Sulfur Dioxide Emission Rates from Kīlauea Volcano, Hawaii, an Update: 2002-2006

By T. Elias and A.J. Sutton

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Cover: Sun seen through fume cloud from Pu`u `O`o, viewed from Uwekahuna overlook at the summit of Kilauea. Fountain heights at Pu‘u ‘O‘o reached a maximum of 295 m around the time this photo was taken during episode 38 (photo by J.D. Griggs, 10/21/85, JG5935)

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Sulfur Dioxide Emission Rates from Kīlauea Volcano, Hawaii, an Update: 2002-2006

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INTRODUCTION

Sulfur dioxide (SO_2) emission rates from Kīlauea Volcano were first measured by Stoiber and Malone (1975) and have been measured on a regular basis since 1979 (Greenland and others, 1985; Casadevall and others, 1987; Elias and others, 1998; Sutton and others, 2001, Elias and Sutton, 2002, Sutton and others, 2003). Compilations of SO_2 emission-rate and wind-vector data from 1979 through 2001 are available on the web. (Elias and others, 1998 and 2002). This report updates the database through 2006, and documents the changes in data collection and processing that have occurred during the interval 2002-2006.

During the period covered by this report, Kīlauea continued to release SO_2 gas predominantly from its summit caldera and east rift zone (ERZ) (Elias and others, 1998; Sutton and others, 2001, Elias and others, 2002, Sutton and others, 2003). These two distinct sources are always measured independently (fig.1). Sulphur Banks is a minor source of SO_2 and does not contribute significantly to the total emissions for Kīlauea (Stoiber and Malone, 1975).

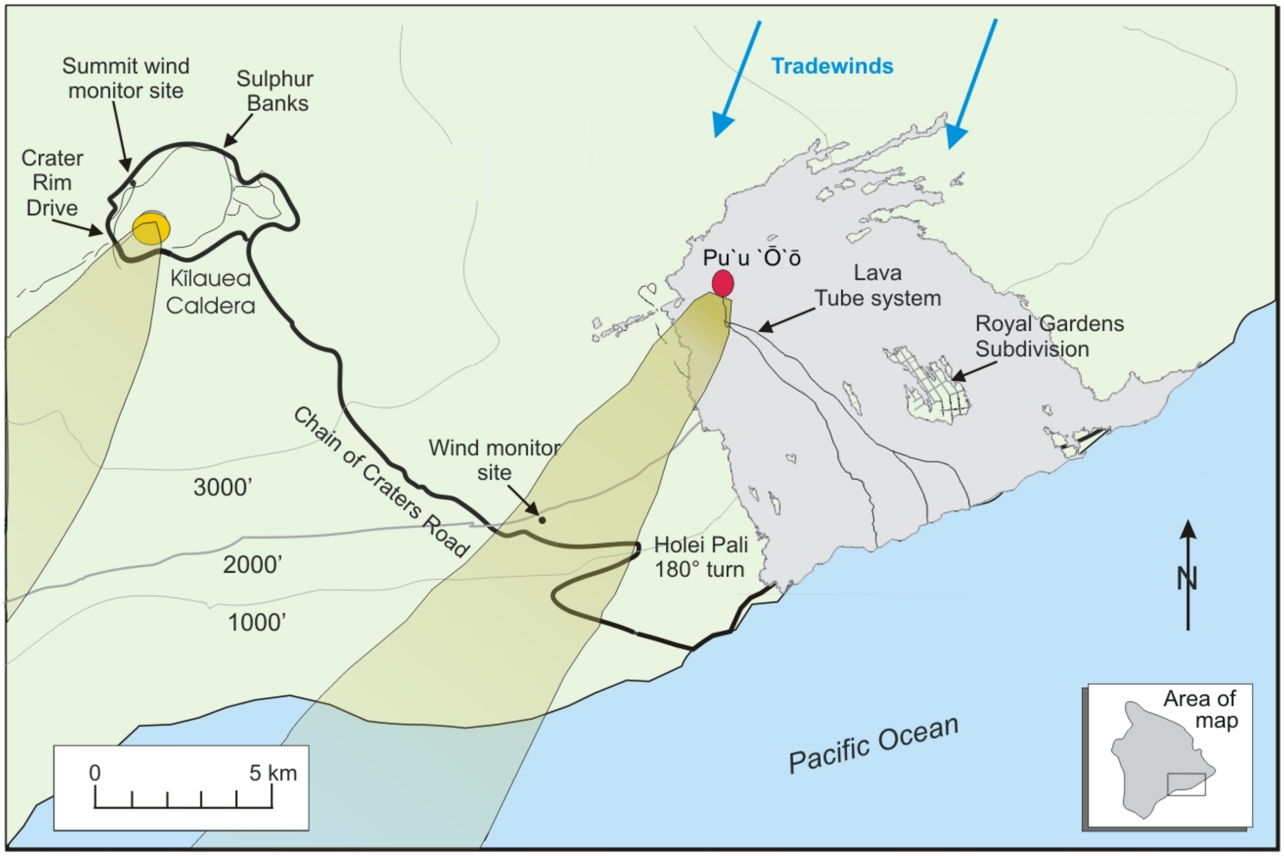


Figure 1. Vehicle-based SO_2 measurements are made downwind of the summit and east rift zone plumes on Crater Rim Drive and Chain of Craters Road during trade-wind conditions. The currently active lava tube system began developing in March 2004. Flow field and lava tube system current as of January 2007.

From 1979 until 2003, summit and east rift zone emission rates were derived using vehicle- and tripod- based Correlation Spectrometry (COSPEC) measurements. In late 2003, we began to augment traditional COSPEC measurements with data from one of the new generation of miniature spectrometer systems, the FLYSPEC (Horton and others, 2006; Elias and others, 2006, Williams-Jones and others, 2006).

ACKNOWLEDGMENTS

We are particularly grateful to the gas geochemistry volunteers at the Hawaiian Volcano Observatory (HVO) who contributed to these 5 years of data which include more than 250 days of measurements and nearly 2800 plume traverses. This work is supported by the USGS Volcano Hazards Program. Many thanks are owed to the University of Hawai'i Center for the Study of Active Volcanoes for the extended use of both their COSPEC V and FLYSPEC instruments. Also, we are grateful to Keith Horton and Harold Garbeil of UH Mānoa, for their patient development of the FLYSPEC using the Kīlauea environment and the COSPEC V as a reference. This allowed for a smooth transition between the two methods and confidence in the continuity of the long-term volcanic SO_2 dataset.

METHODS AND UNCERTAINTIES

Instrumentation

From March 2001 until July 15, 2004, SO_2 measurements at Kīlauea were made using a COSPEC V correlation spectrometer, manufactured by Resonance Ltd., Ontario, Canada. The COSPEC V uses a Cassegrain telescope, high concentration disc assembly, calibration cells of 410 ppm and 1395 ppm, and an onboard data-acquisition system.

In October, 2001, as part of a coordinated field effort for the NASA Earth Observing System (EOS) Interdisciplinary Science program, we measured SO_2 emission rates and concentration path lengths using the well-tested COSPEC along side an experimental spectrometer system belonging to Keith Horton (Hawaii Institute of Geophysics and Planetology of the University of Hawai`i at Mānoa). Horton's system was based on the new Ocean Optics USB 2000 miniature UV spectrometers (Dunedin FL, USA). Thus began a long romance between HVO and the emerging miniature UV spectrometer technology.

In 2002-2003, we conducted multiple experiments with Horton and his miniature spectrometer system, which was referred to as the FLYSPEC for its small size. Running side-by-side with the COSPEC V in the road-based configuration, the noise envelope, response to light, and SO_2 retrieval methods for the FLYSPEC were optimized. Data acquisition and reduction software were tuned to be user-friendly, fast, and convenient. By late 2003, much of the needed refinement of the FLYSPEC system had been achieved, and good agreement existed between the COSPEC and FLYSPEC. We confirmed this by running the two instruments side-by-side until September 2004, at which point, the FLYSPEC effectively replaced the COSPEC (fig. 2a-b).

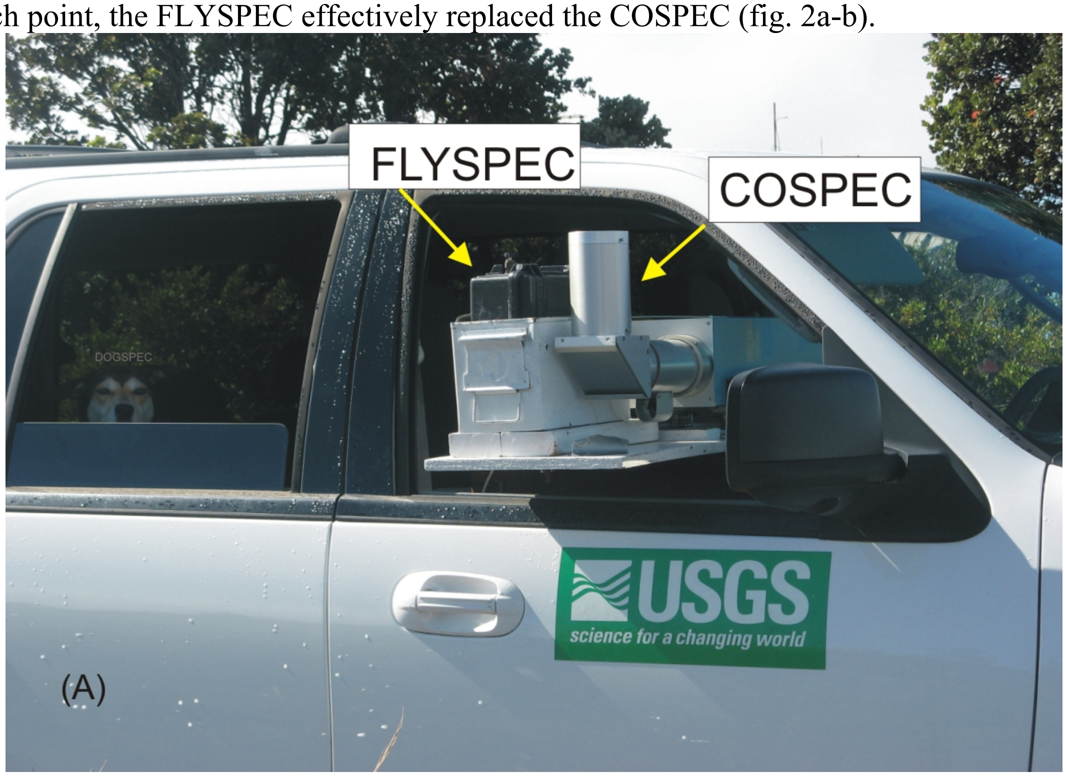


Figure 2. Instrument configurations showing set-up for (A) FLYSPEC and COSPEC coincident measurements (B)current vehicle-based FLYSPEC measurements. Ultraviolet light enters the spectrometer, which is housed in the black pelican case, through a UV window located in the top of the box.

