive eruptions [*Cervelli and Coombs*, 2006]. In the following days, SO_2 emission rates dropped by half or more and, near the end of the explosive period, to below 1000 td^{-1}, likely reflecting depletion of SO_2 in the near-surface magma along with a temporary lack of recharge from below. Carbon dioxide, also measured during the explosive phase, started out high (5000–6000 td^{-1}) but dropped to 1500 td^{-1} by the end of the period further suggesting a temporary stalling or slowing down of magma recharge.

[15] A second period of high SO_2 emissions began in early February 2006 during the early part of the dominantly effusive phase of the eruption. The first half of February saw intense seismicity due to extrusion of blocky andesitic lava and marked deflation of the volcano as withdrawal of magma from depth fed the surface activity [*Cervelli and*

Coombs, 2006; *Power et al.*, 2006]. Emission rates for SO_2 were in the 3000 td^{-1} range but more than doubled in mid-February corresponding to a transition from deflation to inflation and decline in surface extrusion [*Cervelli and Coombs*, 2006]. Very high SO_2 emission rates persisted through the inflationary period until early March when Augustine began to deflate. Later, during another period of intense seismicity, SO_2 emission rates first dropped then increased again, finally reaching levels above 4000 td^{-1} by March 16, then falling to below 2000 td^{-1} by the end of March and below 1000 td^{-1} by the end of April following cessation of extrusion.

[16] The highest CO_2 emission rates during the unrest were recorded on March 9 and 10 during the period of deflation, intense seismicity, and rapid effusion of basaltic andesite [*Power et al.*, 2006] and while SO_2 emission rates were low, likely reflecting deep recharge of magma. Unfortunately CO_2 was not measured again until the end of April when it had dropped to about 600 td^{-1} indicating the influx of new magma had stopped.

6. Comparisons With Earlier Eruptions

[17] Peak SO_2 emissions during 2006 can be compared to similar measurements during the two previous eruptions of Augustine. During the 1976 eruption, *Stith et al.* [1978] made a series of measurements February 8–18 for total gaseous sulfur which they assumed, by smell, to be SO_2. They report a peak value of 25,900 td^{-1} on February 9, 1976 followed by 8,600 td^{-1} on February 11, 13 and 18. Their lowest measured SO_2 was 173 td^{-1} on February 12, 16 and 17. More than a year later on April 22, 1977, they measured 26 $td^{-1}$and, using a scrubber system, estimated an emission rate of 3.5 td^{-1} for H_2S for that measurement.

[18] During the 1986 eruption, *Rose et al.* [1988] made a COSPEC measurement on April 3, 1986 and recorded an SO_2 emission rate of 24,000 td^{-1} under challenging wind conditions and during active ash emission. They noted that earlier observations suggest gas emissions may have been higher during the peak of eruptive activity from March 27 to April 3. Additional measurements of 380 td^{-1} on July 24, 1986 and 45 td^{-1} on May 24, 1987 were made during post-eruption passive degassing [*Symonds et al.*, 1990].

[19] The highest SO_2 emission rate measured during the 2006 unrest was 8650 td^{-1}, about one-third the peak values for 1976 and 1986 suggesting that the earlier eruptions were larger or more gas-rich events or reflecting simply that during 2006 a measurement was not made on a day when SO_2 emissions were at their highest levels. However, total SO_2 emissions for the last three eruptions of Augustine appear to be similar (see next).

7. Comparison to Anthropogenic Emissions

[20] Volcanoes are significant sources of the greenhouse gases CO_2 and H_2O. While some volcanoes degas passively for many years without erupting, others become restless, erupt, and emit gases for a few months to a few years then become dormant again for sometimes hundreds of years. *Gerlach* [1991] suggested that quiescent degassing was responsible for the majority of global volcanic CO_2 emissions while pointing out the need for more data on CO_2 emissions, especially from erupting volcanoes, and concluding that anthropogenic emissions greatly overshadow global CO_2 emissions from volcanoes. The 2006 Augustine eruption provided an opportunity to observe CO_2 degassing throughout the eruptive cycle of a volcano. Using our CO_2 measurements at Augustine and extrapolating to an annual basis, we estimate a total CO_2 output of 1×10^6 tonnes of CO_2 for 2006, the year encompassing the majority of the eruptive activity at Augustine. This rate is similar to the 1.2×10^6 tonnes of CO_2 emitted by the nearby Beluga natural gas-fired power plant on the west side of the Cook Inlet near Tyonek in 2004 and considerably less than most of the nation's coal-fired power generation plants, some of which produce more than 20 million tonnes of CO_2 per year [*U.S. Environmental Protection Agency*, 2007]. Unfortunately no CO_2 data exist for the earlier eruptions of Augustine for comparison.

[21] Augustine, active every 17.5 years on average since the beginning of the last century, represents a class of volcanoes that erupt frequently. Yet it is clear from the results presented here that the CO_2 output of Augustine is negligible compared to the CO_2 emissions from several hundred power plants of all fuel types currently operating in the United States. Moreover, if Augustine erupted continuously for a decade or even a century, it would still be a negligible greenhouse gas contributor to the atmosphere compared to anthropogenic sources of emission. One of the largest volcanic CO_2 sources on Earth is Kilauea volcano, which emits about 9,000 tonnes a day [*Gerlach et al.*, 2002]. Taken over a whole year, this amounts to 3.3×10^6 tonnes of CO_2, still considerably less than the yearly output of a single large coal-fired power plant [*U.S. Environmental Protection Agency*, 2007]. Thus the results of this study show that contemporary eruptive CO_2 degassing is not a significant contributor of greenhouse gases to the atmosphere.

[22] We also estimate that Augustine emitted about 5×10^5 tonnes of SO_2 during 2006, half the amount of CO_2 produced. While not a greenhouse gas, SO_2 combines readily with water droplets to form aerosols and can fall as acid rain or cause cooling if present in the upper atmosphere. The SO_2 output of Augustine during 2006 is equivalent to several coal-fired power plants but the comparatively short duration of the eruption insures that any impact from acid rain or acid-coated ash particles would be minimal. Further, given Augustine's island location and low elevation, most of Augustine's emissions during 2006, with the exception of several days in January, were discharged into the troposphere making it likely that any resulting acid rain fell into the ocean or on sparsely inhabited land areas downwind. By early 2007, the SO_2 output of Augustine was at or below 100 td^{-1} indicating Augustine was no longer a significant SO_2 emitter.

[23] *Stith et al.* [1978] estimated the 1976 eruption of Augustine produced about 1×10^5 tonnes of SO_2 during a one-year period. This is a minimum value, however, since it neglects the paroxysmal emissions of April 1976, although they point out that a significant portion of the SO_2 emitted during paroxysmal eruptions was attached to the surfaces of ash particles and fell out of the plume after a short time. By comparison, using ash leachate and flux data along with seismic information and other estimates, *Rose et al.* [1988]

scaled up their measured SO_2 data of April 3, 1986 and estimated an SO_2 emission rate of 3.75×10^5 td^{-1} that they say was likely achieved on more than one day during the main phase of the 1986 eruption. Thus it appears that the total SO_2 output for each of the eruptions in 1976, 1986 and 2006 may have been of similar magnitude.

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M. P. Doukas and K. A. McGee, U. S. Geological Survey, Cascades Volcano Observatory, Vancouver, WA 98683, USA. (kenmcgee@usgs.gov)

R. G. McGimsey, C. A. Neal, and R. L. Wessels, U. S. Geological Survey, Alaska Science Center, Alaska Volcano Observatory, Anchorage, AK 99508, USA.