Sulfur Dioxide Emission Rates from Kīlauea Volcano, Hawai‘i, 2007–2010

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U.S. Department of the Interior
U.S. Geological Survey

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By T. Elias and A.J. Sutton

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Sulfur Dioxide Emission Rates from Kīlauea Volcano, Hawai‘i 2007–2010

By T. Elias and A.J. Sutton

Abstract

Kīlauea Volcano has one of the longest running volcanic sulfur dioxide (SO_2) emission rate databases on record. Sulfur dioxide emission rates from Kīlauea Volcano were first measured by Stoiber and Malone (1975) and have been measured on a regular basis since 1979 (Elias and Sutton, 2007, and references within). Compilations of SO_2 emission-rate and wind-vector data from 1979 through 2006 are available on the USGS Web site (Elias and others, 1998; Elias and Sutton, 2002; Elias and Sutton, 2007). This report updates the database, documents the changes in data collection and processing methods, and highlights how SO_2 emissions have varied with eruptive activity at Kīlauea Volcano for the interval 2007-2010.

Introduction

During the period covered by this report, activity at both the summit and east rift of Kīlauea changed dramatically. On the East Rift Zone (ERZ), an upper east rift intrusion of June 17, 2007 (referred to as the Father's Day intrusion), and an associated brief eruption on the flank of Kane Nui o Hamo west of Pu‘u ‘Ō‘ō were followed by a 2-week eruptive pause which marked the end of the 10-year-long dominance of Pu‘u ‘Ō‘ō flank vent activity. Lava returned to Pu‘u ‘Ō‘ō briefly, but the onset of the July 21 fissure eruption east of Pu‘u ‘Ō‘ō claimed the spotlight by erupting from four separate fissures, forming short flows, perched lava lakes, and eventually a perched lava channel. The perched channel's dominance was interrupted on November 21, 2007, by the Thanksgiving Eve breakout (TEB); the TEB vent eventually formed a tube system, which carried lava to the ocean and remained active through the period of this report. Degassing from Pu‘u ‘Ō‘ō continued during the consolidation and migration of activity on the east rift, with spattering vents and a lava pond intermittently active on the floor of Pu‘u ‘Ō‘ō (Orr, 2007; Sutton and Elias, 2007; Poland and others, 2008).

At the summit, a new gas-emitting vent opened low on the southeast wall of Halema‘uma‘u on March 12, 2008. The new vent, located directly beneath the Halema‘uma‘u Overlook, became incandescent beginning March 13, and on March 19, an explosive event scattered rock debris and ash over an area of about 50 hectares (ha). This eruption marked the first explosive activity at the summit recorded since 1924, and it produced fine and coarse ash, Pele's hair, lithic and vitric debris, and ballistic fragments which were deposited onto and downwind of Halema‘uma‘u crater rim (Wilson and others, 2008; Poland and others, 2009). Variable summit activity during the 2008–2010 period was characterized by persistent degassing from lava within an enlarging vent cavity, occasional small explosive events, and eruptive pauses in December 2008 and July 2009. Lava was first viewed deep within the vent on September 5, 2008, and continuous lava pond activity ensued in February 2010. The level and vigor of the lava pond fluctuated significantly, and frequent rise-fall cycles in the level of the lava within the vent persisted through the period of this report.

SO_2 emissions at the summit began to increase in late 2007, while the ERZ continued to release significant amounts of SO_2 gas. A pulse of magma moving through the ERZ in mid-2008 yielded a brief but significant increase in SO_2 rift emissions. In 2010 there was a marked decrease in ERZ emissions, with a slight decrease in measured summit SO_2 emissions (Sutton and others, 2009). The two distinct emission sources are measured independently using vehicle-based traverses (fig.1, and Elias and Sutton, 2007). Campaign-style stationary scanning measurements were also collected during this period.

Acknowledgments

We are particularly grateful to the gas geochemistry volunteers and employees at the Hawaiian Volcano Observatory (HVO) who contributed to these 4 years of data which include more than 630 days of measurements and nearly 6,000 plume traverses. Individuals contributing to this work include Emma Passmore, Susan Alford, Marisa Mochizuki, Kate Eiloart, Helen Thomas, Desiree Roerdink, Amy Hoek, Alison Graettinger, Erin Looby, Meghan Lindsey, Christine Sealing, Hilary Morgan, Zoe Ruge, and Kelly Wooten. This work is supported

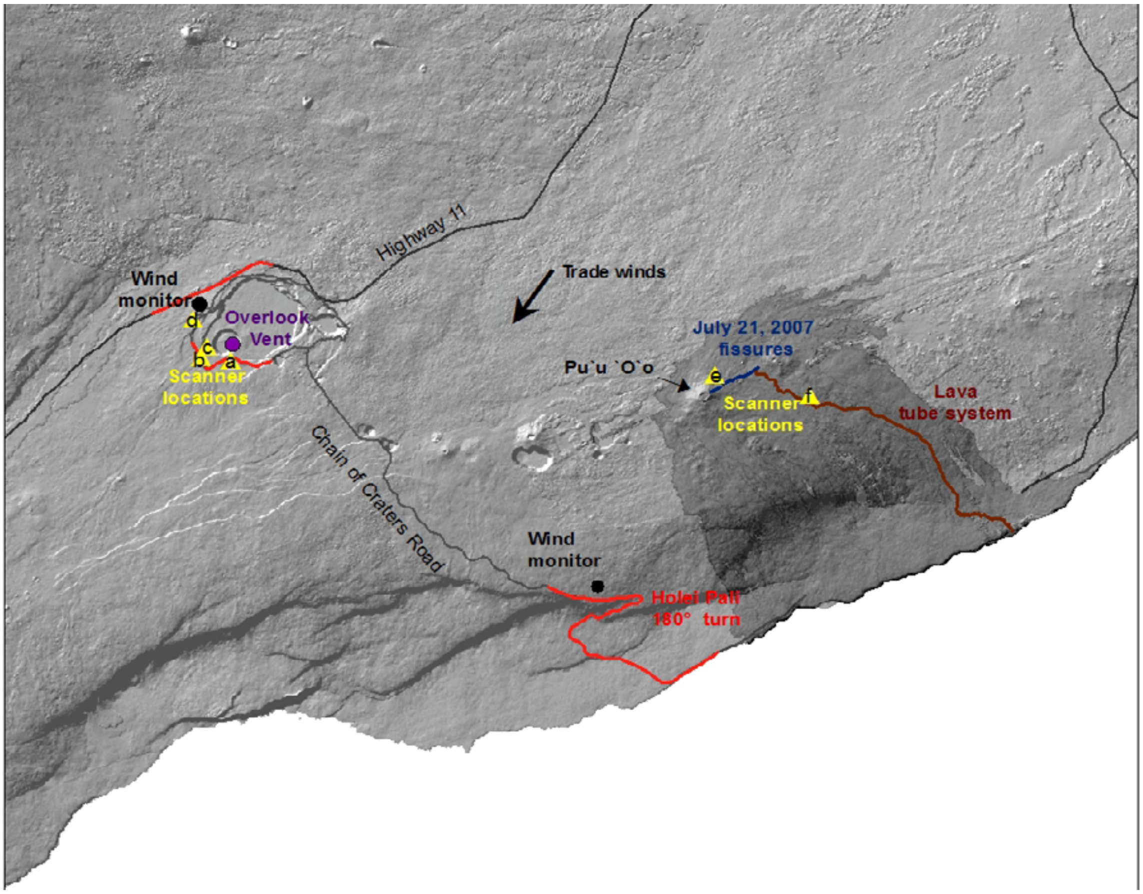

Figure 1. Vehicle-based SO_2 measurements were made downwind of the summit and east rift zone (ERZ) plumes on Crater Rim Drive and Chain of Craters Road during trade-wind conditions, and occasionally along Highway 11 during wind reversals. Traverse paths are marked in red. Yellow triangles mark the locations of stationary scanning measurements. The lava tube system (brown line) represents the tube location for a portion of this study. Base map is digital elevation model from Intermap Technologies Inc.

by the USGS Volcano Hazards Program and Volcano Science Center. We are grateful to Keith Horton and Harold Garbeil of the University of Hawai‘i at Mānoa , who provided patient technical support and continue to develop and refine the FLYSPEC instrument using the Kīlauea environment as a test volcano. We are also very grateful to Christoph Kern, USGS, Cascades Volcano Observatory, whose work has allowed us to quantify the error in the high emission rate data from Kīlauea during 2008–2010. His efforts will help us produce more accurate, refined measurements as we move into the future.

Methods and uncertainties

Instrumentation

Since late 2004, SO_2 emission rates at Kīlauea have been estimated using one of the new generation of miniature spectrometer systems, the FLYSPEC, which uses an Ocean Optics USB spectrometer, internal calibration cells, onboard GPS, and fore optics consisting of a collimating lens (Elias and others, 2006; Horton and others, 2006). FLYSPEC traverse measurements compared favorably to those of traditional COSPEC during a detailed study carried out at Kīlauea during 2003-2004 and showed consistency and continuity with the long-term database (Elias and others, 2006; Elias and Sutton, 2007). A number of observatories and researchers have documented the migration from the COSPEC to the new generation of spectrometers with data and technique comparisons (Weibring and others, 2002; Elias and others, 2006; Barrancos and others, 2008,).

In the spring of 2007 we began using a FLYSPEC version 2, which automates the calibration procedure by using an internal servo motor for calibration cell control. At the end of 2009, the instrument was modified to allow more light throughput by using a 50, rather than 25, micron (µm) slit in the spectrometer and a high efficiency grating. Table 1 shows the configuration of the HVO FLYSPEC for the period of this report. Figure 2 shows the version 2 instrument, and figure 3 the typical vehicle-mount configurations.