The FLYSPEC system is described in Horton and others (2006) and Elias and others (2006). Correlation between the COSPEC and FLYSPEC data sets over an eight month period yields an r^2=0.994, and slope=0.998 (Elias and others, 2006) giving us confidence in the continuity of our data set.

Table 1 describes the various UV spectrometer systems used by HVO for regular SO_2 emission rate measurements at Kīlauea Volcano.

Table 1. UV spectrometer systems used by HVO over time

Date	Spectrometer system	Reference
June 1979- March 2001	COSPEC IV	Barringer Research Ltd., Ontario, Canada
March 2001 - September 2004	COSPEC V	Resonance Ltd., Ontario, Canada
July 2003-September 2004	COSPEC/FLYSPEC[1]	Resonance Ltd., Ontario, Canada/Keith Horton, UH Mānoa/ FLYSPEC Inc., Honolulu, Hawai`i
September 2004-present	FLYSPEC[1]	Keith Horton, UH Mānoa/FLYSPEC Inc., Honolulu, Hawai`i

1. first generation FLYSPEC instrument

Data collection and reduction

We collected routine digital data with the COSPEC V using a palmtop or notebook computer; however, we continued to use an analog strip chart for in situ plume tracking and as back up in the event of computer failure in the field. No simultaneous GPS data were collected, so the wind-normal distances along the traverse segments (to account for non-perpendicular plume and road segment configurations) were calculated by marking the endpoints of each road segment in the data stream (Gerlach and others, 2002; Stoiber and others, 1983; Millan and others, 1976, Willliams-Jones and others, 2007). Emission rates were calculated using a PC-based program described in Elias and Sutton, 2002.

The FLYSPEC data acquisition program, "Lapfly" written by Harold Garbeil (Hawaii Institute of Geophysics and Planetology of the University of Hawai`i at Mānoa), provides a real-time display of the radiance spectrum, a scrolling plot of the gas path-concentration in ppm-m, and the corresponding GPS position and time (fig. 3). The wind-normal distances along the traverse are calculated for each pair of GPS positions. The data reduction software, "FluxCalc" (also by Garbeil) allows the user to quickly and efficiently reduce large amounts of data through an interactive graphical interface (fig. 4a-b). All FLYSPEC data presented in this report were reduced with the peak-to-trough differencing method described in Horton and others (2006) and Elias and others (2006).

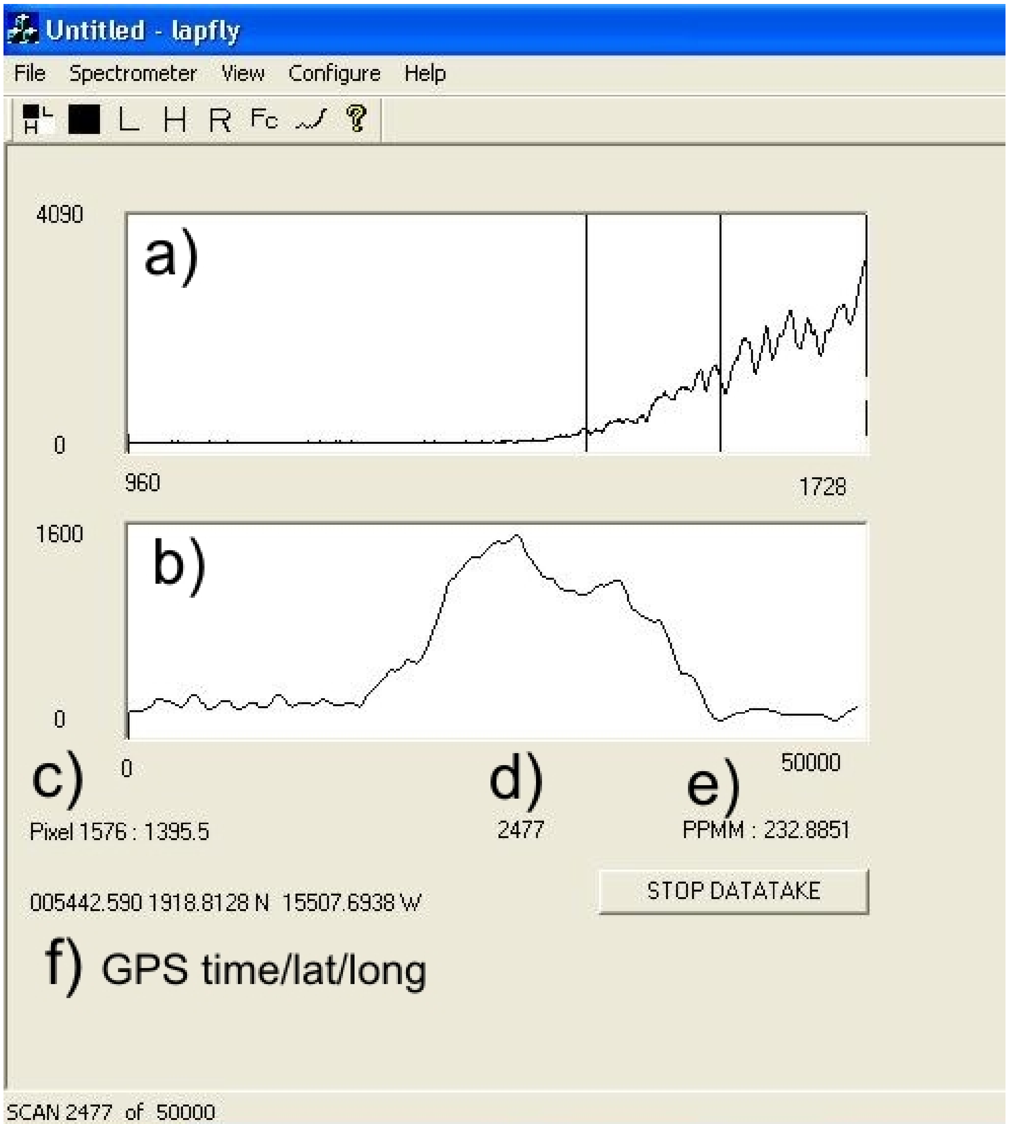
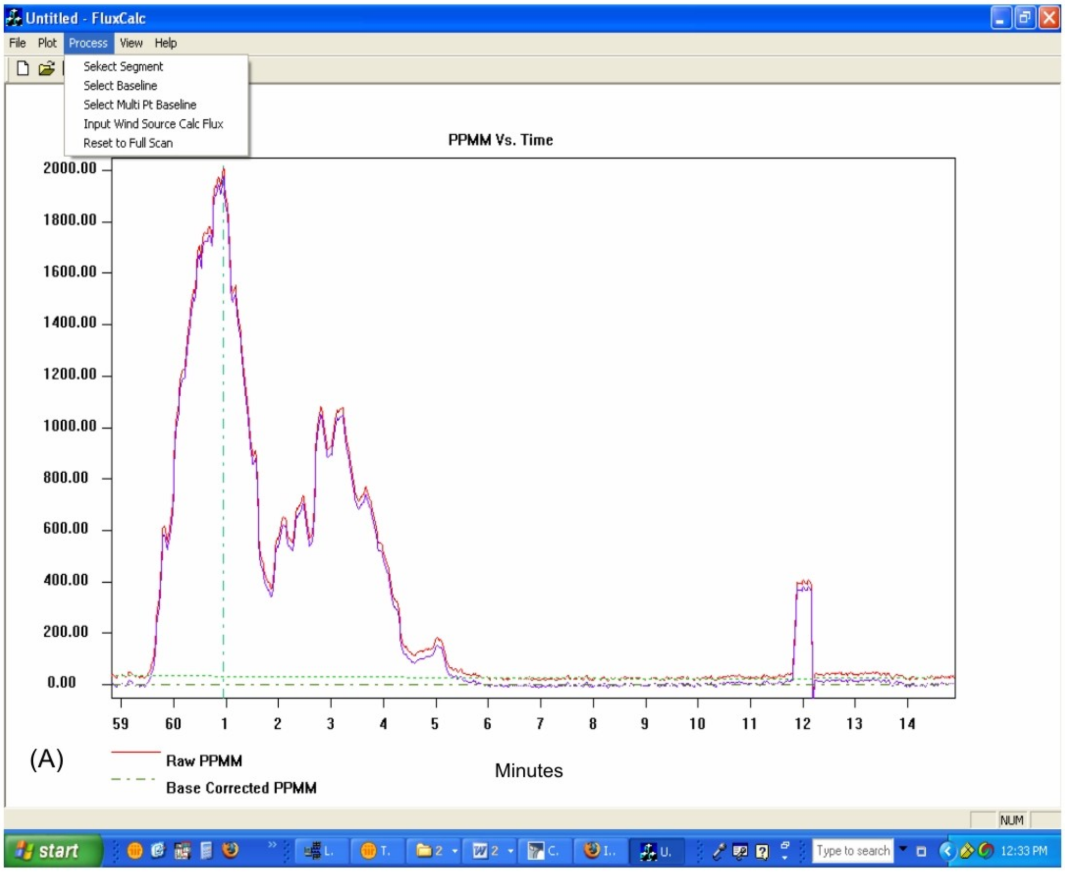


