A compilation of gas emission-rate data from volcanoes of Cook Inlet (Spurr, Crater Peak, Redoubt, Iliamna, and Augustine) and Alaska Peninsula (Douglas, Fourpeaked, Griggs, Mageik, Martin, Peulik, Ukinrek Maars, and Veniaminof), Alaska, from 1995-2006

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Introduction

This report presents gas emission rates from data collected during numerous airborne plume-measurement flights at Alaskan volcanoes since 1995. These flights began in about 1990 as means to establish baseline values of volcanic gas emissions during periods of quiescence and to identify anomalous levels of degassing that might signal the beginning of unrest. The primary goal was to make systematic measurements at the major volcanic centers around the Cook Inlet on at least an annual basis, and more frequently during periods of unrest and eruption. A secondary goal was to measure emissions at selected volcanoes on the Alaska Peninsula. While the goals were not necessarily met in all cases due to weather, funding, or the availability of suitable aircraft, a rich dataset of quality measurements is the legacy of this continuing effort. An earlier report (Doukas, 1995) presented data for the period from 1990 through 1994 and the current report provides data through 2006.

This report contains all of the available measurements for SO_2, CO_2, and H_2S emission rates in Alaska determined by the U. S. Geological Survey from 1995 through 2006; airborne measurements for H_2S began in Alaska in 2001.

The results presented here are from Cook Inlet volcanoes at Spurr, Crater Peak, Redoubt, Iliamna, and Augustine and cover periods of unrest at Iliamna (1996) and Spurr (2004-2006) as well as the 2006 eruption of Augustine. Additional sporadic measurements at volcanoes on the Alaska Peninsula (Douglas, Martin, Mageik, Griggs, Veniaminof, Ukinrek Maars, Peulik, and Fourpeaked during its 2006 unrest) are also reported here.

Instrumentation

For the airborne study of volcanic plumes, we used a Barringer correlation spectrometer (COSPEC V) to measure SO_2 column abundance. This venerable instrument was originally designed more than three decades ago for measuring emissions from power plants and other industrial sources, but its subsequent application for the study of SO_2 degassing from volcanoes has been described in detail by many authors (Malinconico, 1979; Casadevall and others, 1981; Stoiber and others, 1983).

To determine volcanic CO_2, we used a LI-COR Model LI-6252 nondispersive infrared analyzer and a Model LI-670 flow control unit. This instrument and its use for measuring CO_2 in volcanic plumes have been described in detail elsewhere (Gerlach and others, 1997; Gerlach and others, 1999). We also used an Interscan Model 4170 analyzer with a 0-1 ppm range for measuring H_2S and an Interscan Model 4240 analyzer with a 0-2 ppm range for direct measurements of SO_2 in the volcanic plumes. These instruments consist of an electrochemical voltametric sensor coupled to a 1 liter-per-minute sample-draw pump. Gas concentrations are recorded from the calibrated analog output of the instruments. Because the Interscan sensors have some cross-sensitivity to other gases, outboard scrubber tubes connected to the sensor inputs were used to remove the interfering gases. The use of the Interscan for measuring H_2S and SO_2 in volcanic plumes is described in detail by McGee and others (2001) and Werner and others (2006).

Complementing the gas-sensing instrumentation, a pressure transducer mounted within the LI-COR analyzer measured atmospheric pressure in the unpressurized aircraft cabin and a GPS receiver recorded the precise location of each measurement. A type T thermocouple shielded from wind and direct sunlight measured ambient air temperature. Data from all the instruments were recorded on a common 1-s time base, and gas readings were corrected for the actual pressure and temperature at the altitude where the measurements were taken.

Procedure

Two instrument configurations were utilized for the airborne measurements reported here. In one case, only the COSPEC and a GPS receiver were used to determine SO_2 emission rates. For most of the measurements reported here, a twin-engine Piper Navajo aircraft, modified for mounting the COSPEC telescope through portals in either the front passenger side window or through the rear cargo door, was utilized. Typically, four to six traverses were flown under the downwind plume perpendicular to the direction of plume travel with the upward-looking COSPEC to measure an average column abundance of SO_2. Wind circles at the elevation of the plume were then flown to calculate the velocity of plume travel so that a SO_2 emission rate could be computed (Doukas, 2002).