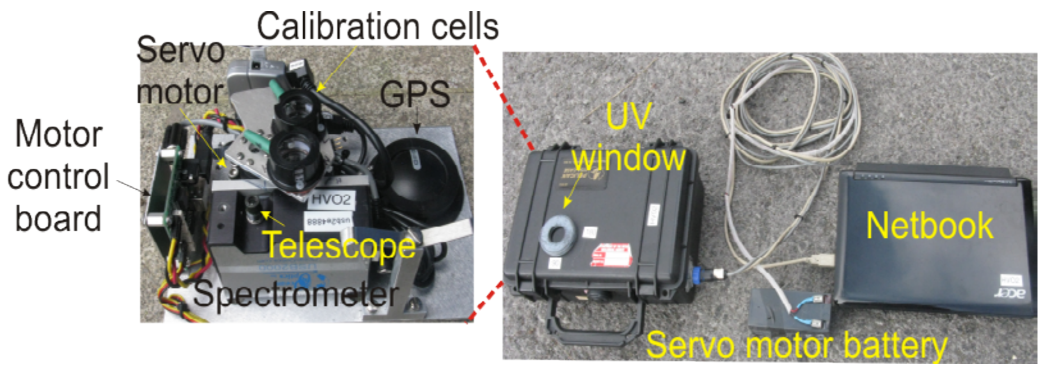

Figure 2. FLYSPEC version 2 instrument consisting of a miniature spectrometer, netbook computer, and battery to power the calibration cell servo motor. High and low calibration SO_2 gas cells are shown mounted above the spectrometer and telescope. Power for the spectrometer and GPS is supplied by the computer.

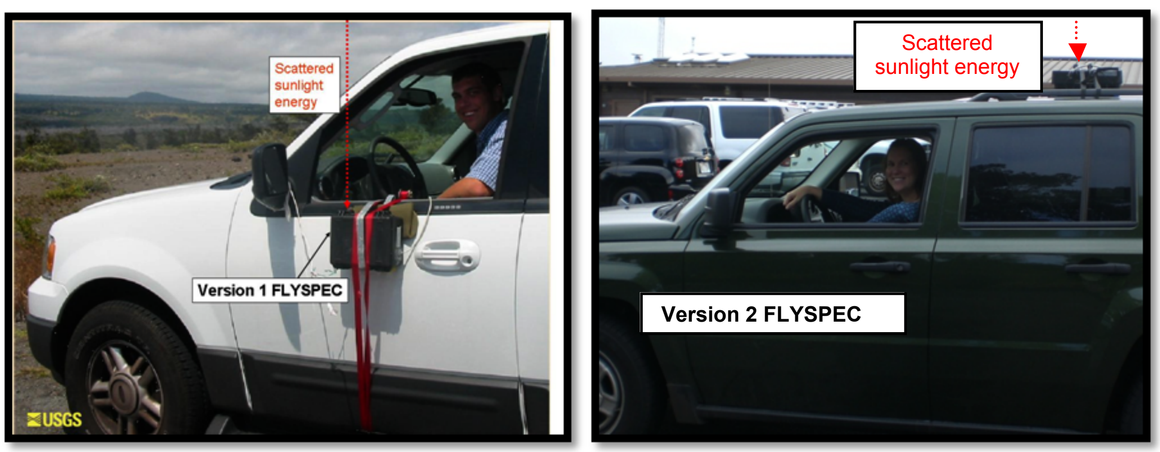

Figure 3. Vehicle-mount configurations for FLYSPEC version 1 and 2 systems. The version 2 system is mounted horizontally in a crate.

Table 1. UV spectrometer system configuration used by HVO

Date	FLYSPEC version	Spectrometer	Entrance slit (um)	Grating*	Optical resolution
9/2004 – 9/2007	1	USB 2E4888	25	7	0.4 nm
4/2007–12/2009	2	USB 2G567	25	7	0.4 nm
12/2009–present	2	USB 2E4888	50	7- high efficiency	0.7 nm

*Grating specification chart at wtww.oceanoptics.com

Figure 4. FLYSPEC with scanning attachment, which incorporates a rotating mirror in a quartz tube.

Intermittently, a version 2 FLYSPEC was adapted for stationary scanning measurements to help quantify short-term degassing processes and contribute to instrument and software development. In this mode, the spectrometer location is fixed, and a rotating mirror is used to traverse the plume through a range of angles to determine the plume cross section. We made these measurements using borrowed instrumentation until HVO purchased its own scanning attachment in 2010. Figure 4 shows the FLYSPEC with the scanning attachment.

Data collection and reduction

Emission-rate measurements at the summit of Kīlauea have traditionally been made by vehicle-based spectrometer traverses within the summit caldera along Crater Rim Drive. Details regarding this measurement technique are described in Elias and Sutton (2002; 2007). We continue to use the FLYSPEC data acquisition program “Lapfly” (Harold Garbeil and Keith Horton, Hawai‘i Institute of Geophysics and Planetology of the University of Hawai‘i at Mānoa, written commun., 2002) which provides a real-time display of the radiance spectrum, a scrolling plot of the gas path concentration in part per million meter (ppm m), the corresponding GPS position and time, calibration cell position, and the radiance at a single pixel in the fit region (fig. 5). All data presented in this report were reduced by using in-situ reference spectra acquired from the internal gas calibration cell and fit to sample gas spectra in the 305–315 nanometer (nm) range, as described in Horton and others (2006) and Elias and others (2006). Later, a sensitivity study was performed to assess the influence of three dimensional radiative transfer effects on the retrieval of SO_2 column densities under conditions with high SO_2 loads. Representative traverses were evaluated with a separate Simulated Radiative Transfer algorithm applied to the Differential Optical Absorption Spectroscopy measurements (SRT-DOAS) to obtain an estimated discrepancy between the two evaluation techniques.

The build-up to, and onset of, the 2008 summit activity included a dramatic increase in SO_2 emission rates and column amounts measured above Crater Rim Drive. Typical maximum path length concentrations (ppm m) for 2007 and 2008 were 350–800 ppm m and 900–3400 ppm m, respectively. The very high column amounts of 2008 revealed a math error in the data acquisition software that was specific to very high ppm m, and the error was subsequently corrected. Summit data from March 12 through March 31 presented in this report have been reprocessed with the corrected retrieval algorithm and should replace online or personnel communication values reported for March 2008.

The data reduction software “FluxCalc,” also by Garbeil and Horton (Hawai‘i Institute of Geophysics and Planetology of the University of Hawai‘i at Mānoa, written commun., 2002), allows the user to quickly and efficiently calculate emission rates from multiple traverses through an interactive graphical user interface (GUI). The GUI enables the user to identify the plume azimuth using the coordinates of the source location and the user-selected maximum or median of the plume trace (fig. 6). The wind-normal distances along a traverse are calculated for each pair of GPS positions.

Stationary scanning data reported here were collected with a single-spectrometer system. The two-spectrometer arrangement allows constraint of the plume height. Data presented in this report were reduced using the software “ScanCalc”, scanning reduction software developed by Horton and Garbeil (Hawai‘i Institute of Geophysics and Planetology of the University of Hawai‘i at Mānoa, written commun., 2011),) or using a spreadsheet approach developed by this report’s authors. Several approaches to data reduction were explored for the Kīlauea scanning measurements, but the simple spherical plume model (Williams-Jones and others, 2007) provided the most consistently reasonable results for the challenging, frequently

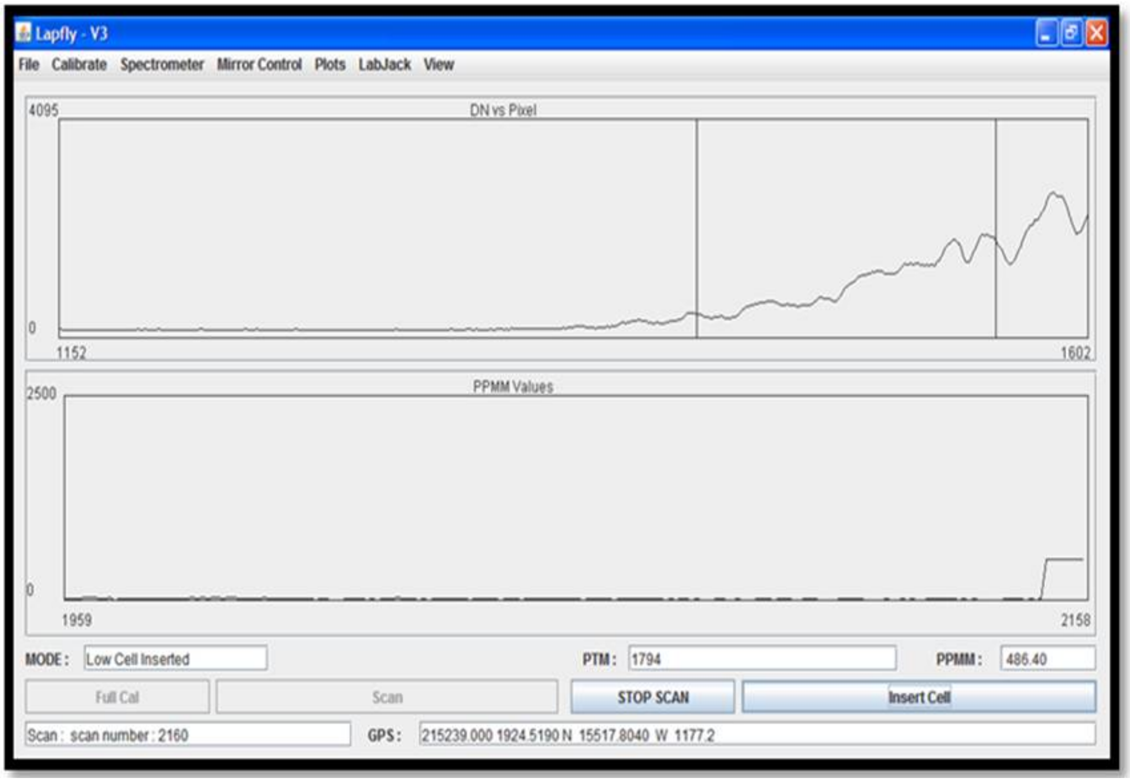

Figure 5. The Lapfly data acquisition program actively displays the current radiance spectrum with fit window (upper trace), scrolling gas pathlength concentration plot (lower trace), cell position, radiance at a single pixel in the fit region (PTM or pixel to monitor), and GPS position and time.