Figure 3. FLYSPEC data collection screen in data acquisistion program “Lapfly” provides: a) the current radiance spectrum (upper plot) b) scrolling plot of gas path-concentration in ppm m (lower plot) c) radiance at a pixel within the SO_2 fitting region d)spectrum number e) path-concentration value for the current spectrum (ppm m) and f) GPS time and position data.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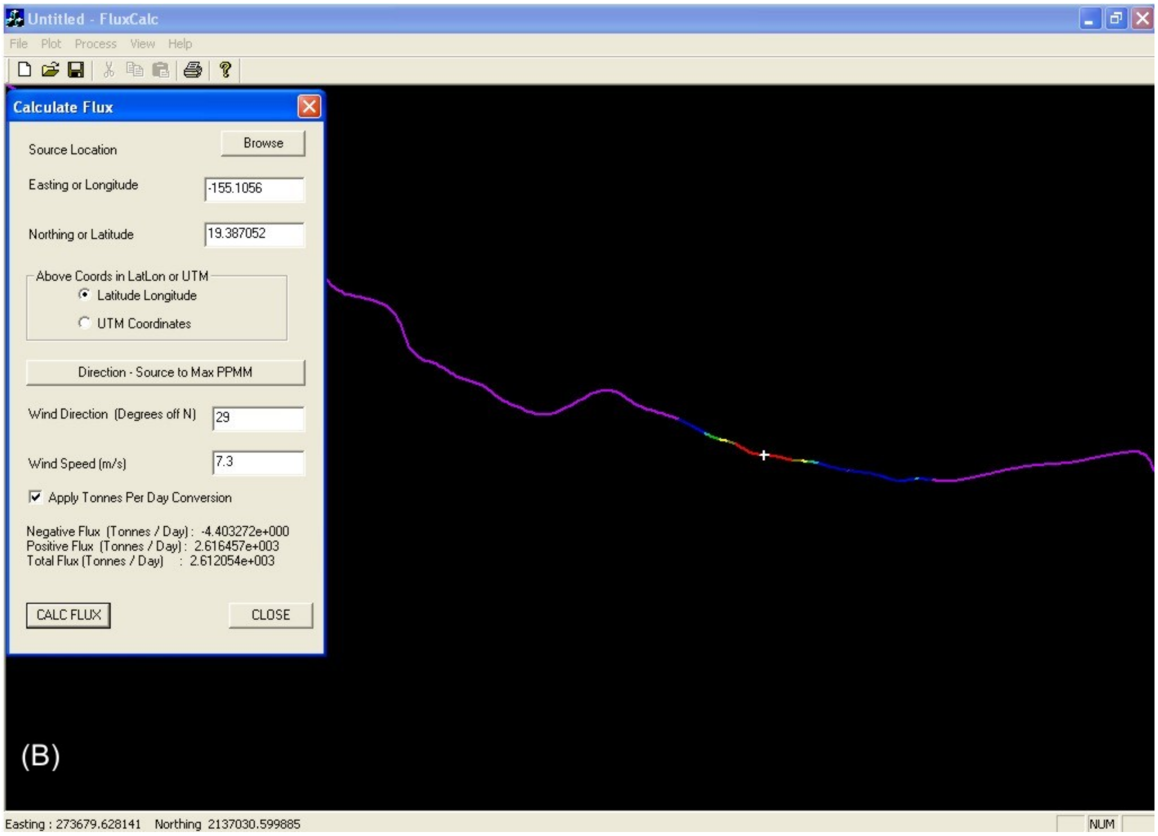


Figure 4. "FluxCalc" screens showing (A) a traverse of the east rift plume followed by the low calibration cell. The software allows the user to graphically select and adjust the baseline for each traverse. The two traces represent the original plume (red) and baseline corrected PPM M values (blue) respectively (B) GPS referenced traverse of plume transect along Chain of Craters Road. Higher gas pathlength concentrations along the traverse are designated by warmer colors, with the location of the peak concentration indicated by the "+". The gas source location *or* wind direction, and wind (or plume) speed are used with the wind-normalized curve area to calculate an emission rate in metric tonnes/day.

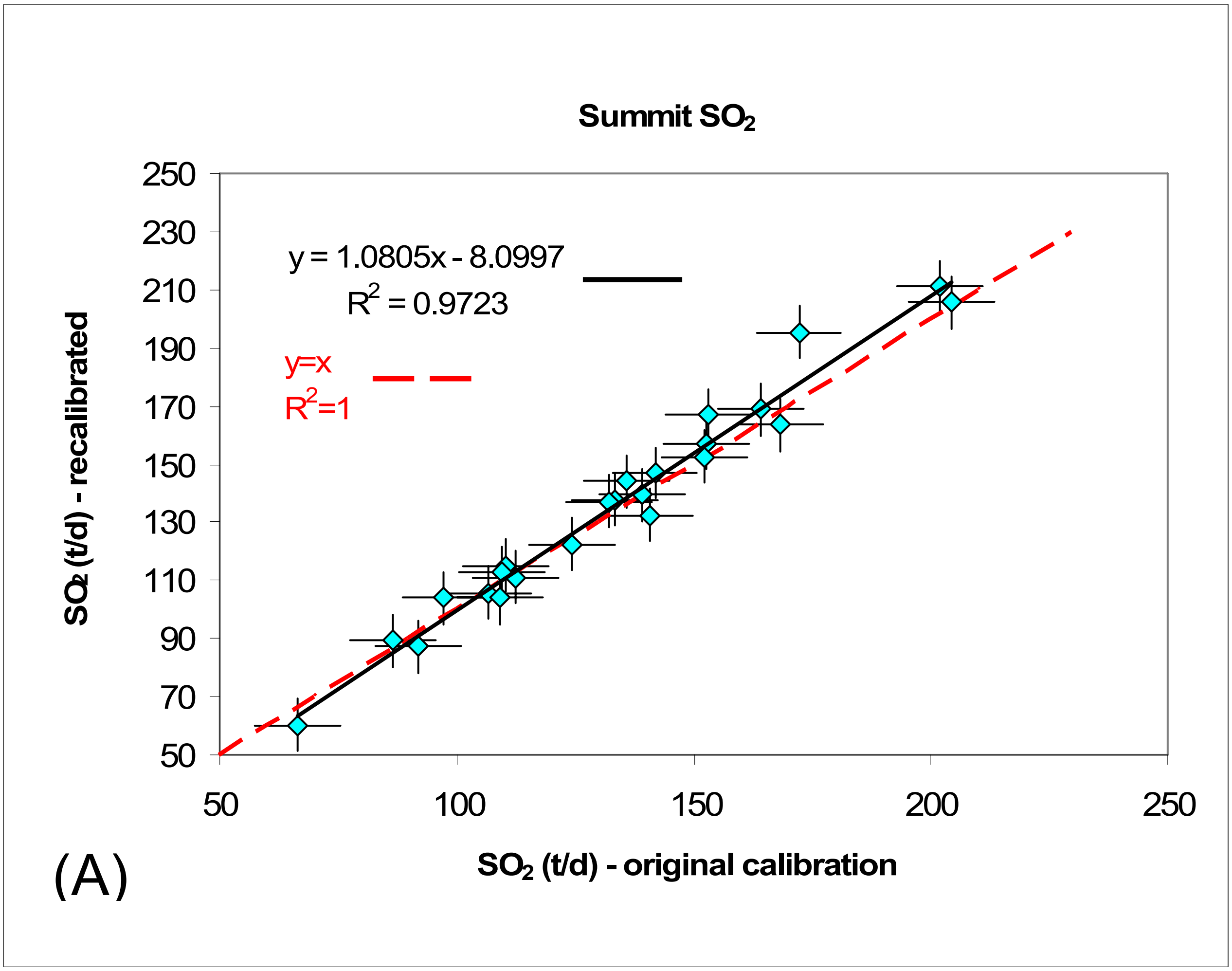
Units of measure

Individual vehicle-based traverses at Kīlauea's summit and along Chain of Craters Road take approximately seven and twelve minutes to complete, respectively. Data are collected for approximately one hour each measurement day (usually 6 plume traverses), and the results are scaled up to metric tonnes per day (t/d). This familiar unit of measure is convenient for comparing Kīlauea's emissions to other volcanoes as well as anthropogenic sources. On the overview plots, we also present data in kilograms per second (kg/s) to more accurately reflect the short collection interval, and for convenient comparison to data from current and future real-time scanning spectrometer systems.

FLYSPEC data calibration

The FLYSPEC data acquisition program produces calculated SO_2 pathlength concentration (ppm m) based on the dark spectrum, the calibration spectra collected in situ with the internal high and low SO_2 calibration cells, and the clear sky reference. In Hawai‘i, sky conditions are often dynamic, thus the calibration spectra recorded at the beginning of a day’s measurements might not be representative of the 1-2 hour collection period. Ideally, new calibration spectra would be recorded at the beginning of each traverse, however, for efficiency, we generally record a single set of calibration spectra for the entire measurement period. In order to test the contribution of unrepresentative calibration spectra to measurement errors, we re-calibrated the calculated concentration pathlengths for several individual sets of data, using the known value of the low calibration cell, which was put into the light path during each traverse.

To address precision in the data reduction process and subjectivity of choosing a base-line reference, each traverse of both the original and re-calibrated data was reduced 5 times by the same person, and the average and standard deviation calculated. Selecting consistent baselines is particularly challenging for the summit Crater Rim Drive data, where the signal to noise ratio is significantly lower than for the ERZ Chain of Craters Road data. Figures 5a-b show the relationship between the original and recalibrated data; the x- and y- error bars represent the averaged standard deviations for the multiple reductions of the subsets of data. With few exceptions, the summit and east rift data and their associated errors overlap a line with slope of 1. The maximum, minimum, and mean difference between the two treatments of the data, as well as the errors associated with the reduction itself, are presented in table 2. Since the variation that exists between the original and re-calibrated data is well within the precision of the reduced data, we conclude that there is little gained by adjusting data from either emission source using the known ppm m value of the recorded calibration cell.


Summit SO2
y = 1.0805x - 8.0997
R2 = 0.9723
y=x
R2=1
SO2 (t/d) - recalibrated
SO2 (t/d) - original calibration
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230
210
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170
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130
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100
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200
250
(A)