In the other configuration, the full instrument package for measuring CO_2, SO_2, and H_2S was mounted in the 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 through the plume at successively different altitudes from top to bottom of the plume all at the same distance downwind of the vent to record a vertical cross section of the plume for each gas present.

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) and subtracted from each peak and zeroed to obtain the CO_2 due only to the volcanic source. A similar procedure was used for H_2S and SO_2 although no H_2S and SO_2 were present in the background air. Plume traverses through a vertical slice of the plume were flown either in an orbital fashion, where all traverses run in the same direction, or in a back-and-forth fashion where each traverse travels the opposite direction from the one above it and the one below it. At those volcanoes where traverses were flown in a back-and-forth fashion in a vertical plane through the plume, alternate traverses were inverted prior to 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 (Surfer v. 8). Emission rates were then calculated from the average plume pressure and temperature, wind speed, and the volcanic gas concentration anomaly in cross-section as explained in detail in Gerlach and others (1997) and McGee and others (2001).

Results

From January 1995 through the end of 2006, more than 135 airborne volcano plume measurements were made by the USGS to characterize baseline gas emissions and assess the extent of unrest at volcanoes in Cook Inlet and Alaska Peninsula (fig. 1). Sulfur dioxide measurements were attempted in every case whereas CO_2 and H_2S measurements were attempted less frequently.

Two significant improvements since 1994 have advanced our capability to make high quality measurements. First, beginning in 1995, we began using a LI-COR infrared spectrometer for measuring CO_2 in volcanic plumes. This instrument is vastly superior to the older MIRAN spectrometer used in earlier years and provides considerably better resolution and a lower detection limit for CO_2. Second, the biggest improvement in methodology from the 1990-1994 measurements to the present is the adoption of wind circle measurements for more accurate wind speed determinations to estimate plume velocity. This technique, begun in Alaska in 1998 and described in detail in Doukas (2002), results in wind speed errors of only about ±5%, a considerable improvement over earlier methods, and allows for a direct measurement of the wind at the actual altitude of the core of the plume.

A small number of the COSPEC measurements were made by flying over the top of the plume with the telescope directed downward, a possible configuration noted in the manual of operation for the COSPEC (Barringer Research Limited, 1981, p. 1 and 45). This was an experiment to determine the validity of this strategy so that it might possibly be used in those instances where winds, clouds or topography prevented the aircraft from flying beneath the plume. The majority of the down-looking measurements were made in conjunction with up-looking measurements on the same flight so that a rigorous comparison could be made. Our results indicate that while a few of the down-looking measurements agree very well with the traditional up-looking measurements, most of the down-looking measurements seem to overestimate SO_2 emission rates, often by 50% and sometimes by as much as