ground-level Kīlauea plume. Data collected with a single-spectrometer system were evaluated by determining the distance to the base of the plume using the spectrometer location, the vent location, and wind vector, and assuming that the average wind azimuth was a reasonable approximation for the trajectory of the middle of the plume. This distance was adjusted using the midpoint of the subtended scan angle to approximate the distance to the core (statistical center) of the plume. The distance traveled for each subtended increment scanned through the plume was then calculated using this slant distance to the core of the plume and the scan increment. Scanning data collected after 2009 were generally of better quality, as they used spectrometers configured for higher light throughput, used an integration time 4–10 times shorter with a higher number of co-adds, and traversed the plume within a shorter period of time.

Units of measure

Individual vehicle-based traverses at Kīlauea's summit and along Chain of Craters Road typically take approximately 3–7 and 6–15 minutes to complete, respectively. Data are collected for approximately 1 hour each measurement day (usually 4–10 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.

FLYSPEC data calibration

The FLYSPEC data acquisition program produces calculated SO_2 pathlength concentrations 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 (Elias and others, 2006; Horton and others, 2006). Typically we calibrate the spectrometer one to three times during each hour-long measurement period.

In mid-February 2009, the FLYSPEC high calibration cell failed. For several weeks we used previously collected calibrations or manual calibrations using an external calibration cell. On March 6, 2009, new calibration cells from Resonance Ltd. were received and installed, and data retrieval and analysis returned to a standard protocol. For the 2007–2010 time period, the low and high calibration cells ranged between 400–500 ppm m and 1,500–1,650 ppm m, respectively.

Baseline Noise

The noise envelope for the Kīlauea FLYSPEC data is variable, due to changes in sky conditions (for example, cloud cover and UV levels) and spectrometer response (which is affected by temperature). The FLYSPEC data reported here co-added 1–20 spectra with integration times of 1,000–50 milliseconds (ms) in order to report 1-hertz (Hz) data consistent with the GPS

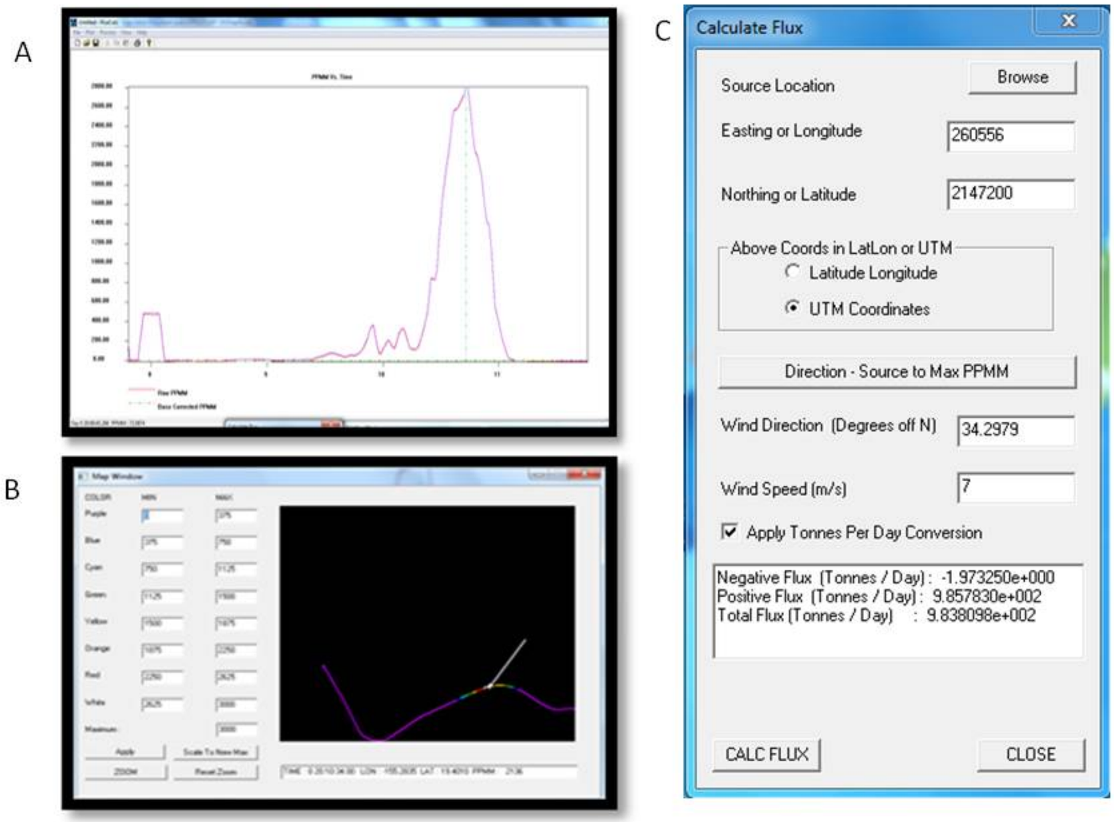

Figure 6. FluxCalc displays part per million meter values for the vehicle-based plume traverse (*A*) and a path length concentration map (*B*) with azimuth (white line segment) from the source vent to the plume maximum, which is user adjustable. Wind direction can be manually entered or can be calculated from the plume trajectory (*C*).

data acquisition rate; 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 2007-2010 time period, baseline noise ranged from 3–20 ppm m.

Over 2007–2010, the summit and ERZ datasets exchanged character with respect to contribution of baseline noise to measurement error. This character exchange was caused by profound changes in bulk emission rates from each of these sources.

For the first half of 2007, the typical maximum summit in-plume SO_2 signal was 350–500 ppm m; however, in 2008 this increased by as much as an order of magnitude, to a maximum of 900–3,400 ppm m. During 2009-2010, maximum summit SO_2 column densities remained high. In contrast, Chain of Craters Road plume maxima dropped substantially from a peak of 1,500–3,000 ppm m in mid-2008 to its 2010 maxima of 60–200 ppm m. This decrease in the Chain of Craters Road signal yielded a relative increase in the contribution of baseline noise to the measurement error.

The increase in light throughput for the newly rebuilt spectrometer in late 2009 facilitated data collection with a shorter integration time, and higher number of co-adds. Since the signal-to-noise ratio is proportional to the square root of the number of co-added spectra, the new spectrometer configuration yielded less noisy radiance spectra.

Measurement errors

Summit plume velocity measurements

Plume speed is a critical parameter for calculating gas emission rates and has been estimated using a variety of techniques during the 28-year SO_2 flux measurement history at Kīlauea (Elias and others, 1998; Elias and Sutton, 2002; 2007). Since April 2006, the summit wind speed has been measured from a permanent, 10-meter (m)-tall meteorological tower located on the north end of HVO, 30 m from the rim of Kīlauea Caldera and ~2 kilometers (km) from the core of the plume transect (lat.19.33360 N., long. -155.38559 W.). During 2007, the summit plume was generally ~3.5 km wide and was produced by multiple SO_2 sources in the caldera that appeared to be intermittently affected by micro-climate wind regimes. However, we believe that the 10-m wind measurement station provided a suitable estimate of the overall plume velocity, with an uncertainty of ~10–30 percent (Williams-Jones and others, 2006; Elias and Sutton, 2007).

With the onset of the 2008 summit activity, however, the relationship between plume and wind speed became more complex, and plume speed uncertainty may have increased to as much as 50–60 percent. This uncertainty is based on quantitative (Beaufort scale) surface level wind speeds observed along the traverse, and qualitative observations of visible plume speeds compared to measured and observed surface and 10-m winds. From March 2008 through December 2010, the vent size grew from an initial diameter of 35 m to ~130 m through sporadic vent wall collapse and small explosive events. These changes, along with variability in the height of the lava pond within the vent, affected the plume buoyancy and near-vent wind regimes. While the values recorded by the 10-m wind measurements may not accurately reflect the short-term (minutes) plume vector variations, they continue to provide a useful relative gage of the local wind conditions. For March 2008–December 2010, the estimated plume height during favorable SO_2 measurement conditions (northeast trade winds >4 meters per second, m/s) ranged from ~1,200–2,500 m above sea level (asl) (fig. 7). While the top of the plume was generally higher than the 1,250-m elevation of the tower wind measurement, the core of the plume was within the range of the wind measurement elevation. Plume heights were calculated using the angle to the top of the plume as measured via inclinometer and the distance to the plume as recorded from a digital map.

We believe that recording 10-m winds represents a practical and reasonable method to estimate plume speed until a more precise method is available. Data from continuously monitored gas sensors located at rim level downwind of the Overlook Vent show changes in ambient SO_2 gas concentrations that are correlated with wind vector shifts as measured at the observatory 10-m wind station.