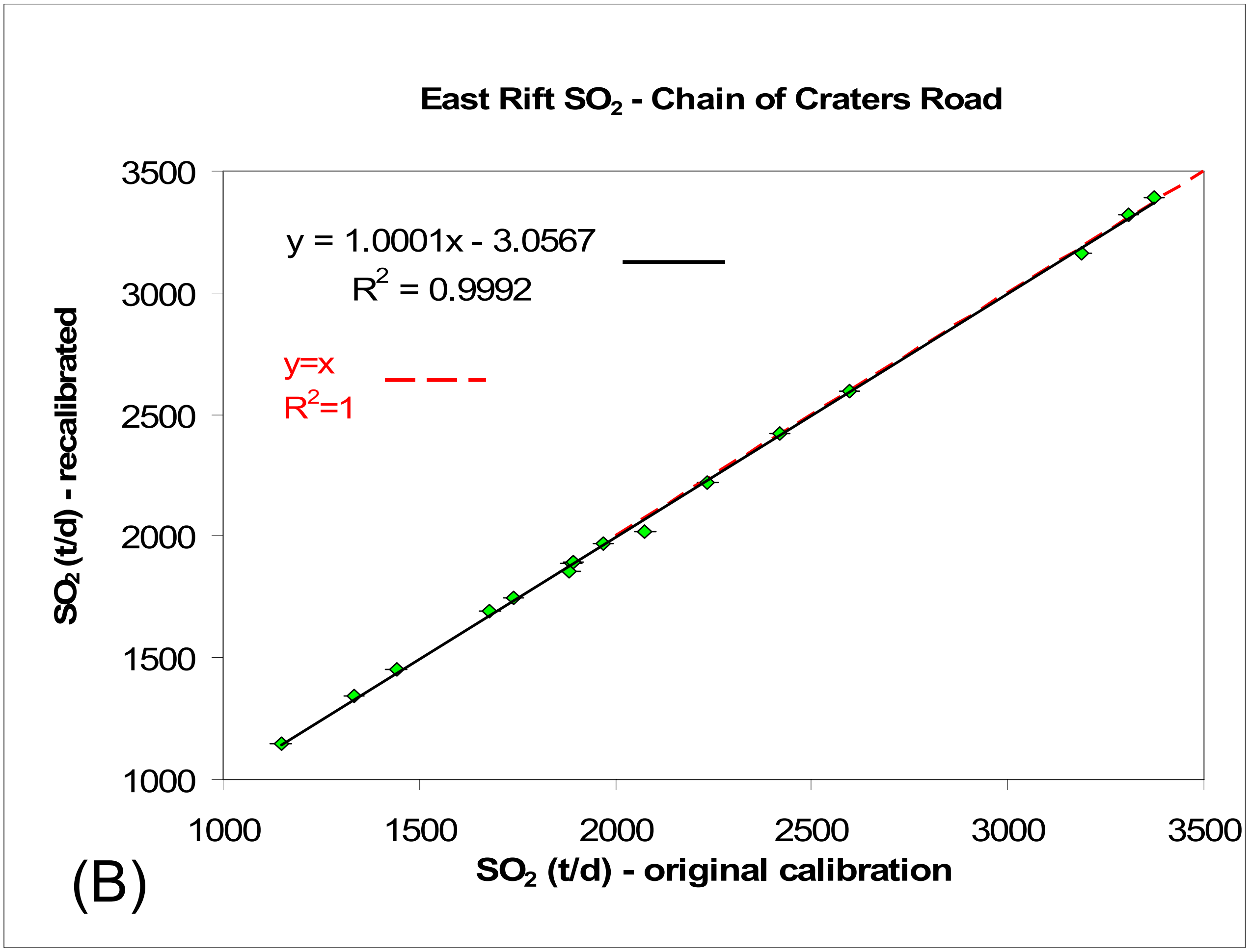

Figure 5. Representative SO_2 emission rate measurements comparing the recalibrated versus the originally-calibrated data. The x- and y- error bars characterize the precision of the data reduction, and are the average standard deviation for the multiple reductions of the subset of data (A) summit data, with x- and y- error bars of ±9 t/d (B) east rift data with x- and y- error bars of ±26 t/d and ±23 t/d respectively.

Table 2. Uncertainties associated with the original versus re-calibrated data sets, and precision in the data reduction process.

Dataset	**% difference**			
	Mean	**SD**	**Maximum**	**Minimum**
SUMMIT (60-200 t/d signal)				
Multiple-reductions	15.8	6.5	34.0	6.7
Original and re-calibrated	1.5	5.0	13.4	-9.3
CHAIN OF CRATERS ROAD (1100-3400 t/d signal)				
Multiple-reductions	2.9	2.0	9.0	0.9
Original and re-calibrated	-0.1	0.9	0.9	-2.6

Baseline Noise

The noise envelope for the Kīlauea FLYSPEC data is variable due to changes in sky conditions (ie. cloud cover and UV levels) and spectrometer response (which is affected by temperature and humidity). The FLYSPEC data reported here averaged 1-4 spectra to yield 1 Hz data, however, no systematic change in baseline noise was observed as a function of integration time, number of spectra averaged, season, or time of day. For the 2003-2006 time period, baseline noise ranged from 2.7 – 6.7 ppm m. Figure 6 characterizes the baseline noise by presenting the standard deviation for a 50-second period of SO_2-free baseline from a single, randomly-selected, representative data set for each month. Ideally, the baselines should be steady and near zero outside of the volcanic plume so that the plume signal can be easily recognized and evaluated. At the summit, the maximum in-plume SO_2 signal typically ranges from 200-400 ppm m. After extreme rain fall events, maximum SO_2 concentration-pathlengths are as low as 35 ppm m, and low signal-to-noise ratios can contribute to emission rate measurements with a high associated error. Along Chain of Craters Road, where the SO_2 plume maxima seldom drop below 300 ppm m and are often above 1000 ppm m, the baseline noise contributes little to the measurement error. Overall, the baseline noise for the FLYSPEC is comparable to that of the COSPEC (Elias and others, 2006).

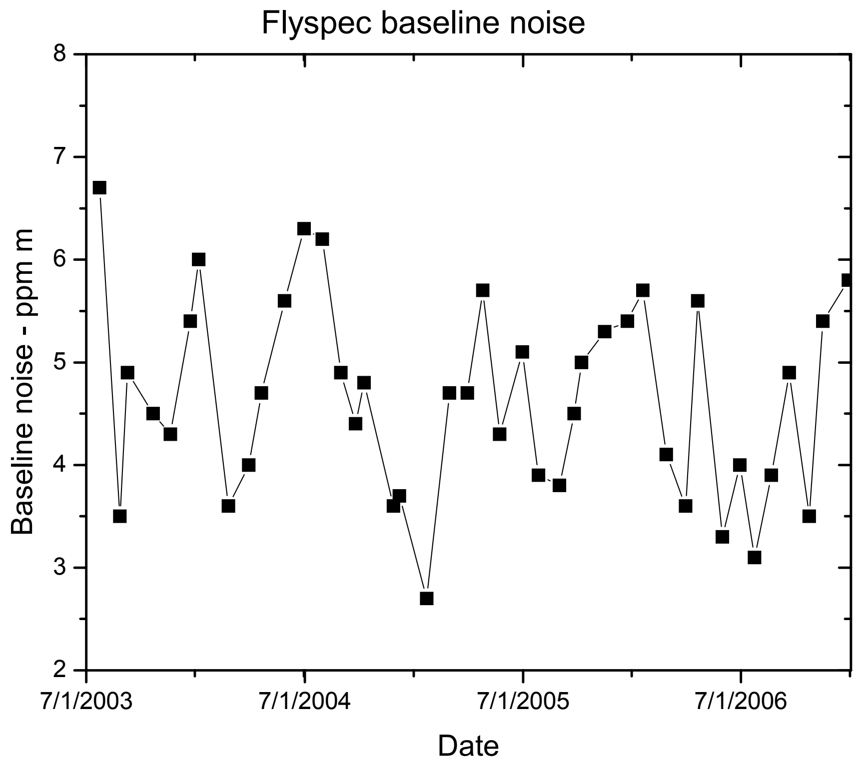

Figure 6. The standard deviation for a 50-s section of baseline outside of the plume from a representative dataset from the Kīlauea summit for each month during 2003-2006.

Summit vehicle-based data

The emission-rate measurements at the summit of Kīlauea have traditionally been made by vehicle-based COSPEC traverses within the summit caldera along Crater Rim Drive. Casadevall and others (1987), Elias and others (1998), and Elias and Sutton (2002) describe details regarding this measurement technique. Because of the high water-solubility of SO_2, extreme rainfall events contribute to the shallow subsurface scrubbing of SO_2 and cause a decrease in measured emissions. SO_2 emissions and rainfall for 2002 through 2006 are shown in figure 7 and table 3.

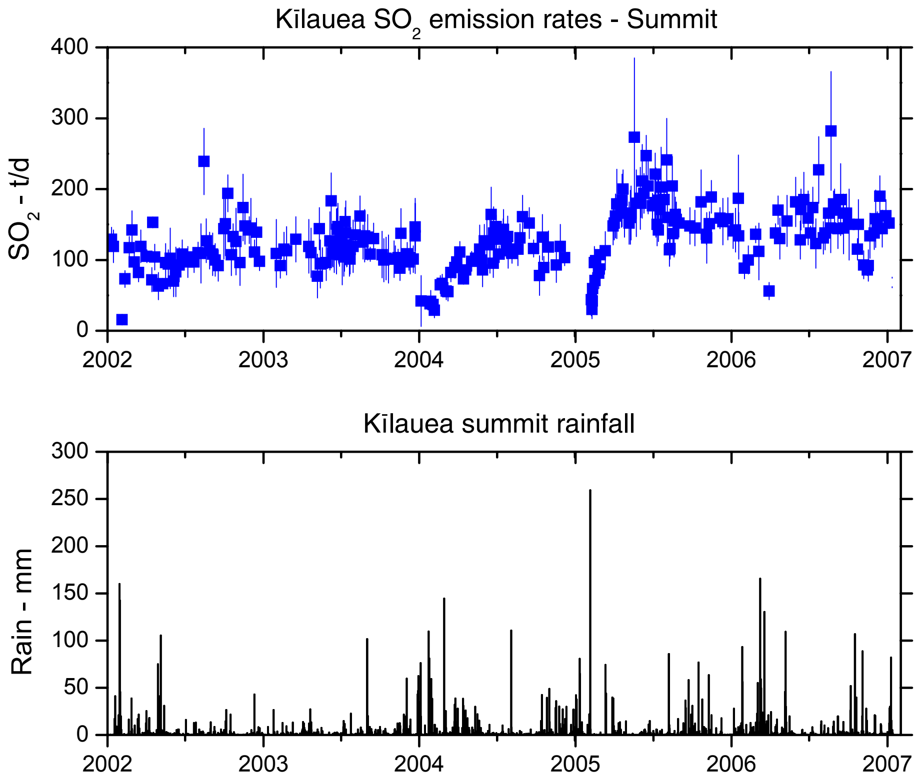

Figure 7. SO_2 emission rates and rainfall at the summit of Kīlauea. High rainfall events contribute to shallow subsurface scrubbing of SO_2 and are a factor in the annual decrease in measured emissions observed most winters. All summit measurements after July 16, 2004 were made with the FLYSPEC.

Summit plume velocity measurements

Plume speed is a critical parameter for calculating gas emission-rates and has been approximated using a variety of techniques during the 28-year SO_2 flux measurement history at Kīlauea (table 4).

Table 4. Methods used for Kīlauea summit plume speed estimates

Date	Location	Height (m)	Instrument	Average interval	% difference[1]	Database corrected?
6/79-12/97	adjacent to HVO	1	wind counter[2]	5 min	____	Y[3]
1/98-8/01	30 m W of caldera rim	3	RM Young model 05103	10 min	+20	N
9/01-3/06	30 m W of caldera rim	3	Handar ultrasonic - 425A	10 min	+10	N
4/06-present	tower - N side of HVO	10	RM Young model 05103	10 min	+5.6	N

[1] % difference from previous method
[2] Weathertronics model 2411 Air Meter
[3] data adjusted up 20% to account for higher wind speeds above ground level

In April 2006, the summit wind speed measured 3-m above ground level (agl) was replaced by wind measurements from a permanent, 10-m meteorological tower located ~ 20 m SW of the 3-m agl site. A comparison of contemporaneous measurements from the two methods, shows a consistent difference of ~6% (fig. 8). No corrections to the summit flux database were made due to this change in technique since this difference is less than the estimated precision in the data reduction process.