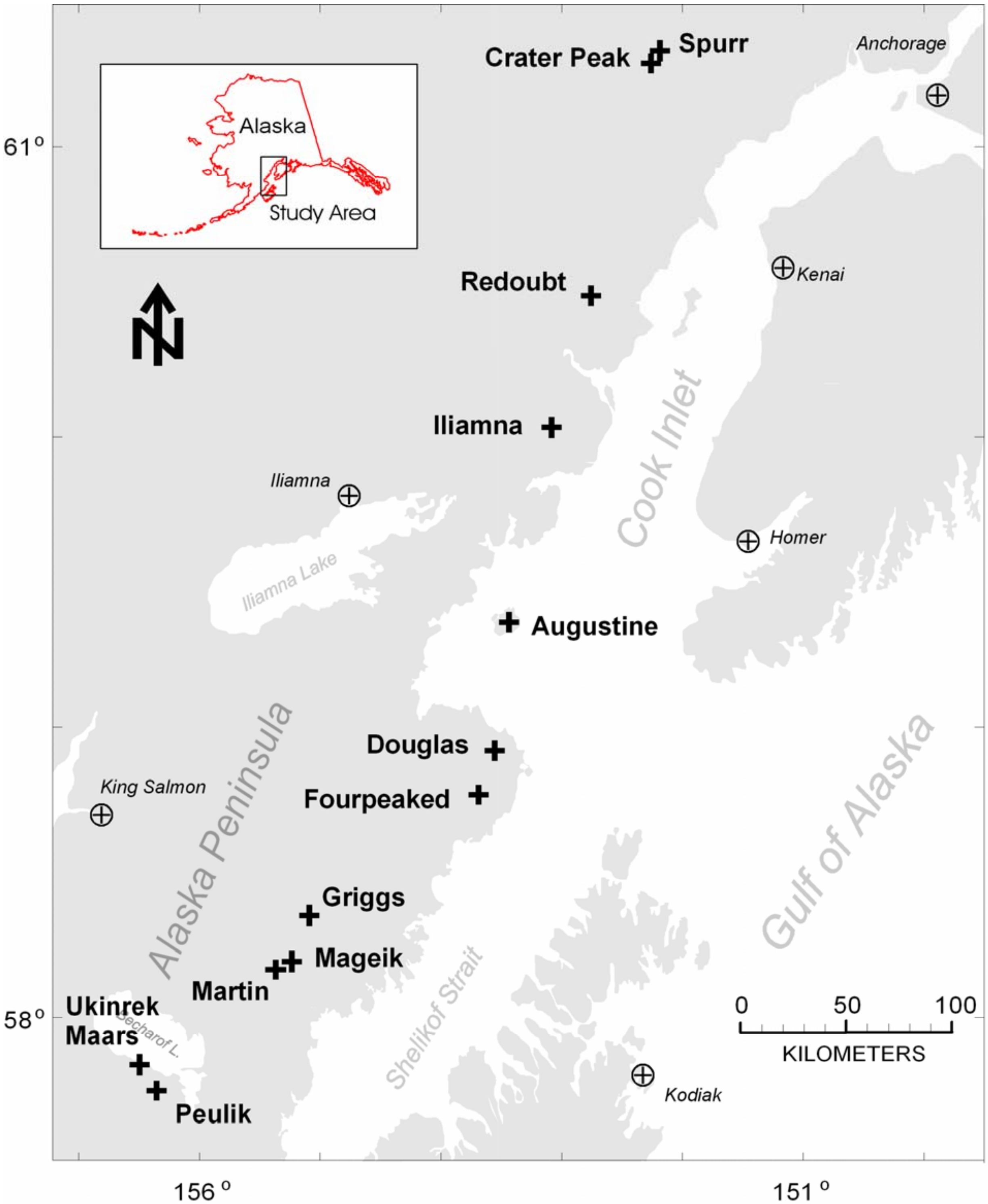

Figure 1. Map of the Cook Inlet area and upper Alaska Peninsula showing the location of the volcanoes included in this report. Crosses designate volcanoes where measurements have been made. Veniaminof volcano is off the map to the WSW.

100%, compared to the up-looking measurements during the same flight. We suspect the down-looking measurements may be highly susceptible to variation of sun angle and the albedo of the ground surface. At some sun angles, sunlight can pass through the plume and reflect off the ground surface beyond the edge of the plume, thereby creating an apparent shadow plume. In other cases, sunlight can pass through the plume and be reflected upward from the bottom edge of the plume, thereby passing through the plume twice before it is measured. Additionally, some sunlight can be reflected upward from the top of the plume without ever passing through the plume even once. For light that does reflect off the ground, the amount of return will depend on whether the surface is bare ground, water, or snow. Thus the degree of agreement between down-looking and up-looking COSPEC measurements is likely a function of sun angle, ground surface albedo, and possibly other parameters. It appears that radiative transfer problems are too complex for casual use of this mode, so without further rigorous testing, we cannot recommend this strategy except in those cases where a measurement from beneath the plume is simply not possible and an order-of-magnitude estimate of SO_2 emissions is required, or where a determination of the presence or absence of SO_2 is sufficient. For this compilation, we report only the traditional up-looking COSPEC measurements except in three cases, all at Fourpeaked volcano, where there is no corresponding up-looking measurement.

Tables 1 through 13 list the date of measurement with the corresponding gas emission rates determined by airborne plume measurements at each volcanic center studied. Gas emission rates are usually expressed as td^{-1} (metric tons per day). One metric ton per day equals 10^3 kilograms per day or 1 megagram per day (Mg/d). Emission rates are not rounded and are listed as we calculated them from the measurements without regard for significant figures. We estimate the uncertainty for the measurements reported herein to be ±20% or less. A blank space in the table indicates that a measurement for that particular gas was not attempted that day. A zero indicates that an attempt was made to measure the gas but no gas was detected. A ‘tr’ indicates that the gas was present in the plume but was of either insufficient concentration to be quantified or, in the case of CO_2, not resolvable due to variations in ambient atmospheric CO_2.