East rift plume velocity measurements

Since April 2005, contemporaneous wind velocities for plume measurements made above Hōlei Pali were determined using a continuous wind monitor 3.5 m above the ground located approximately 2.5 km above the 180º turn and ~0.6 km north-northwest of Chain of Craters Road at lat. 19.323296 N., long. -155.156993 W. (fig.1). These data are telemetered to HVO. We believe that these data reasonably represent plume velocities above Hōlei Pali, because at least a portion of the east rift plume is frequently on or close to the ground as it crosses Chain of Craters Road in this location. For measurements made below Hōlei Pali on the coastal flats, wind speeds were determined using a combination of methods including (1) 5- to 10- minute wind measurements (Extech Vane Thermo-Anemometer) 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 180º turn on Chain of Craters Road adjusted for observed and measured discrepancies. Contemporaneous wind measurements indicate that wind speeds measured 3.5 m above ground level (agl) above Hōlei Pali are often ~25 percent higher than those measured below Hōlei Pali, and thus are adjusted and accordingly reported for plumes measured below Hōlei Pali. The uncertainty in wind-speed measurements for east rift vehicle-based data is estimated to be 10-60 percent. This uncertainty is based on wind-characterization experiments (Elias and others, 1998), other Kīlauea emission-rate studies (Casadevall and others, 1987; Andres and others, 1998), and qualitative observations

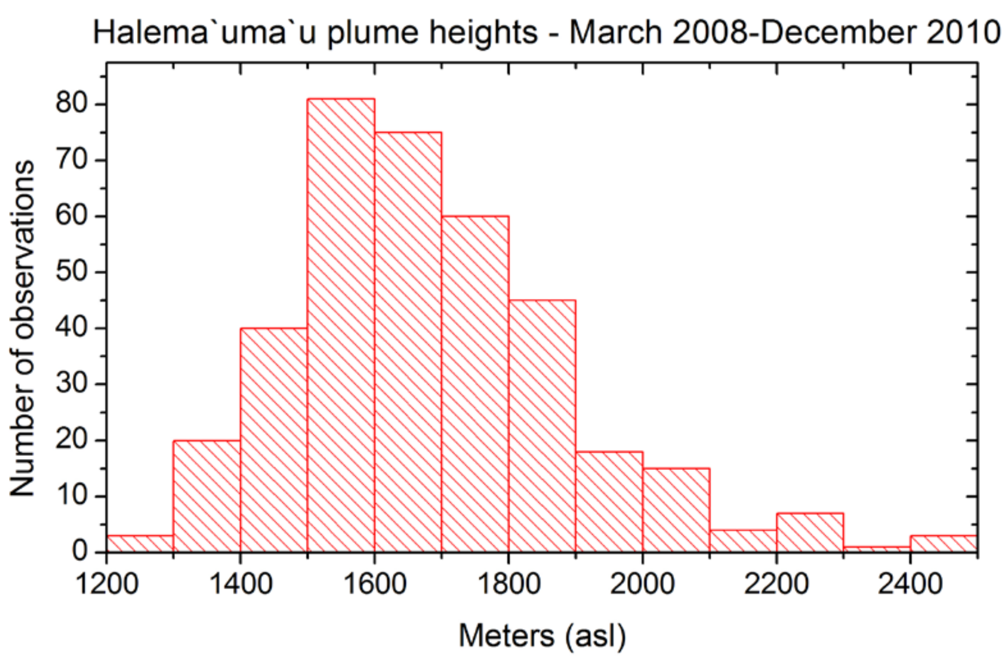

Figure 7. Halemaʻumaʻu plume height frequency for wind speeds greater than 4 meters per second, March 2008-December 2010 (HVO data). Abbreviation: asl, above sea level.

of visible plume speeds compared to measured and observed surface level winds.

Calibration cell concentrations

SO_2 concentration pathlength values measured from the summit and ERZ sources can, at times, exceed the value of the internal SO_2 high concentration cell of the FLYSPEC. As optical densities approach very high values, the linear relationship between optical density and column density established by Beer's law may not be accurate for calculating part per million meter values. This suggests that, when column amounts exceed the high cell concentration, concentration pathlength and emission-rate quantities may underestimate the actual values. Generally, however, column amounts above the high cell concentration, account for only a small portion of a traverse, and on days with a very dense plume. We estimate the emission-rate uncertainty contributed by having an insufficiently high calibration cell to be <15 percent. Experiments using combinations of calibration cells show an underestimation in measured ppm m of ~3–15 percent at concentration pathlengths above 1,500 ppm m (Kazahaya and others, 2004; Elias and others, 2006). Thus, some improvement in calculation of part per million meter could be achieved for the high-concentration pathlengths measured at Kīlauea since 2008 by utilizing a high cell that brackets the measured values more precisely. For instance, if an additional cell of 3,000 ppm m were incorporated into the measurement and fitting regime, the path concentrations that are currently underestimated at high SO_2 burdens would be more accurately quantified. The error of the SO_2 concentration in the calibration cell itself is on the order of 2–5 percent.

Scanning geometry

Errors in the scanning measurements are significant for the Kīlauea environment. Short-term variability in plume shape and location make constraining an accurate plume cross section challenging. Since the plume is grounded much of the time, most measurements incorporate very low scan angles and the errors associated with increased scattering of light at the horizon. Conditions and configurations which allow measurement of a lofting plume return better quality data. Since the measurements reported here were made with a single-spectrometer system, the measurement errors incorporate uncertainties in the distance to the plume. Measurements made with two-spectrometer systems could help constrain plume heights but are still plagued with errors associated with plume inconstancy and light scattering. Comparing temporally similar scanning and traverse measurements shows them to be within a factor of 1–3 of each other.

Wind speed dependencies for summit data

Historically, calculated traverse-based emission-rate values have not been correlated with wind speed (fig. 8). A series of vent collapses at the summit in 2010, however, changed the vent geometry and plume dynamics such that summit measurements at wind speeds above 8 m/s are consistently high. We speculate that the new vent configuration gives rise to a plume that is more susceptible to wind shear, causing it to pile up above the roadway. Data collected in 2010 with wind speeds greater than 8 m/s should be used with care. Less dependency is seen for data collected at wind speeds of 5–8 m/s, which comprise 75 percent of the measurements in 2010 (fig 9–10).

Radiative transfer

The quantification of SO_2 column amounts that are used to compute the emission rates reported here assumes that scattered solar radiation takes the most direct linear path through the gas plume to reach the spectrometer. One recent quantitative study shows that, depending upon plume conditions, the error in this assumption can cause both under- and over-estimations spanning more than an order of magnitude in retrieved part per million meter values (Kern and others, 2010). With the onset of the 2008 summit activity, there was a dramatic increase in the summit SO_2 column amount and presence of light-scattering aerosol. Large errors due to poor light throughput in the optically dense core of the plume, and increased scattering, were introduced. Traditionally, the largest

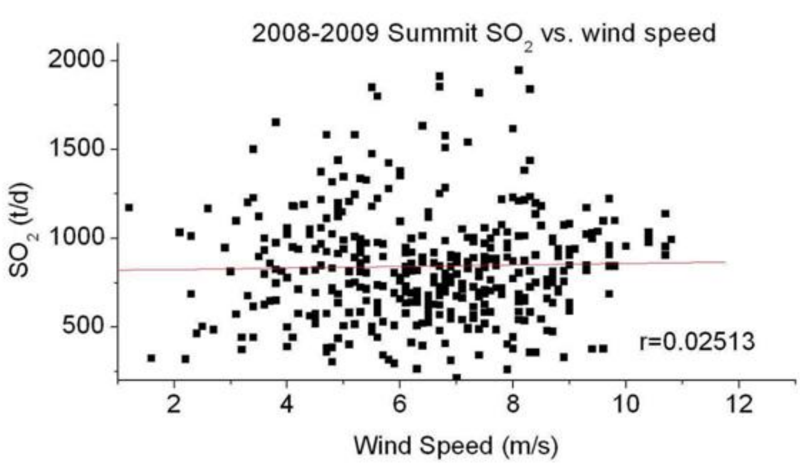

Figure 8. Kīlauea summit SO_2 emission rate and wind speed for 2008-2009. Abbreviations:m/s, meters per second; t/d, tonnes per day.

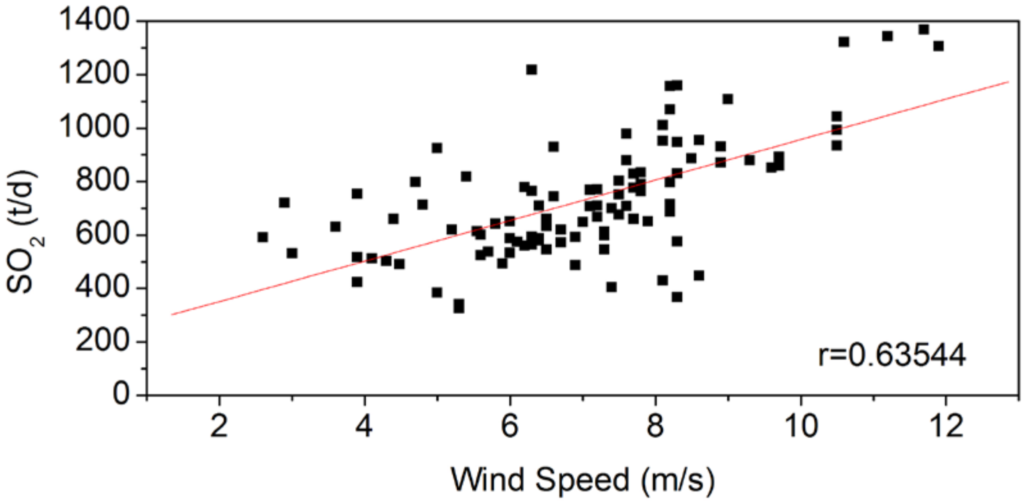

Figure 9. Calculated Kīlauea summit SO_2 emission rate and its relationship to wind speed for all speeds for 2010. Abbreviations:m/s, meters per second; t/d, tonnes per day.