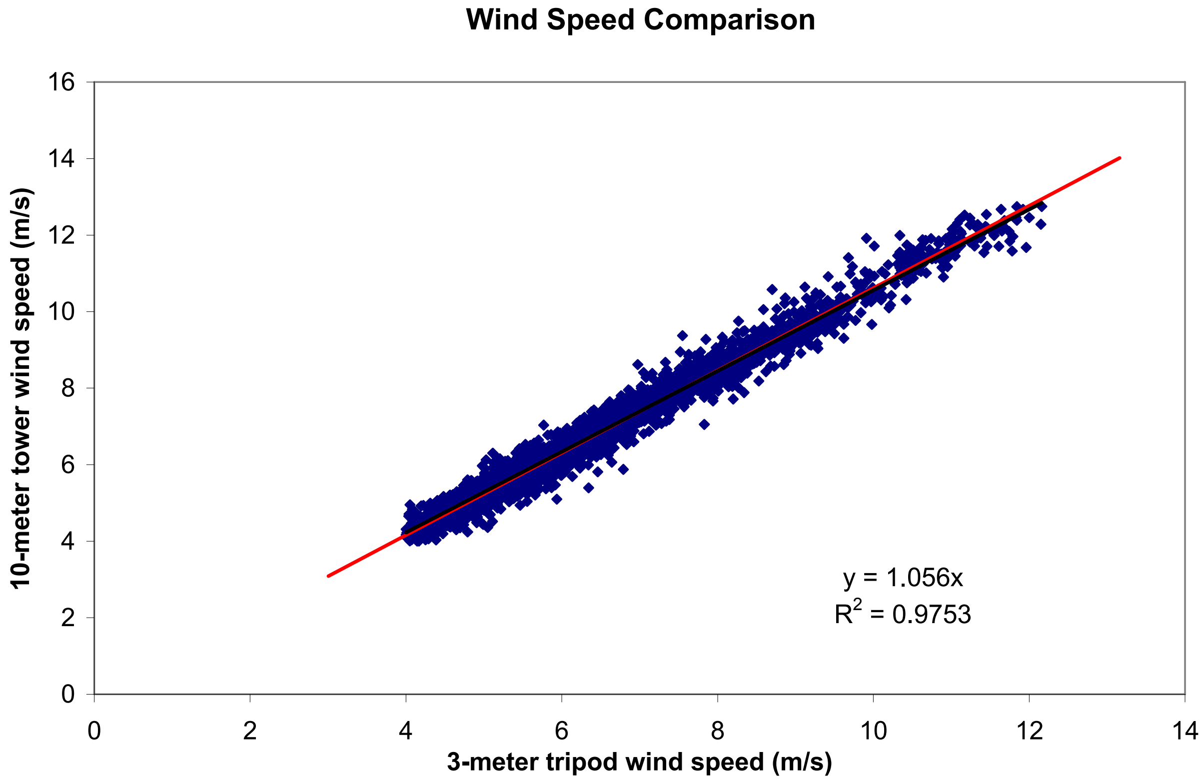

Figure 8. A comparison of contemporaneous measurements from the 3-m tripod mounted wind sensor (Handar ultrasonic) and the 10-m tower mounted wind sensor (RM Young propeller/vane model) over the 7- month period August 2005-March 2006. Wind speeds less than 4 m/s and from between 45N°-355 N° are not favorable for Kīlauea summit SO_2 measurements and were not considered in this comparison.

Williams-Jones and others (2006) used multiple, stationary, upward-looking UV spectrometers set a known distance apart to determine plume velocity at Kīlauea's summit in 2003. By measuring the time required for an identifiable SO_2 concentration feature to pass from the field of view of one instrument into that of the other, and the exact separation of the instruments, the plume velocity can be determined. An initial experiment conducted in March 2003 under wind conditions unfavorable for SO_2 measurements showed a 65%- 67% difference between the spectrometer and the caldera rim anemometer located 3-m above ground level. However, further measurements made under more stable wind conditions yielded a maximum difference of 11% (table 5) and lend support to the continued use of the fixed-position anemometer data as a practical approximation for plume velocity. A comparison of a larger set of data from the two techniques is warranted.

Table 5. Comparison of measured wind speeds (WS) and standard deviations (SD).

DATE	TIME (HST)	WS[1]	SD	WS[1]	SD	% difference
		Spectrometers		Anemometer		
8/21/03	10:47-11:57	7.4	0.3	7.6	0.7	2.7
	13.26-14:33	7.5	0.3	8.3	0.3	10.7
	14:49-15:56	7.3	1.8	7.8	0.6	6.8

[1]Values represent the average of all measurements during a given time interval. Data from Williams-Jones and others, 2006.

The largest single source of error in our emission rate measurements continues to be plume speed uncertainty, which we estimate at 10-30%. Because the summit plume is generally ~3.5 km wide, and has multiple SO_2 sources along the traverse, there are likely micro-climate wind regimes that affect the plume. This raises the question as to how accurately the entire plume can be characterized by a single wind vector measurement, using any method. Based on our experience, data from the current 10-m tower wind measurement site provide a practical, average representation of wind conditions affecting the plume. In 2003, a helicopter-based reconnaissance showed that the core of the summit plume was at an elevation between ~ 3,600'- 3,800' above sea level (1,097m-1,158 m) directly adjacent to Crater Rim Drive, to the southwest and south, during easterly winds blowing 5-8 m/s. During summit fixed-wing measurements in 1998 with winds at 4-6 m/s, the top of the plume was between 4,500'-5,000' above sea level (1370-1525 m). The tower wind measurements are made at an elevation of ~ 4,070' (1,240m).

East rift vehicle-based data

During 2002-2006, we measured Kīlauea's integrated East Rift Zone (ERZ) SO_2 release by collecting emission rate data along Chain of Craters Road (table 6 and fig. 9). While the Pu`u `Ō`ō eruption site is the main source of SO_2 on the ERZ, much of the gas released from the ~10 km long tube system is also blown across Chain of Craters Road and quantified along the traverse (fig. 1). A description of the details and limitations of this measurement technique is provided in Elias and others (1998) and Elias and Sutton (2002). These measurements likely under-estimate the source emissions by ~3-8 percent due to the conversion of SO_2 gas to sulfate aerosol as it travels the ~9 km to the measurement site (Porter and others, 2002).

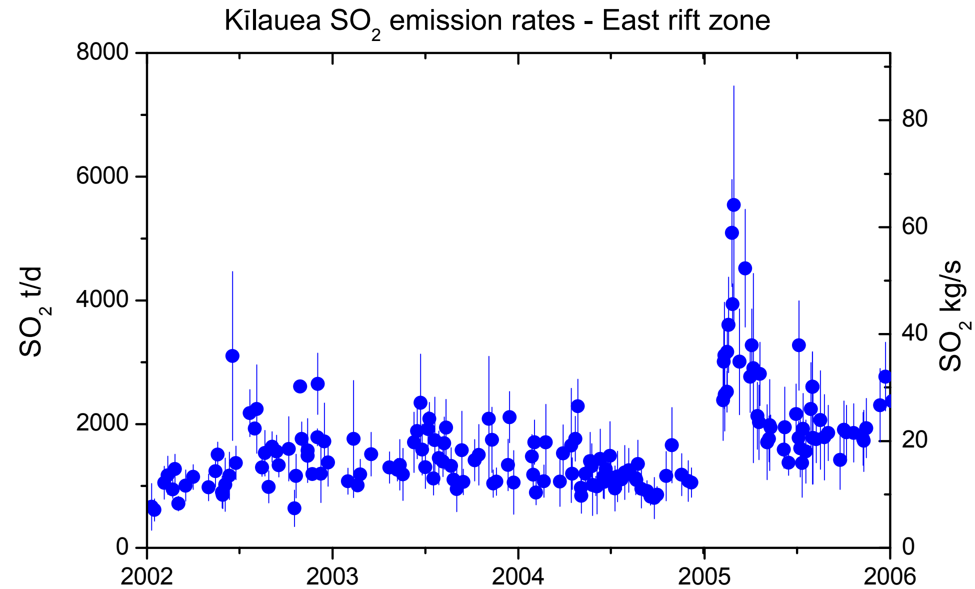

Figure 9. Averaged SO_2 emissions from Kīlauea 's east rift zone as measured by vehicle-based spectrometer along Chain of Craters Road, 2002 through 2006. The vertical bars represent the standard deviation of all traverses (typically 6) on a single day. All ERZ measurements after September 17, 2004 were made with the FLYSPEC.

From 1994-April 2005, contemporaneous wind velocities for plume measurements made above Holei Pali were determined using a continuous wind monitor 3.5 m above the ground approximately 2.5 km above the 180^{o} turn on Chain of Craters Road (fig.1). On April 21, 2005 the site was relocated 0.4 km NNW to facilitate the telemetering of the signal back to HVO. We believe that these data reasonably represent plume velocities above Holei Pali, because at least a portion of the east rift plume is frequently close to the ground as it crosses Chain of Craters Road in this location. For measurements made below Holei Pali on the coastal flats, wind speeds were determined using a combination of methods including (1) 5-10 minute wind-measurements (Weathertronics model 2411 Air Meter) made 4 m above ground level just before and/or right after a day's traverses, and (2) continuous data from the wind station above the 180^{o} turn on Chain of Craters Road adjusted for observed and measured discrepancies. Contemporaneous wind measurements above and below Holei Pali indicate that 3.5 m winds are often ~25 percent lower along Chain of Craters Road below Holei Pali than above it. Thus, when used for calculating emission rates for plumes below Holei Pali, the data from the wind station located above Holei Pali are adjusted by this factor. The uncertainty in wind speed measurements for east rift vehicle-based data is estimated to be 10-40 percent.

Total Kīlauea SO_2 emission rates

Figure 10 shows the averaged emission rate for each day of measurements for the ERZ and summit for 2002-2006. Emission rates for both data sets spiked in early 2005 and remained elevated with respect to pre-2005 levels. This is consistent with other geophysical and geochemical observations that suggest an increase in the magma supply rate to Kīlauea (Miklius and others, 2006).