Sixteen measurements were made at the summit of Spurr beginning in August 2004 after the onset of a series of volcano-tectonic and long-period earthquakes followed by the formation of a summit ice cauldron. Similarly, seventeen measurements were made at Crater Peak, with the majority made after the fall of 2004, although Crater Peak, unlike the summit of Spurr, has been measured periodically since its eruption in 1992. Spurr/Crater Peak continues to exhibit restless behavior but has not erupted as of this writing.

Redoubt volcano has not degassed significantly since it erupted in 1989-90 but has been measured periodically to check for any anomalous degassing. Similarly, Douglas volcano is not producing any significant amount of gas and is visited only occasionally as a precaution. The plume of Iliamna has been measured twenty times from 1995 through 2006 with several of those measurements occurring in 1996 during a dike emplacement episode (Roman and others, 2004). In recent years, Iliamna has consistently degassed a small amount of SO_2 with occasional small amounts of H_2S.

Augustine received the most attention of any volcano in Alaska with 54 gas measurements during the period covered by this report; more than half of those were made during the eruption that occurred between January and April 2006. Peak gas emission rates for Augustine in 2006 were 8650 td^{-1} (SO_2), 13000 td^{-1} (CO_2), and 8 td^{-1} (H_2S). As of late 2007, Augustine was producing less than 100 td^{-1} SO_2 and CO_2, and no H_2S.

Fourpeaked volcano became restless in September 2006. An explosion of gas, ash, and steam rising from high on the ice-clad northeast flank of the volcano on September 17 signaled the beginning of the unrest. Shortly thereafter, a linear series of vigorously degassing vents was observed. Six gas measurement flights were made from September 23 through the end of the year and recorded peak emission rates of 2940 td^{-1} (SO_2), 834 td^{-1} (CO_2), and 140 td^{-1} (H_2S). The gas data suggest an intrusion of magma to shallow levels under the summit but, however, no eruption has occurred. The 140 td^{-1} value for H_2S is the largest emission rate we have recorded anywhere for that gas.

Mageik and Martin volcanoes were measured four and five times respectively from 1998 through 2006. Interestingly, on the August 2004 flight, significant degassing rates of CO_2 and H_2S were recorded at Mageik, but no SO_2, whereas at nearby Martin volcano SO_2 and H_2S were recorded, but no CO_2 was detected. The other volcanoes on the Alaska Peninsula that have been measured (Griggs, Peulik, Ukinrek Maars, and Veniaminof) were successfully visited only once. This is due primarily to the high costs associated with flying to these sites, and also the frequently poor weather. The single successful measurement at Ukinrek Maars was at a nearby feature called Gas Rocks.

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Table 1. Spurr volcano gas emission rates.

Day	Month	Year	SO_2	CO_2	H_2S
07	August	2004	0	609	0.2
15	September	2004	0	1300	1.0
16	September	2004	0	1167	tr
29	October	2004	0	1400	3.0
28	February	2005	83	327	0
02	March	2005	47	536	0
10	May	2005	110	750	2.0
11	May	2005	72	760	6.7
20	September	2005	54	246	0.3
06	April	2006	184		
23	April	2006	62	184	2.6
26	April	2006	49	498	2.5
12	July	2006	100		
28	August	2006	53		
25	September	2006	64	150	1.5
17	November	2006	390	308	3.9

Note: Emission rates expressed as metric tons per day (td^{-1}); for this and successive tables, a blank space indicates no measurement, a zero indicates gas not detected, and 'tr' indicates gas present but not quantifiable.

Table 2. Crater Peak vent on Spurr volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
19	August	1996	0	10	
02	April	1997	0		
24	May	1997	0	1010	
09	August	2000	0	140	0
10	September	2001	tr	10	tr
07	August	2003	0	160	0
15	September	2004	0	1000	0
16	September	2004	0	10	0
30	October	2004	0	116	0
28	February	2005	9	447	0
02	March	2005	0	812	0
10	May	2005	3	413	
11	May	2005	tr	10	0
20	September	2005	59		
23	April	2006	0	722	0
26	April	2006	0	145	0
25	September	2006	0	0	0

Note: Emission rates expressed as metric tons per day (td^{-1})

Table 3. Redoubt volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
02	April	1997	0	0	0
09	August	2000	0	10	0
10	September	2001	0	10	1
10	May	2005	9	52	0