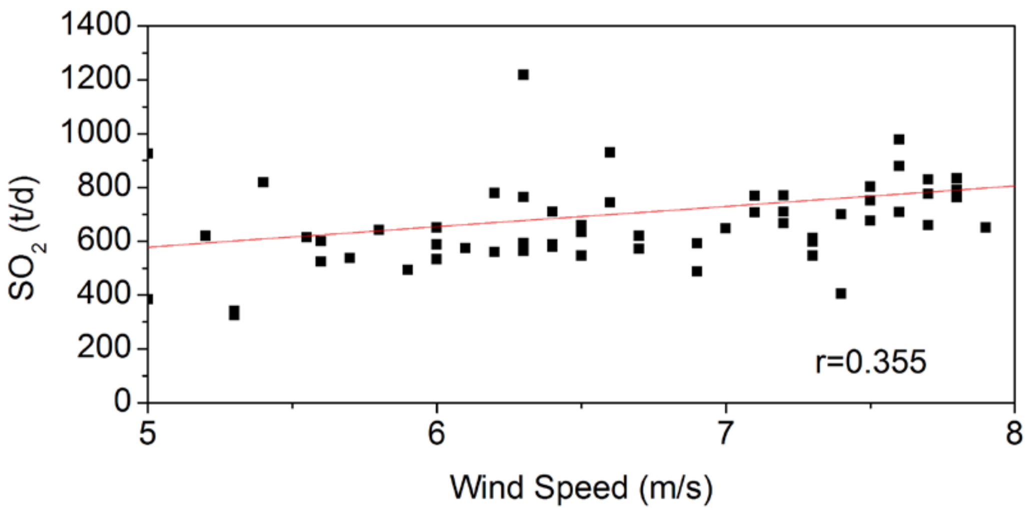

Figure 10. Calculated Kīlauea summit SO_2 emission rate and its relationship to wind speed for speeds between 5 and 8 meters per second (m/s) for 2010. Abbreviations: t/d, tonnes per day.

source of error for traverse-style emission-rate calculations has been attributed to errors in plume speed (Casadevall and others, 1987; Williams-Jones and others, 2006; 2007), which, at Kīlauea, we estimate to be 10–60 percent. For the 2008-2010 period, unquantified errors from inaccurate assessment of radiative transfer through the volcanic plume may dwarf all other errors for certain plume configurations and vent activity.

To explore the magnitude of the errors caused by the multiple scattering effects of incoming radiation to our measurements, four test cases were investigated. The plume configuration and activity for these cases are (1) a large, thick, opaque plume generated from an active Halemaʻumaʻu pond, (2) a moderately thick plume generated from an active Halemaʻumaʻu pond, (3) a thin, wispy translucent plume generated during a lava high stand/stagnant pond, and (4) the pre-2008 plume, when there were multiple distributed small degassing sources within the caldera, rather than a single point source.

An evaluation scheme that combines radiative transfer modeling with spectral analysis of traverse data was used to derive more accurate SO_2 column densities as compared to the conventional FLYSPEC 305–315 nm fit-window retrievals. The scheme, known as Simulated Radiative Transfer DOAS (SRT-DOAS), simulates realistic light paths in and around the volcanic plume containing variable amounts of SO_2 and aerosols (Kern and others, 2011). An inversion algorithm is applied to derive the true SO_2 column density. For the test cases, it was assumed that the plume extended from ground level to 600 m agl (a typical measured plume configuration), with the plume maximum

Table 2. Kīlauea Volcano summit test data for SRT-DOAS examination and correction.

Note: Simulated Radiative Transfer DOAS (SRT-DOAS), simulates realistic light paths in and around the volcanic plume containing variable amounts of SO_2 and aerosols

Date/Time (HST)[1]	Average SO_2 (tonnes/day)				Maximum ppm m[3]			Conditions
	N[2]	Original	SRT	% change	Original	SRT	% change	
3/1/10 10:07	3	915	1545	+70	2,500–2,750	4,600–6,100	70–135	Large, thick plume emitted from vigorous lava pond.
7/26/11 10:36	4	780	1010	+30	2,250–2,850	3,790–4,150	50–80	Moderately thick plume emitted from active pond. Unsaturated dataset incorporates extended wavelength range for optimizing fit.
11/5/10 10:17	6	405	411	+2	1,150–2,450	1,260–3,700	10–50	Thin wispy plume during lava high stand episode.
9/18/07 9:53	2	218	166	−24	270–360	230–280	−(15–20)	Diffuse, multi-source plume prior to 2008 Overlook Vent configuration.

[1] Hawaiian Standard Time

[2] Number of traverses examined

[3] Range of values bracket maximum part per million meter (ppm m) for all traverses

centered at 300 m agl. Other influences that factored into the evaluation include the atmospheric extinction coefficient, the distance to the plume, and the altitude of the measurement.

The test case results, presented in table 2, suggest that individual emission-rate underestimates for the summit may range from negligible for thin, wispy plumes to over a factor of 2 for plumes with very high amounts of SO_2 and aerosol. An alternate estimate of annual emission rates, taking into account the preliminary SRT-DOAS adjustments, is included in table 7. A plot showing the original and estimated SRT adjusted emission rates based on the test cases is included in the Summit SO_2 Emission Rates section (see fig. 12). It should be noted that this first-order adjustment is very preliminary and is applied by simply categorizing emission rates and maximum ppm m values for the measured data as compared to the few test cases. As a first-order adjustment, summit emission rates for 2007-2010 that were less than 600 t/d were uncorrected (35 percent of data), those between 600 t/d and 900 t/d were increased by 30 percent (37 percent of data), and those >900 t/d were increased by 70 percent (28 percent of data). These adjustments themselves may underestimate emissions during some conditions. While calculating each day’s emission rates using SRT-DOAS may be possible in the future, at this time a slightly more refined adjustment could be applied by examining the duration of the maximum ppm m values for the measured data, as compared to the test cases. Significant differences to the originally calculated data were not sufficient to warrant use of this approach at this time.

The overall contributions of the preliminary summit SRT-DOAS adjustments to the annual emissions for Kīlauea are reasonably low, at approximately 10 percent for 2008, and 30 percent for 2009 and 2010. The increased contribution of the corrected summit emissions for 2009-2010 reflects the decrease in the ERZ’s relative contribution to Kīlauea’s total emissions. The contributions of the preliminary summit SRT-DOAS adjustments to the summit emissions themselves are more significant; the preliminary corrected data represent an increase of ~30 percent for 2008 and ~40 percent for 2009 and 2010.

During periods of elevated ERZ emissions in 2008, SO_2 column amounts reached 3,000 ppm m, and high emission rates may be under-estimated. However, the measurement location along Chain of Craters Road is 10 times the distance from the emission source as is the summit measurement configuration, and since the dilution and dispersion of the plume are greater, the effects may not be as pronounced for the ERZ plume. While no test data were examined for the ERZ dataset, we present alternative emission-rate plots that speculate the potential increase in emissions based on the maximum observed column amounts, minimum observed radiance at the lower wavelengths, and the summit test cases (see figs. 27 and 29). Periods of very high column amounts for the ERZ during the 2007-2010 interval were limited to the first 9 months of 2008, thus only these data were considered, and the overall impact of underestimated ERZ emissions is constrained. As a first-order adjustment, the January-September 2008 ERZ emissions less than 2,000 t/d were left uncorrected (80 percent of data), those between 2,000 t/d and 4,000 t/d were increased by 30 percent (17 percent of data), and those >4,000 t/d were increased by 70 percent (3 percent of data). The combined estimated summit and ERZ recalculated emission rates result in an increase in the 2008 annual emissions of ~25 percent.

The absolute accuracy of the high emission-rate data is a line of inquiry that we are eager to pursue, and a rigorous recalculation of these data is warranted. While there is compelling evidence that real changes in emission rate are measured on a time scale of minutes to days (see the following sections of this report), emission rates for very robust plumes represent a minimum constraint. The 2008-2010 SO_2 emission-rate data should be treated thoughtfully for uses such as evaluating contributions to global SO_2 budgets, calculating emission rates for gas species scaled to SO_2, particularly for the summit, and constraining effects on local air quality.