The dip in emission rates measured at the summit each winter is attributed to high rainfall, and is not mirrored in the east rift emissions. Accumulation of subsurface water likely contributes to the effective scrubbing of the already low summit SO_2 emissions. The hotter, drier subsurface conditions at the ERZ degassing sites are less favorable for scrubbing the large ERZ SO_2 signal.

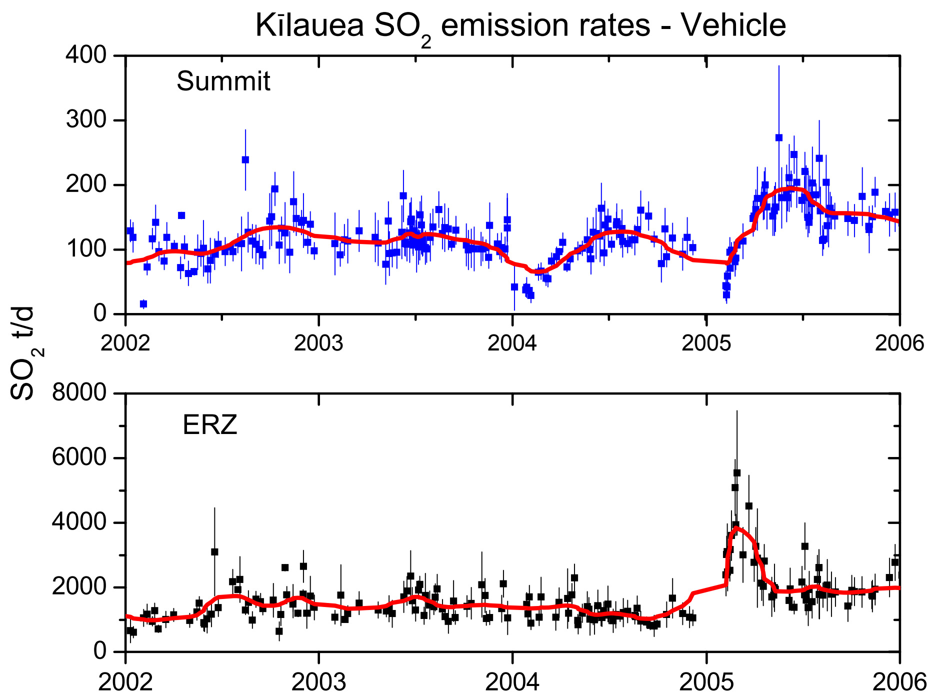

Figure 10. Kīlauea summit and ERZ emissions for 2002-2006. Averaged SO_2 emission and standard deviation of all traverses on a single day are shown by the solid squares and vertical bars. The solid red line represents FFT smoothing after data were processed with a non-parametric digital filter. The increase in emissions observed in 2005 may have been due to an increase in magma supply to Kīlauea.

Table 7 provides an estimate of the total integrated yearly SO_2 emissions for Kīlauea Volcano during 2002-2006. Annual emissions were calculated by summing daily emission rates generated using a non-parametric digital filter (Peakfit software version 4, Jandel Scientific, San Rafael, California) for the summit and east rift data sets. Data treatment is discussed further in Sutton and others, 2001. While the increase in gas emissions from Kīlauea during 2005 supports an increase in the magma supply rate to the volcano (Miklius and others, 2006), the near doubling of sulfur dioxide emissions from the ERZ also implies an increase in eruption volume (Sutton and others, 2003). Indeed, a surge in eruptive activity was observed in early 2005 coincident with the onset of the peak in SO_2. The possibility of enhanced magma circulation and degassing at Pu`u `Ō`ō (for example, Salerno and others, 2005) could also explain the observed increase in SO_2.

Based on Andres and Kasgnoc's 1998 inventory of global subaerial volcanic sulfur emissions, Kīlauea's 2002-2006 SO_2 average of 0.65 teragram/annum (Tg/a) represents ~5% of the global volcanic SO_2 contribution of 13 Tg/a (based on a time-average for the early-1970s -1997). Using representative S_{total}/SO_2 ratios for Kīlauea ranging from 1.02-1.17 (Shinohara, 1998) to calculate the sulfur species present in the volcanic plume other than SO_2, we find that Kīlauea contributes ~ 0.6-0.7 % of the sulfur emissions released through anthropogenic activities (Bates and others, 1992; Spiro and others, 1992; Andreae, 1990.) Despite the relatively small proportion of Kīlauea's contrubution to the atmospheric sulfur cycle, its emissions provide notable local and regional effects (Sutton and others, 1997).

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Table 3.
Kilauea summit SO_2 emission rates - vehicle-based

Date	SO_2 (t/d)	SD (t/d)	WS (m/s)	WD (degree)	N
1/10/2002	130	20	9.5	26	6
1/15/2002	120	20	7.9	12	6
2/4/2002	20	7	6.4	29	4
2/11/2002	70	10	7.2	22	5
2/21/2002	120	20	6.7	9	6
2/27/2002	140	30	8.9	19	10
3/5/2002	100	20	4.6	39	6
3/15/2002	80	10	4	32	6
3/20/2002	120	20	6.6	31	6
4/3/2002	110	9	3	15	3
4/15/2002	70	20	4.7	24	6
4/17/2002	150	4	5.3	47	3
4/22/2002	100	20	5.4	47	6
4/30/2002	60	20	5.4	30	5
5/10/2002	70	5	4.8	29	4
5/17/2002	100	30	6	39	6
5/23/2002	90	20	5.1	33	6
5/28/2002	100	40	4	34	6
6/5/2002	70	20	4.5	32	8
6/10/2002	80	40	4.9	42	6
6/18/2002	90	20	6	33	3
6/25/2002	110	20	8.9	25	5
7/8/2002	100	20	5.1	22	6
7/18/2002	100	7	6.5	29	5
7/23/2002	100	20	5.1	38	6
8/1/2002	110	20	4.6	30	6
8/8/2002	110	40	4.9	33	6
8/15/2002	240	50	7	31	6
8/20/2002	130	30	7.2	18	6
8/28/2002	110	30	5.1	25	6
9/4/2002	110	30	5.9	26	6
9/10/2002	100	20	3.9	25	6
9/17/2002	90	20	4.9	28	6
9/30/2002	140	40	6.7	31	6
10/4/2002	150	50	5.9	26	6
10/10/2002	190	30	7.6	22	6
10/18/2002	110	30	4.9	30	5
10/22/2002	130	20	6.9	26	6
10/29/2002	130	50	6.6	26	5
11/7/2002	100	30	3	32	6
11/14/2002	170	50	8	31	4
11/19/2002	150	30	6.3	33	7
11/29/2002	140	20	5.9	30	4
12/3/2002	150	40	5.7	23	6
12/11/2002	110	20	4.6	29	6
12/16/2002	140	20	6.5	28	6
12/23/2002	100	10	5.4	25	6
1/31/2003	110	50	8.8	34	6

2/10/2003	90	20	7.9	33	6
2/18/2003	120	20	8.2	27	6
2/24/2003	110	30	8.1	31	6
2/26/2003	80	40	4.3	77	5
3/4/2003	60	20	3	59	6
3/18/2003	130	30	9.9	27	6
4/17/2003	120	40	5.7	33	7
4/23/2003	110	40	7.6	29	6
5/7/2003	80	30	3	52	6
5/12/2003	140	30	4.4	25	4
5/14/2003	90	30	6.3	30	6
5/19/2003	90	20	6	27	6
5/28/2003	100	30	4.2	45	6
6/6/2003	130	40	4	60	6
6/9/2003	180	40	5.2	24	7
6/12/2003	110	20	5.4	28	7
6/13/2003	110	20	5.3	29	4
6/16/2003	110	30	7.6	24	6
6/21/2003	130	50	6.1	31	6
6/23/2003	140	30	7.2	30	8
6/24/2003	150	30	6.7	34	6
6/26/2003	120	20	7.4	25	10
6/27/2003	120	20	6.3	30	6
6/28/2003	110	20	5.5	32	6
6/30/2003	130	20	31	5	4
7/3/2003	120	20	4.9	31	8
7/4/2003	110	50	3.4	35	8
7/5/2003	120	10	4.4	31	4
7/8/2003	100	30	6	32	8
7/10/2003	110	20	4.2	23	7
7/11/2003	150	20	8.6	11	6
7/13/2003	140	50	7.9	15	6
7/14/2003	120	30	7.3	21	4
7/15/2003	120	30	5	33	16
7/16/2003	110	20	5.6	21	4
7/21/2003	100	30	6.7	19	5
7/23/2003	100	20	5.2	27	6
7/30/2003	120	40	7.9	37	6
8/4/2003	140	30	5.7	25	8
8/15/2003	160	30	9	28	5
8/22/2003	130	20	8.3	22	6
8/26/2003	130	40	6.9	21	7
9/2/2003	130	30	7.7	20	6
9/8/2003	110	10	6	30	5
9/16/2003	130	20	5.6	28	4
10/6/2003	110	30	5.8	33	7
10/10/2003	100	30	4.4	32	8
10/15/2003	100	30	6	30	6
10/21/2003	100	30	4.4	23	5
11/3/2003	100	30	5.5	34	7
11/6/2003	100	20	5.9	42	3
11/12/2003	100	10	5.7	28	6

11/17/2003	90	20	3.6	28	6
11/19/2003	140	40	12.2	18	6
12/4/2003	110	20	4.3	29	6
12/8/2003	100	10	6.9	26	6
12/11/2003	100	20	7.1	29	6
12/18/2003	100	20	6.3	19	6
12/22/2003	130	50	5.7	25	6
12/22/2003	150	30	6	23	6
1/5/2004	40	40	3.1	31	6
1/26/2004	40	10	3.4	47	7
1/28/2004	40	20	7.5	21	5
2/2/2004	40	9	6.7	30	6
2/5/2004	30	10	5.6	29	6
2/19/2004	70	10	2.9	39	6
2/24/2004	70	10	4	16	6
3/4/2004	60	10	5	40	6
3/8/2004	60	10	6.8	31	6
3/15/2004	80	10	7.8	14	6
3/24/2004	90	20	6.3	40	6
3/29/2004	100	5	7.9	30	5
4/5/2004	110	20	4.9	27	6
4/13/2004	70	7	4	30	6
4/19/2004	90	7	5.4	35	6
5/3/2004	100	10	9.3	32	6
5/12/2004	100	10	3.9	54	5
5/21/2004	120	30	4.5	33	5
5/26/2004	100	9	6.7	34	6
5/28/2004	90	20	4.1	33	6
6/1/2004	130	20	5.8	27	6
6/7/2004	130	40	7.5	32	6
6/14/2004	120	40	3.8	33	7
6/17/2004	160	40	6.5	32	4
6/22/2004	100	20	2.5	53	6
6/23/2004	140	40	4.2	30	8
6/29/2004	150	20	7.1	33	8
6/30/2004	130	20	6.6	31	8
7/6/2004	110	10	4.4	47	7
7/15/2004	140	20	6.9	24	8
7/16/2004[1]	140	30	6.1	26	6
7/23/2004	120	20	7.1	33	11
7/26/2004	130	30	5.9	28	6
7/27/2004	110	30	4.5	25	8
8/5/2004	110	10	4.2	32	8
8/13/2004	120	10	7.2	33	8
8/19/2004	120	20	4.1	21	8
8/24/2004	130	20	8.8	25	8
8/30/2004	160	30	6.2	29	8
9/14/2004	150	20	5	31	6
9/24/2004	120	10	6.2	28	5
9/30/2004	110	6	7.3	29	3
10/8/2004	80	30	4.9	37	6