Note: Emission rates expressed as metric tons per day (td^{-1})

Table 4. Iliamna volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
11	January	1995	9		
09	August	1996	137		
13	August	1996	120	270	
18	August	1996	70	883	
20	September	1996	282		
08	October	1996	404		
10	October	1996	111		
02	April	1997	0		
24	May	1997	163	130	
25	May	1998	56	72	
09	August	2000	54	44	
10	September	2001	0	1	0
01	July	2002	0	0	0
02	July	2002	tr	0	0
10	September	2002	0	0	0
01	August	2003	127	0	0
03	August	2003	tr	tr	tr
07	August	2004	29		4
08	August	2004	20	304	2
10	May	2005	30	0	0

Note: Emission rates expressed as metric tons per day (td^{-1})

Table 5. Augustine volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
11	January	1995	0	0	
09	August	1996	0	0	
13	August	1996	0	0	
18	August	1996	0	0	
20	September	1996	0	0	
08	October	1996	0	0	
10	October	1996	0	0	
02	April	1997	0	0	
24	May	1997	0	30	
25	May	1998	0	0	
09	August	2000	0	0	
10	September	2001	0	0	0
01	July	2002	0	tr	tr
02	July	2002	0	tr	tr
10[1]	September	2002	0	0	0
10[2]	September	2002	0	0	0
01	August	2003	0	0	0
03	August	2003	0	0	0
07	August	2004	0	0	0
10	May	2005	0	0	0
20	December	2005	660		
04	January	2006	6560		
09	January	2006	2800		
10	January	2006	5500		
16	January	2006	2780	4980	tr
19	January	2006	3020	5970	8.2
24	January	2006	914	1480	4.9
08	February	2006	3960		
13	February	2006	3384		
16	February	2006	7800		
24	February	2006	7830		
01	March	2006	8650		
09	March	2006	1020	13000	0
10	March	2006	3110	9100	0
16	March	2006	4260		
22	March	2006	1070		
29	March	2006	1270		
06	April	2006	1965		
11	April	2006	1220		
19	April	2006	1440		
27	April	2006	751	626	1.3
12	May	2006	400		
23	May	2006	223		
02	June	2006	430		
12	July	2006	495		
28	August	2006	450		
24	September	2006	283	289	1.3
25	September	2006	266	0	0

12	October	2006	953		
23	October	2006	100		
04	November	2006	160		
16	November	2006	225	tr	0
17	November	2006	220	300	0
18	November	2006	211	400	0

Note: Emission rates expressed as metric tons per day (td^{-1}), [1]Morning measurement, [2]Afternoon measurement

Table 6. Douglas volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
10	August	2000	0	tr	
02	July	2002	tr	tr	0
10	September	2002	tr	tr	tr
18	November	2006	tr	tr	tr

Note: Emission rates expressed as metric tons per day (td^{-1})

Table 7. Fourpeaked volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
23	September	2006	2353	834	140
24	September	2006	1620	340	74
30	September	2006	2207		
12	October	2006	2264[1]		
23	October	2006	2940[1]		
04	November	2006	820		
17	November	2006	1650[1]		
18	November	2006	1000	595	27

Note: Emission rates expressed as metric tons per day (td^{-1}), [1]COSPEC measurement with down-looking telescope

Table 8. Griggs volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
01	July	2002	0	0	0

Note: Emission rates expressed as metric tons per day (td^{-1})

Table 9. Mageik volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
10	August	2000	tr	tr	
01	September	2002	tr	tr	
07	August	2004	0	1365	69
24	September	2006	tr	tr	tr

Note: Emission rates expressed as metric tons per day (td^{-1})

Table 10. Martin volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
24	May	1998	114	280	
10	August	2000	tr	tr	
01	September	2002	0	0	0
07	August	2004	73	0	43
24	September	2006	24	tr	tr

Note: Emission rates expressed as metric tons per day (td^{-1})

Table 11. Peulik volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
24	May	1998	0	0	

Note: Emission rates expressed as metric tons per day (td^{-1})

Table 12. Ukinrek Maars gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
24	May	1998	0	187	

Note: Emission rates expressed as metric tons per day (td^{-1})

Table 13. Veniaminof volcano gas emission rates

Day	Month	Year	SO_2	CO_2	H_2S
02	August	2003	0	0	0

Note: Emission rates expressed as metric tons per day (td^{-1})