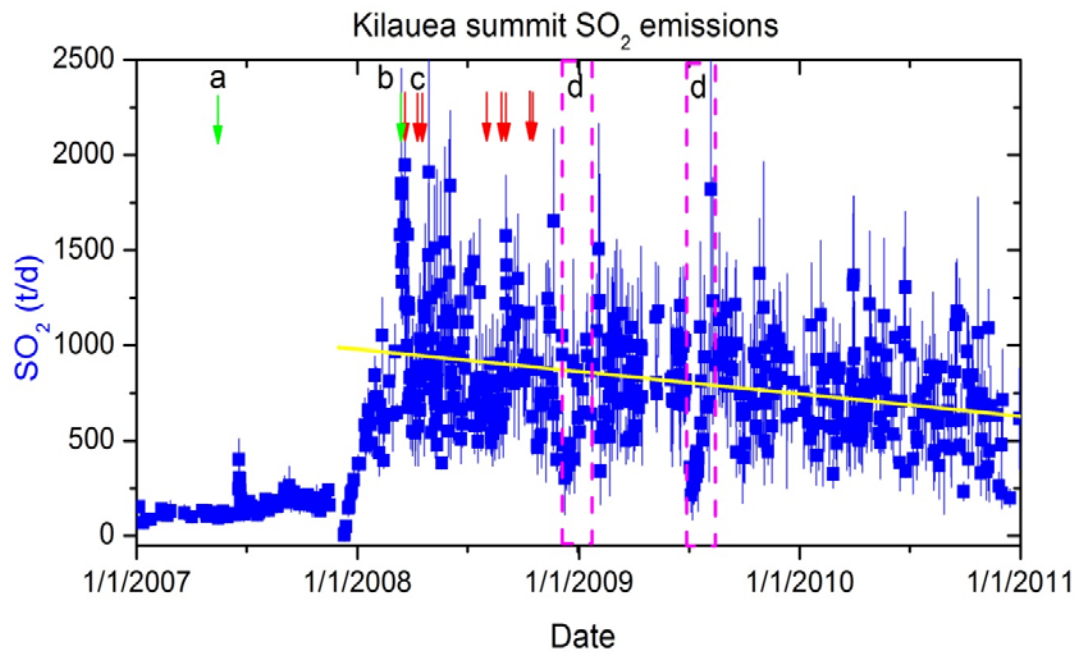

Figure 11. Average Kīlauea summit SO_2 emission rates for 2007–2010, presented without SRT-DOAS adjustments. Vertical bars represent the standard deviation for all traverses on a single day. Yellow line is linear fit to data for period of Halemaʻumaʻu vent opening through 2010. Letter codes: a, Father's Day ERZ intrusion/eruption; b, Halemaʻumaʻu Overlook Vent opens; c, explosive events; d, eruptive pauses. Abbreviations: t/d, tonnes per day.

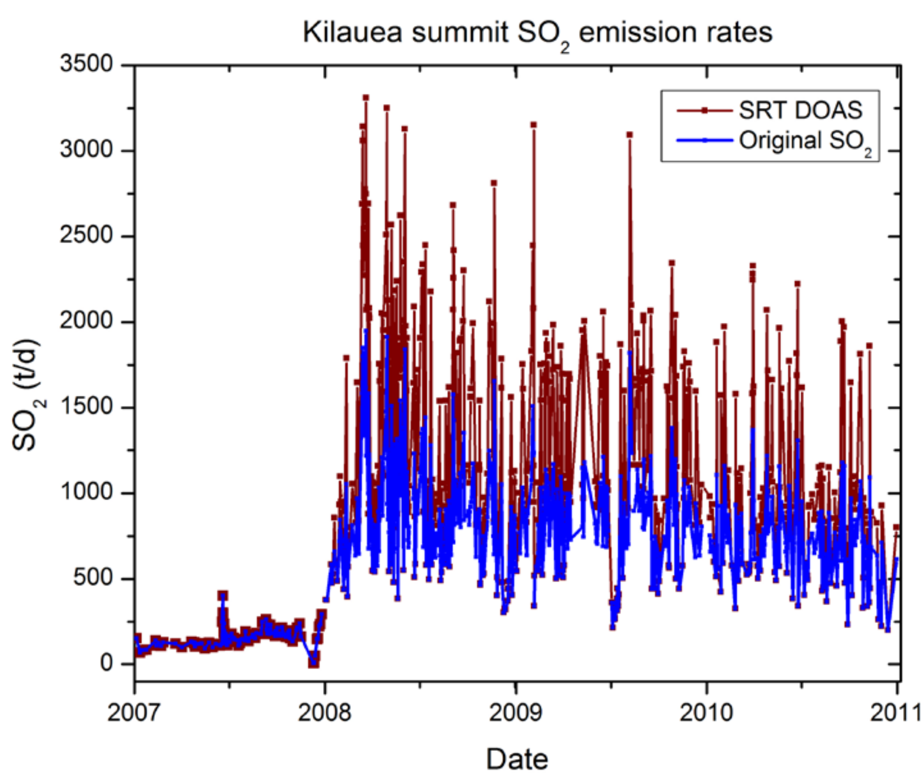

Figure 12. Original and SRT-DOAS adjusted Kīlauea summit SO_2 emission rates for 2007-2010. Abbreviation: t/d, tonnes per day.

Summit SO_2 emission rates and eruptive changes

SO_2 emission rates during the varied summit and ERZ eruptive activity of 2007-2010 can help elucidate eruptive process depths and dynamics. An overview of SO_2 as it relates to eruptive activity is presented in the following section. The vehicle-based traverse SO_2 emission rates for 2007 through 2010 are presented in figure 11, and table 3. These data have not been adjusted using SRT-DOAS. The originally calculated and SRT-DOAS adjusted summit SO_2 emission rates for 2007-2010 are presented in figure 12. A subset of the summit scanning measurements collected during 2008-2010 is presented in table 4. These data have not been adjusted using SRT-DOAS. The summit scanning measurements generally agree with temporally similar traverse measurements within a factor of 2, depending on the plume configuration, and consistency of meteorological conditions. As observed for earlier datasets for Kīlauea emissions (Andres and Kasgnoc, 1998; Elias and others, 1998; Sutton and others; 2001, Elias and Sutton, 2002), emission rates based on scanning measurements are generally lower than those based on vehicle measurements, except under conditions with low emissions and a thin, compact plume (Elias and Sutton, 2002).

Plume and vent dynamics

Changes in SO_2 emission rate at the summit commonly mirrored the Real-time Seismic-Amplitude (RSAM) (Endo and Murray, 1991) recorded at nearby stations during changes in activity, consistent with observations that an increase in RSAM can be related to magma or gas movement (Chouet, 1996). SO_2 and RSAM correlations are observed at various volcanoes (that is, Olmos and others, 2007; Nadeau and others, 2011). Coincident gas and surface deformation changes were also observed for some events. Events with coincident seismic, deformation, and summit gas signatures include the June 2007 ERZ Father’s Day event and the lead-in to the 2008 summit eruption (Poland and others, 2009) (fig. 13); events with coincident seismic and gas signatures included the pauses

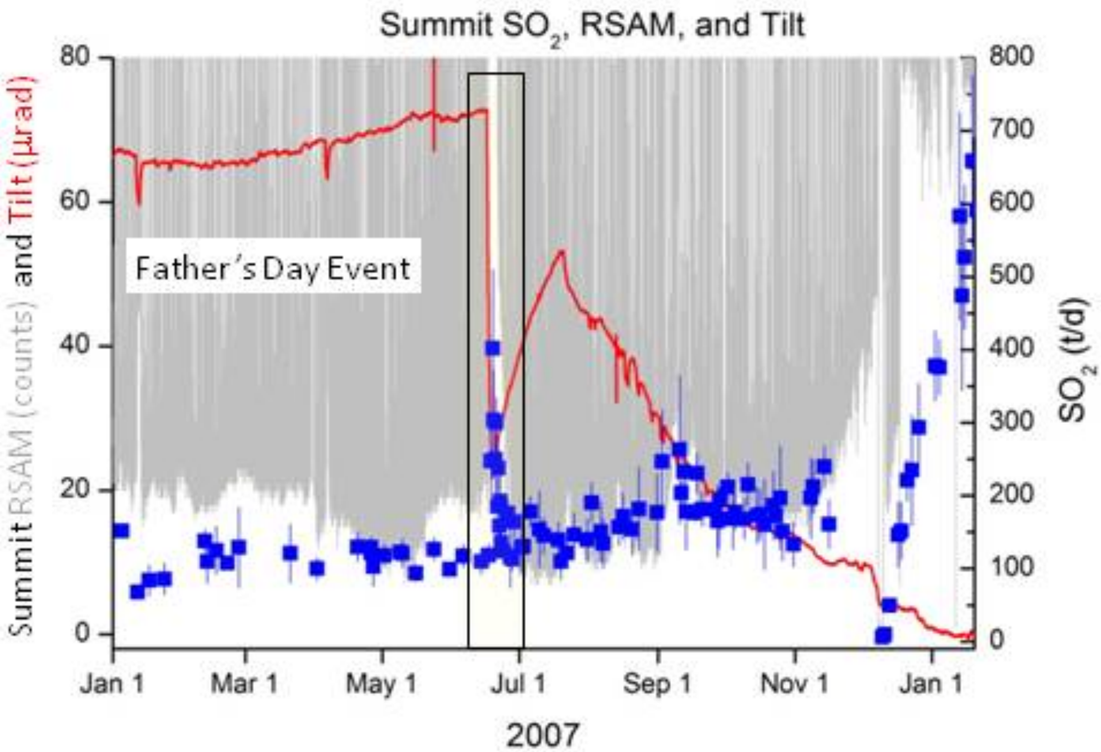

Figure 13. Kīlauea summit SO_2 emissions (blue) are correlated and anti-correlated with seismic tremor levels (gray) and tilt (red), respectively, during the East Rift Zone Father’s Day event. Increases in gas and seismic energy beginning in November 2007 herald the opening of the Overlook Vent in March 2008. Deflation and decompression at the summit following the Father’s Day event triggered magma degassing and was proposed as the trigger for the 2008 summit eruption (Poland and others, 2009). Heavy rainfall effectively scrubbed SO_2 emissions in late 2007 (data gap). SO_2 data are presented without SRT-DOAS adjustment. Abbreviation: t/d, tonnes per day; μrad, microradians.

in summit vent activity in late 2008 and mid-2009 (figs. 14, 15), and the vent drain/fill events of 2010.

Collapses within the vent and of the vent rim resulted in ash-laden plumes and were accompanied by tremor bursts or composite seismic events (short bursts of high frequency energy which punctuate long-period seismicity, which in turn rides on a very long period signal). Increases in measured SO_2 along with other observations suggest that degassing drove the vigorous plumes (Orr and Patrick, 2009) (figs. 16–19).