10/15/2004	130	30	4.2	28	6
10/18/2004	90	20	8.2	29	6
10/29/2004	120	20	6.2	28	6
11/17/2004	90	30	5.8	33	6
11/26/2004	120	30	4	26	6
12/6/2004	100	10	7.3	32	6
2/7/2005	40	20	6.1	28	5
2/8/2005	30	10	7.6	31	5
2/9/2005	40	20	4.8	26	7
2/10/2005	60	20	7.6	34	6
2/14/2005	100	20	8.3	21	6
2/15/2005	70	8	8.8	19	6
2/17/2005	99	10	9.8	29	6
2/24/2005	80	20	6.1	29	5
2/25/2005	90	20	7.7	22	6
2/28/2005	110	10	5.1	38	5
3/11/2005	110	30	6.6	25	6
3/30/2005	150	30	5.4	31	7
4/1/2005	150	20	9.9	19	6
4/4/2005	160	30	6.5	32	6
4/7/2005	180	50	6.9	30	7
4/15/2005	180	20	5.9	44	6
4/18/2005	170	30	5.4	34	6
4/20/2005	180	40	8.2	23	5
4/22/2005	200	30	5.8	35	5
4/25/2005	170	30	5.6	32	6
5/6/2005	150	30	4.8	30	6
5/9/2005	160	40	4.7	40	6
5/11/2005	170	40	5	39	5
5/18/2005	270	100	5.7	27	7
5/23/2005	180	50	5.3	34	5
6/1/2005	200	50	6.3	35	6
6/3/2005	180	20	4.9	35	4
6/6/2005	210	50	7.4	31	6
6/10/2005	190	30	8.3	32	6
6/15/2005	250	30	9.4	15	5
6/20/2005	200	40	5	30	6
6/30/2005	180	20	5.7	32	6
7/5/2005	180	30	4.3	25	8
7/6/2005	220	30	8.2	20	6
7/8/2005	180	50	8.7	24	8
7/11/2005	150	30	5	31	7
7/12/2005	180	40	7.8	30	6
7/14/2005	140	20	6.4	31	6
7/15/2005	180	30	5.6	27	8
7/18/2005	170	30	6.1	32	8
7/20/2005	200	60	10.4	34	6
7/27/2005	190	20	6.6	26	6
8/2/2005	240	60	8.5	18	8
8/4/2005	160	40	7.3	30	7
8/8/2005	110	20	2.7	62	7
8/10/2005	120	20	3.7	35	6

8/15/2005	200	40	7.8	22	8
8/17/2005	140	30	5.8	32	8
8/19/2005	160	50	7.4	31	7
8/22/2005	160	30	3.8	22	8
8/25/2005	160	30	5.4	31	6
8/31/2005	150	20	5.7	27	6
9/25/2005	150	30	4.8	36	5
10/7/2005	180	30	8	28	6
10/22/2005	180	50	10.4	12	6
11/3/2005	140	10	9.2	30	6
11/4/2005	130	40	4.4	23	6
11/10/2005	150	20	7.8	21	6
11/15/2005	190	20	8.9	24	6
12/5/2005	160	20	5.9	25	6
12/12/2005	150	30	8.5	23	6
12/23/2005	160	30	5.5	30	4
1/5/2006	140	30	7.7	18	6
1/10/2006	140	30	6.2	27	5
1/17/2006	190	60	5.6	37	8
1/18/2006	130	30	4.1	28	7
1/31/2006	90	20	3.4	28	6
2/9/2006	100	20	8	26	6
2/26/2006	140	10	5.6	20	6
3/6/2006	110	40	5.6	33	6
3/30/2006	60	10	3.8	25	5
4/14/2006	140	10	7.2	33	3
4/20/2006	170	20	10.5	23	6
4/24/2006	130	30	7.3	36	4
5/11/2006	160	40	6.8	36	6
5/31/2006	180	40	4.4	37	6
6/11/2006	130	30	5.1	36	4
6/12/2006	170	30	5.9	48	6
6/19/2006	190	40	8.8	32	6
6/29/2006	160	40	8.2	41	7
7/5/2006	140	10	8.1	25	4
7/10/2006	170	30	9.3	24	6
7/17/2006	120	40	5.6	40	6
7/24/2006	230	50	7.5	40	6
8/4/2006	130	20	12.4	28	6
8/8/2006	140	20	6.2	38	6
8/16/2006	170	20	7.5	37	6
8/21/2006	150	40	5.9	42	6
8/22/2006	280	80	7.3	40	4
8/28/2006	180	20	8.5	39	5
8/30/2006	170	30	8.2	29	6
9/7/2006	140	30	7.4	33	6
9/13/2006	190	50	5.1	31	6
9/19/2006	170	30	8.1	37	6
9/20/2006	150	40	6.1	39	6
9/27/2006	170	30	7.2	21	6
10/3/2006	150	50	5.6	40	6
10/23/2006	120	20	5.8	39	6

10/25/2006	150	40	8.3	39	6
11/6/2006	90	20	3.8	40	6
11/15/2006	90	8	3.9	38	3
11/17/2006	90	20	4	32	2
11/21/2006	130	30	5.5	33	6
12/1/2006	140	20	4.7	24	6
12/4/2006	160	40	6.9	39	6
12/8/2006	150	20	8.8	29	6
12/14/2006	190	30	8.1	17	6
12/20/2006	140	30	5.7	39	7
12/28/2006	160	20	8.9	31	6

Abreviations: t/d=metric tonne (1000 kg)/day, SD=standard deviation, WS=wind speed, WD=wind direction east of true north, N=number of traverses

[1]Reported SO_2 measurements prior to this date are by COSPEC; those from this date onward are by FLYSPEC.

Table 6.
Kilauea east rift zone SO_2 emission rates - vehicle-based

Date	SO_2 (t/d)	SD (t/d)	WS (m/s)	WD (degrees)	N	Location	Code
1/10/2002	660	380	9.2	9	6	L	C
1/16/2002	610	180	8.9	14	7	L	C
2/1/2002	1710	--	3.5	70	1	U	C
2/4/2002	1050	270	5.5	54	3	U	C
2/11/2002	1170	310	10.3	30	7	L	B
2/21/2002	950	150	7.9	30	6	L	C
2/25/2002	1280	240	11.3	30	6	L	C
3/4/2002	720	120	5.2	40	6	UL	C
3/18/2002	1010	250	14.7	30	7	L	A
4/2/2002	1150	200	8.3	355	5	L	B
5/2/2002	980	220	5.6	34	5	U	C
5/16/2002	1240	260	6.1	34	7	U	B
5/20/2002	1510	200	7.2	70	3	U	C
5/29/2002	900	250	5	80	7	U	C
5/30/2002	860	230	4.7	56	4	U	C
6/4/2002	1020	430	6	48	8	U	B
6/12/2002	1170	380	7	25	7	U	C
6/18/2002	3100	1370	6.5	50	5	U	C
6/25/2002	1370	270	9.1	25	8	L	B
7/22/2002	2180	380	9.6	35	7	UL	B
8/1/2002	1930	0	7.5	35	1	U	C
8/5/2002	2240	710	10	40	6	U	B
8/15/2002	1300	140	6.9	41	5	U	B
8/21/2002	1530	370	7	36	6	U	B
8/28/2002	990	260	6.2	57	3	U	C
9/4/2002	1630	250	8.4	27	6	U	A
9/13/2002	1560	260	8.2	17	4	U	B
9/17/2002	1340	190	7	52	6	U	A
10/7/2002	1600	520	6.2	45	6	U	C
10/18/2002	640	300	5.2	78	4	U	C
10/21/2002	1160	350	7.1	40	5	U	B
10/29/2002	2610	90	9.7	15	2	L	C
11/1/2002	1760	270	7.1	31	5	U	A
11/13/2002	1490	230	7.3	33	6	U	A
11/13/2002	1570	520	6.7	40	8	U	B
11/22/2002	1190	100	4	30	3	U	C
12/2/2002	1790	140	4.6	30	4	U	C
12/3/2002	2650	490	10.8	1	3	L	A
12/9/2002	1200	470	7.8	28	5	U	B
12/16/2002	1720	620	7.4	18	4	U	B
12/23/2002	1380	390	6.7	36	6	U	A
1/31/2003	1080	210	6.1	35	6	U	B
2/11/2003	1760	950	6	31	6	U	C
2/19/2003	1010	0	6.8	13	1	U	C
2/24/2003	1190	240	7.4	25	6	U	A
3/18/2003	1510	350	9.2	17	6	U	A
4/23/2003	1300	250	7.7	21	10	UL	B