Periods when seismic and gas signals were not well correlated also occurred and may provide information regarding the coupling of the volatile phase in the magma. One example is around the time of the opening of the summit vent in March 2008 (fig. 20).

Gas-driven summit vent drain and fill events have likely been present for much of the eruption; however, the first clear correlation between SO_2 emission rate and drain/fill cycles was observed in May 2010 when visiting researchers with a continuously recording UV camera system recorded a rise/fall event (Nadeau and others, 2010). Traverse measurements also consistently revealed a change in emissions during these events. From July through December 2010, the period of frequent coincident traverse emission-rate measurements and summit vent rise/fall cycles, the lava pond was in a high-stand condition ~21 percent of the time. The mean SO_2 emission rates during high stand and low stand (includes intra- and post-drain period) were 370 t/d, σ=190 t/d, N=193 and 890 t/d, σ=430, N=58, respectively. Mean emission rate

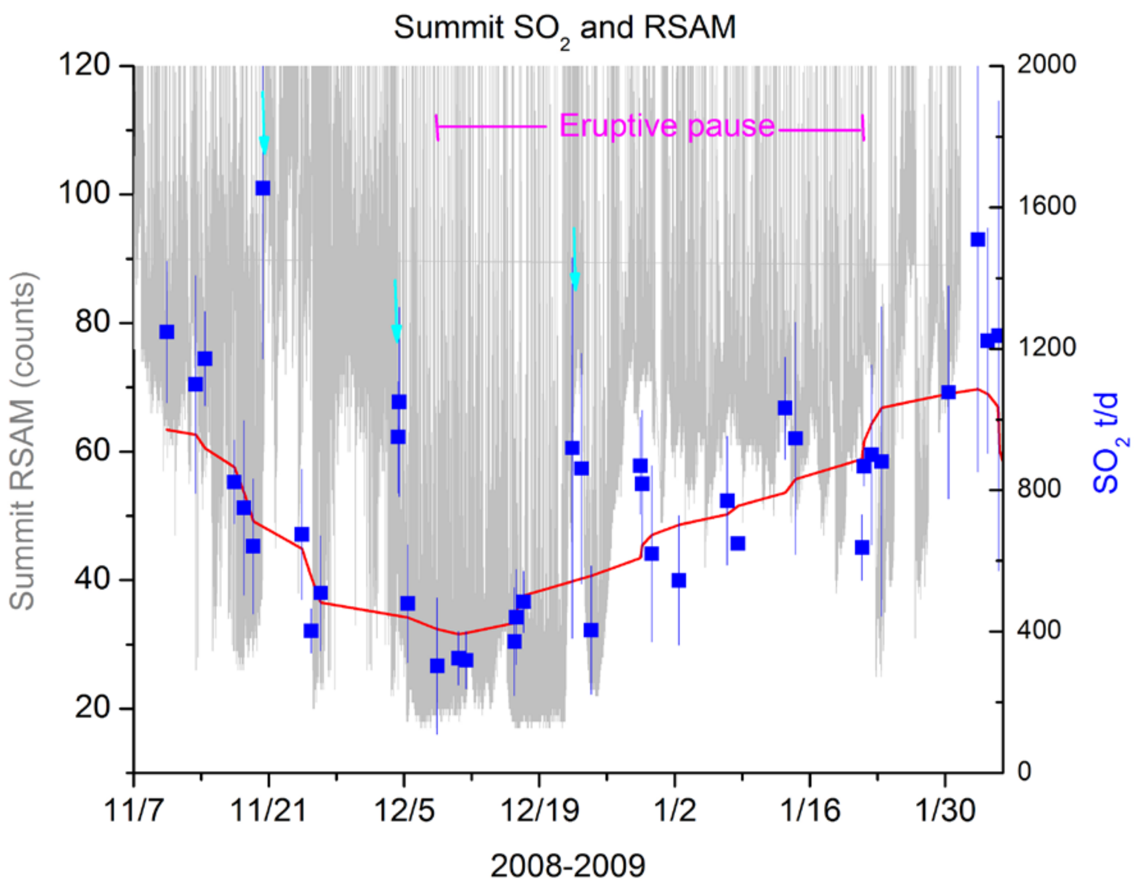

Figure 14. Daily average SO_2 emissions and 1-minute RSAM from the summit of Kīlauea leading up to the December 2008-January 2009 eruptive pause. Cyan arrows denote periods of vent collapse, inferred lava column drain-back events, or tremor bursts. The red line is the smoothed SO_2 dataset excluding the marked SO_2 outliers. The SO_2 and seismic signatures heralded the early December through mid-January eruptive pause. SO_2 data are presented without SRT-DOAS adjustment. Abbreviation: t/d, tonnes per day.

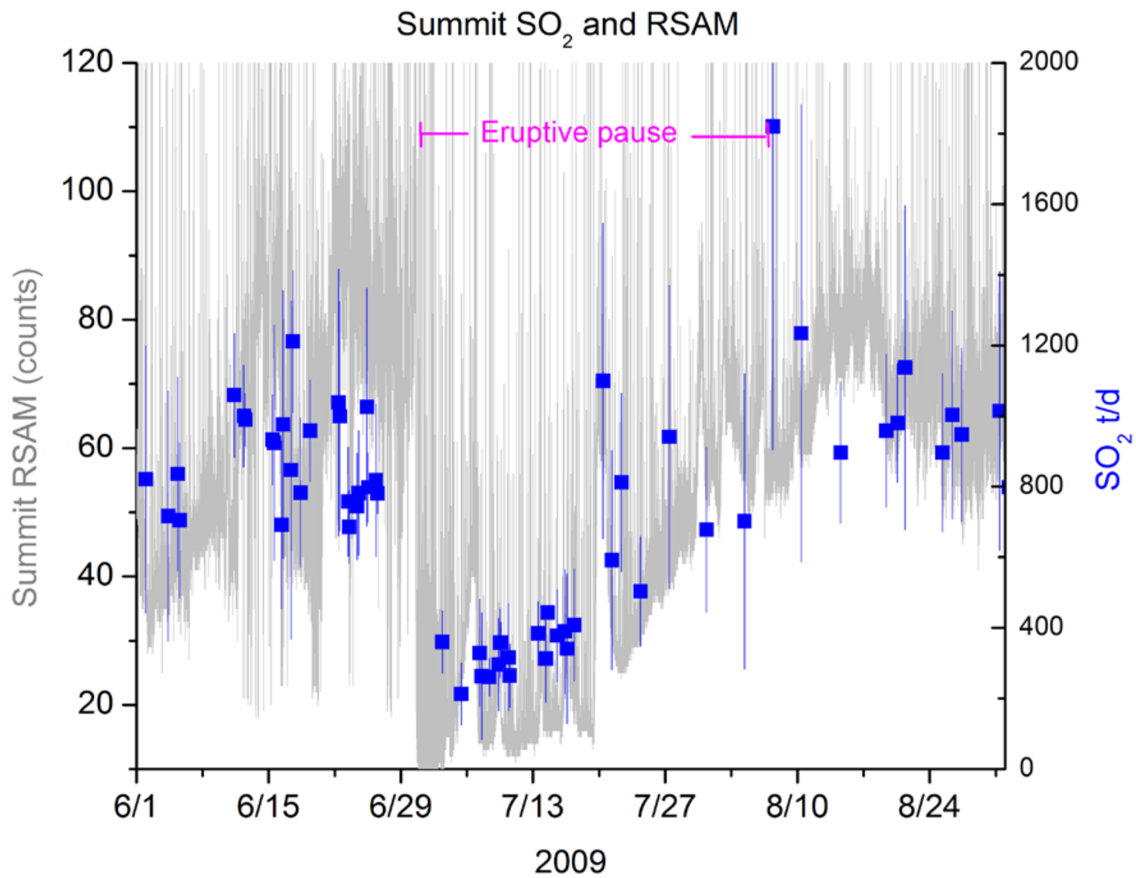

Figure 15. Daily average SO_2 emissions and 1-minute RSAM from the summit of Kīlauea leading up to the June-July 2009 eruptive pause. SO_2 data are presented without SRT-DOAS adjustment. Abbreviation: t/d, tonnes per day.

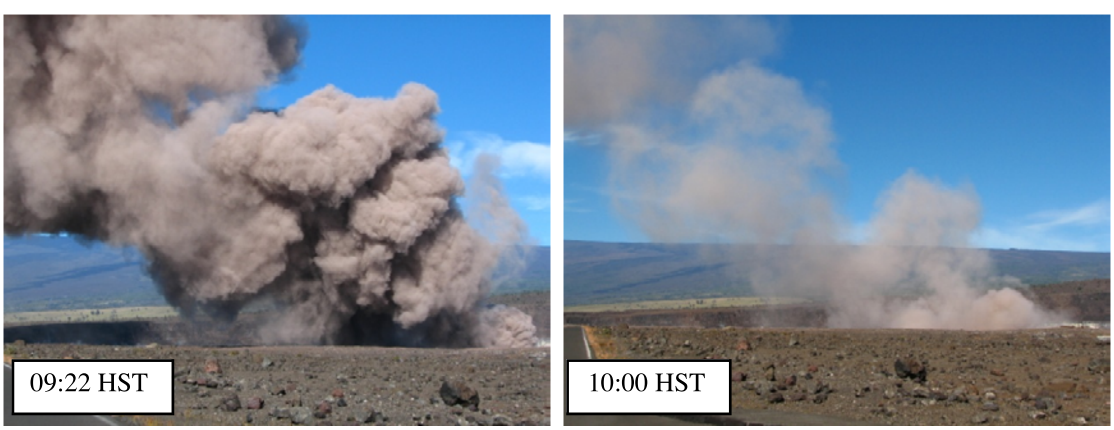

Figure 16. On December 4, 2008, a large collapse within the Overlook Vent was accompanied by a Very Long Period signal (VLP) and ejected a large dust cloud of reddish ash, which was followed by a weak, wispy plume.