5/8/2003	1270	180	5	48	2	U	C
5/13/2003	1340	410	5	30	7	U	B
5/19/2003	1190	420	6.4	48	7	U	C
6/10/2003	1710	490	5.4	27	10	L	B
6/16/2003	1890	450	6.6	16	6	U	C
6/23/2003	2340	790	7.2	18	7	U	A
6/26/2003	1590	410	6.8	27	7	U	B
7/2/2003	1300	340	7.9	18	7	U	B
7/8/2003	1920	280	5.8	25	3	U	C
7/10/2003	2090	260	7.6	5	6	U	C
7/18/2003	1120	270	9	8	6	L	C
7/21/2003	1740	700	9.6	13	6	UL	C
7/23/2003	1350	590	5.9	50	6	U	C
7/29/2003	1450	430	9.6	15	7	U	C
8/6/2003	1400	240	6.3	45	8	U	B
8/8/2003	1690	420	8.9	7	8	U	B
8/12/2003	1950	460	10.4	17	4	U	B
8/22/2003	1330	290	8.1	25	6	U	B
8/27/2003	1100	140	7.8	6	5	UL	C
9/2/2003	950	370	7	31	5	U	C
9/12/2003	1580	630	6.1	31	6	U	C
9/15/2003	1070	210	9.6	10	6	U	A
10/7/2003	1420	330	5.6	25	6	U	B
10/15/2003	1510	490	6.8	22	6	U	A
11/4/2003	2090	1010	5.5	10	5	U	C
11/10/2003	1750	530	7.3	25	6	U	C
11/13/2003	1040	220	7.7	13	6	U	C
11/19/2003	1070	220	12.6	357	6	L	C
12/12/2003	1340	420	6.3	60	5	U	C
12/15/2003	2110	420	7.7	30	7	U	C
12/23/2003	1060	520	6.6	73	6	U	C
1/28/2004	1250	290	7.3	11	7	UL	C
1/30/2004	1180	210	6.5	13	5	UL	C
2/2/2004	1710	360	5.9	29	6	U	C
2/5/2004	890	200	6.9	352	6	L	C
2/20/2004	1080	260	5.7	29	6	U	B
2/24/2004	1700	610	6.5	34	6	U	C
3/18/2004	460	50	3	175	3	H	C
3/23/2004	1070	400	8	359	6	L	C
3/29/2004	1530	460	8.2	27	6	U	B
4/14/2004	1650	930	5.3	46	5	U	C
4/16/2004	1200	260	9.2	14	8	U	A
4/22/2004	1760	360	4	71	3	U	C
4/27/2004	2290	430	5.5	356	4	L	C
5/3/2004	970	200	12.4	12	6	UL	C
5/4/2004	840	280	10	24	6	U	C
5/12/2004	1200	290	6.2	69	5	U	C
5/21/2004	1400	470	6.8	59	5	U	C
5/24/2004	1320	360	4.6	40	6	U	C
5/26/2004	1010	490	6.6	24	6	U	C
6/1/2004	1000	160	5.3	45	6	U	C
6/4/2004	990	450	8.4	23	4	U	B

6/10/2004	1440	480	9.3	13	6	U	B
6/16/2004	1150	340	5.1	13	6	U	B
6/18/2004	1060	270	5.3	16	6	U	B
6/21/2004	1280	280	7	18	6	U	A
6/29/2004	1490	560	7.6	37	6	U	B
7/1/2004	1140	260	6.4	20	7	U	B
7/9/2004	960	370	5	35	5	U	B
7/14/2004	1150	410	6.4	52	7	U	A
7/22/2004[1]	1110	170	6	20	8	U	C
7/28/2004[1]	1220	440	7.1	46	6	U	B
8/5/2004	1260	350	6.6	10	8	U	B
8/19/2004	1130	270	4.1	21	8	L	C
8/20/2004	1100	80	9.7	8	3	U	C
8/23/2004	1360	390	8.8	14	3	U	B
8/30/2004	950	310	7	21	5	U	B
9/10/2004	920	160	7.5	2	5	L	C
9/17/2004[2]	830	140	5.5	40	6	U	B
9/24/2004	810	330	8	10	6	U	C
9/30/2004	860	130	6.2	10	4	L	C
10/18/2004	1160	400	7.7	30	7	U	B
10/29/2004	1660	610	5.8	26	6	U	B
11/17/2004	1180	340	5.8	28	5	U	B
11/30/2004	1080	330	7.4	15	9	U	B
12/6/2004	1060	240	8.7	15	6	L	A
2/7/2005	2390	650	5.8	29	6	U	B
2/8/2005	3010	580	6.5	17	6	U	A
2/9/2005	3110	860	5.9	55	7	U	B
2/10/2005	2480	590	5.8	31	7	U	B
2/14/2005	2520	330	8.3	351	6	L	B
2/15/2005	3170	540	8.8	19	6	U	B
2/17/2005	3600	770	10.4	11	3	L	C
2/24/2005	5090	870	6.8	57	7	U	A
2/25/2005	3940	330	9.1	25	3	L	C
2/28/2005	5540	1930	6.8	8	6	U	B
3/11/2005	3010	850	9.1	350	6	L	B
3/22/2005	4520	950	6.4	32	7	U	A
4/1/2005	2770	580	12	6	6	U	A
4/4/2005	3270	590	7.7	35	6	U	B
4/7/2005	2910	1530	6.8	15	5	U	C
4/15/2005	2130	540	5.9	21	7	U	B
4/18/2005	2030	600	5	71	4	U	C
4/20/2005	2810	510	9.3	18	6	U	B
5/4/2005	1710	610	4.9	92	4	U	C
5/8/2005	1760	370	7.3	36	5	U	B
5/9/2005	1990	740	6.1	41	5	U	A
5/11/2005	1940	210	5.1	39	6	U	A
6/6/2005	1800	530	7.1	32	5	U	C
6/8/2005	1950	650	8.9	30	6	U	C
6/15/2005	1380	200	7.4	41	5	U	B
6/30/2005	2160	490	6.6	46	8	U	B

7/5/2005	1780	270	10.5	6	2	L	C
7/6/2005	3270	720	15.2	10	8	L	B
7/8/2005	1610	460	7.5	43	10	U	A
7/12/2005	1370	550	8.7	34	8	U	A
7/14/2005	1930	570	5.7	46	8	U	A
7/19/2005	1560	510	9	32	4	U	B
7/29/2005	2250	750	8.3	33	8	U	A
8/1/2005	2610	560	7.3	26	4	U	B
8/2/2005	1780	750	8.8	38	6	U	B
8/9/2005	1760	380	6.1	40	3	U	C
8/17/2005	2070	800	5.9	43	6	U	B
8/25/2005	2040	890	9.4	16	6	L	C
9/1/2005	1860	450	6.9	41	7	U	A
9/25/2005	1420	480	6.8	45	5	U	B
10/2/2005	1910	470	8.3	19	6	U	B
10/7/2005	1870	440	8.1	44	8	U	B
10/21/2005	1860	470	8.1	29	6	U	B
11/9/2005	1760	430	6.4	29	3	U	C
11/10/2005	1730	490	7	42	8	U	B
11/15/2005	1940	480	8.5	38	6	U	B
12/8/2005	1950	370	7.2	37	5	U	C
12/12/2005	2310	600	10	25	6	L	B
12/23/2005	2770	560	6.3	10	4	L	B
1/5/2006	2370	420	10.7	15	8	UL	C
1/10/2006	1210	350	7.4	27	6	U	B
1/11/2006	1210	420	6.8	40	6	U	B
1/19/2006	1870	240	6.7	26	6	U	C
3/30/2006	2640	450	4.8	90	4	U	C
4/3/2006	1840	610	7.6	33	6	U	A
4/13/2006	1780	520	8	40	6	U	B
4/19/2006	1740	390	9	27	6	U	B
5/8/2006	1490	460	5.8	61	8	U	C
5/11/2006	1910	590	8.1	28	8	U	B
5/30/2006	1580	600	6.6	58	6	U	B
6/13/2006	1500	480	6.9	48	6	U	C
6/19/2006	1630	140	8.4	40	6	U	B
6/29/2006	3000	590	8	40	5	U	A
6/30/2006	1720	590	9	40	6	U	A
7/5/2006	2260	360	7	30	6	U	B
7/6/2006	2130	500	7.4	31	5	U	B
7/11/2006	2940	650	8.7	33	5	U	B
7/17/2006	1460	370	6.7	79	5	U	C
8/4/2006	2040	600	10.6	28	6	U	B
8/7/2006	1740	550	6	47	6	U	B
8/14/2006	2680	570	7.2	29	6	U	B
8/17/2006	2830	1200	8.2	28	6	U	B
8/21/2006	2040	650	7.4	27	6	U	C
8/31/2006	2010	580	8.4	36	6	U	B
9/7/2006	2310	630	7	30	6	U	A
9/13/2006	1820	500	5.8	38	6	U	C
9/20/2006	1510	420	8.1	37	6	U	A
9/21/2006	1960	550	6.1	59	5	U	C

9/27/2006	2090	810	7.1	39	6	U	B
9/28/2006	2290	690	5.7	36	5	U	C
10/3/2006	3700	2200	6.4	27	6	U	C
10/23/2006	1880	450	6.5	29	4	UL	C
10/24/2006	2020	860	5.8	38	4	U	B
10/25/2006	2100	640	9.1	30	6	U	A
11/8/2006	1830	780	10.3	27	6	U	A
11/16/2006	2250	600	6.8	34	6	U	B
11/21/2006	1940	1000	5	60	6	U	C
11/22/2006	2450	790	6.9	30	7	U	B
12/1/2006	2300	350	5.5	42	5	U	C
12/11/2006	1550	550	5.2	60	6	U	C
12/14/2006	2330	650	7.3	24	5	U	C
12/20/2006	1830	830	5.7	33	6	U	C
12/29/2006	1680	630	4.4	80	6	U	C

Location Codes: (see fig. 1)
U- Above the 180° turn at Holei Pali (upper Chain of Craters Road)
L- Below Holei Pali (lower Chain of Craters Road)
UL-individual traverses were made both above and below the 180° turn at Holei Pali
H- Highway 11

Data Quality Codes:
A - BEST QUALITY DATA -usually with strong, steady, well constrained wind conditions, and a compact, consistent plume shape (15.7% of data).
B - GOOD QUALITY DATA - usually with moderately consistent plume shape and location of plume on road. Collected under moderately strong, uniform winds, with good constraint on wind speed and direction (40.7% of data).
C - ACCEPTABLE DATA - may have variable plume location and shape. Wind speed and direction may be variable or poorly constrained. Some runs may measure a partial plume, and result in a minimum emission rate. Measurements with instrument inconsistencies are included in this category (43.5% of data).

Abreviations: t/d=metric tonne (1000 kg)/day, SD=standard deviation, WS=wind speed, WD=wind direction east of true north, N=number of traverses

[1]SO_2 measurements by FLYSPEC

[2]Reported SO_2 measurements prior to this date are by COSPEC; those from this date onward are by FLYSPEC.

Table 7.
Estimate of average and total Kilauea SO_2 emission rates, 2002-2006

Year	Summit			East rift zone			Total
	SO_2 t/y	Days of data	Daily average	SO_2 t/y	Days of data	Daily average	t/y
2002	3.97E+04	47	110	5.03E+05	41	1380	5.43E+05
2003	4.11E+04	61	115	5.19E+05	37	1420	5.60E+05
2004	3.57E+04	49	100	4.49E+05	45	1230	4.84E+05
2005	5.47E+04	62	150	8.17E+05	49	2240	8.72E+05
2006	5.32E+04	47	145	7.34E+05	44	2010	7.87E+05
Totals							
2002-2006	2.24E+05	266	125	3.02E+06	216	1660	3.25E+06

Abbreviations: t/y= metric tonne (1000 kg)/year