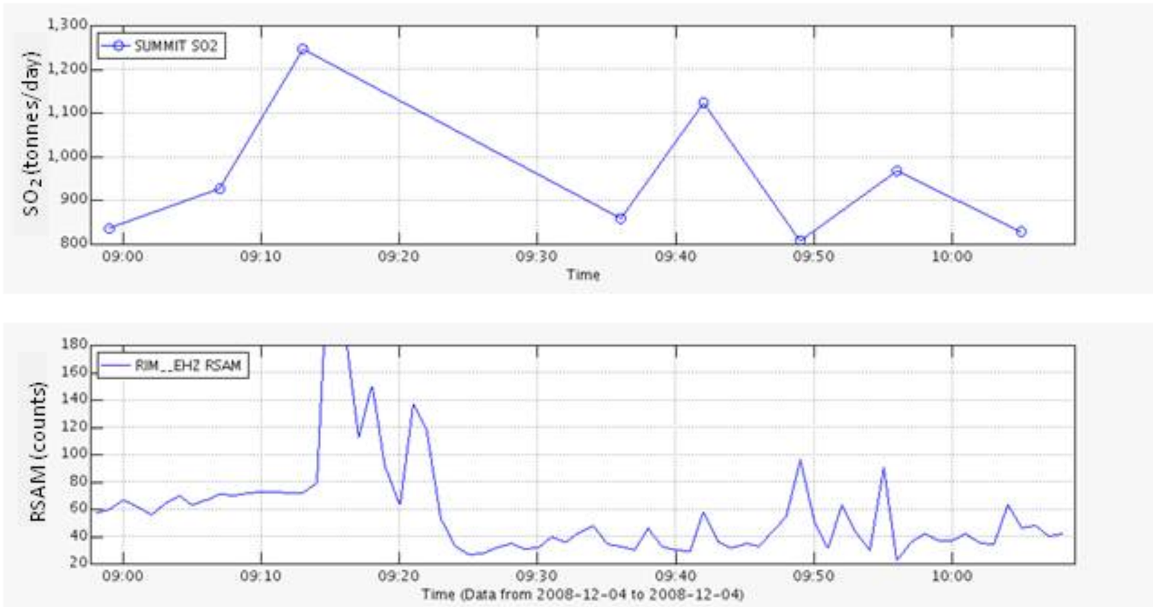

Figure 17. An ~50-percent increase in SO_2 coincident with the onset of the December 4, 2008, Overlook Vent collapse may have been related to a gas burst associated with the vigorous plume. SO_2 data are presented without SRT-DOAS adjustment.

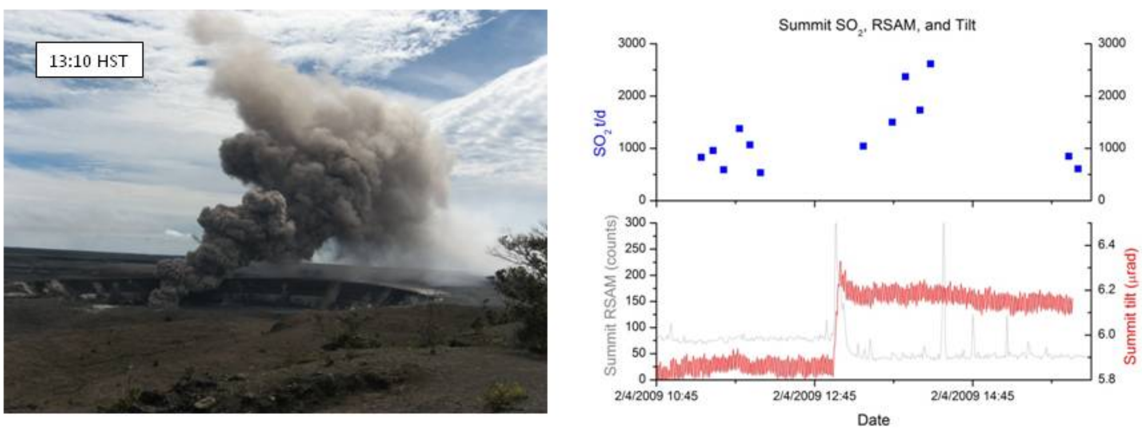

Figure 18. A spike in SO_2 accompanied the Kīlauea brown plume event (left) of February 4, 2009, suggesting that degassing may drive the vigorous plumes. Right: SO_2 emissions, summit tilt, and RSAM during the event. As lava withdrew during a 37-hour deflation event, the bottom of the vent cavity collapsed, and a significant composite event occurred. The increase in emissions measured directly after the composite event represents a minimum, as residual gas caused a broad feature which compromised the quantification of SO_2. SO_2 data are presented without SRT-DOAS adjustments. Abbreviation: t/d, tonnes per day; μrad, microradian.

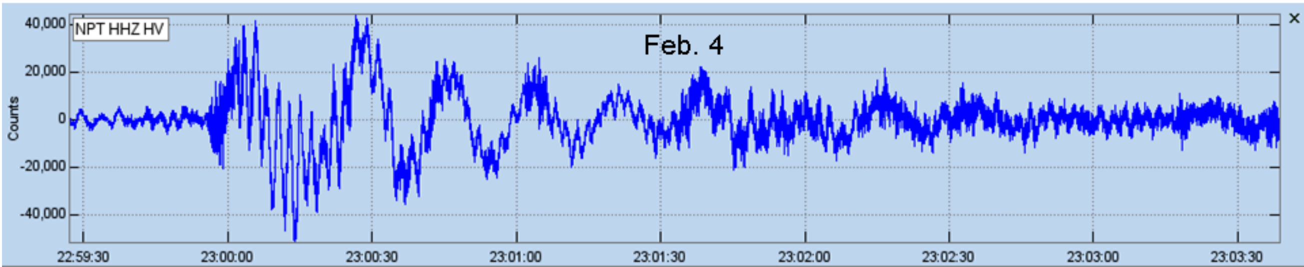

Figure 19. Composite seismic event of February 4, 2009, Kīlauea summit.

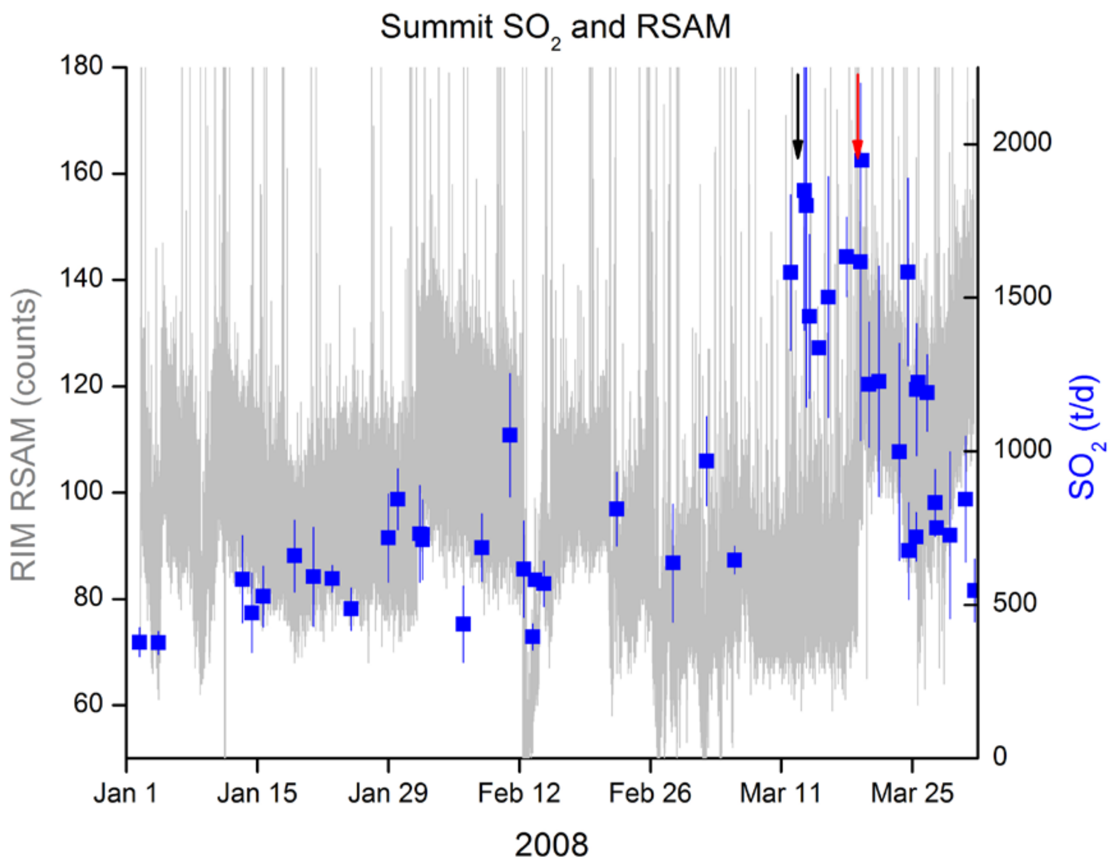

Figure 20. A two- to three-fold increase in SO_2 (blue squares) accompanied the opening of the Overlook Vent in Halema‘uma‘u , while an increase in summit tremor (gray) occurred about a week later. The black and red arrows denote the opening of the Halema‘uma‘u gas vent on March 12 and the March 19 explosive events, respectively. SO_2 data are presented without SRT-DOAS adjustments. Abbreviation: t/d, tonnes per day.

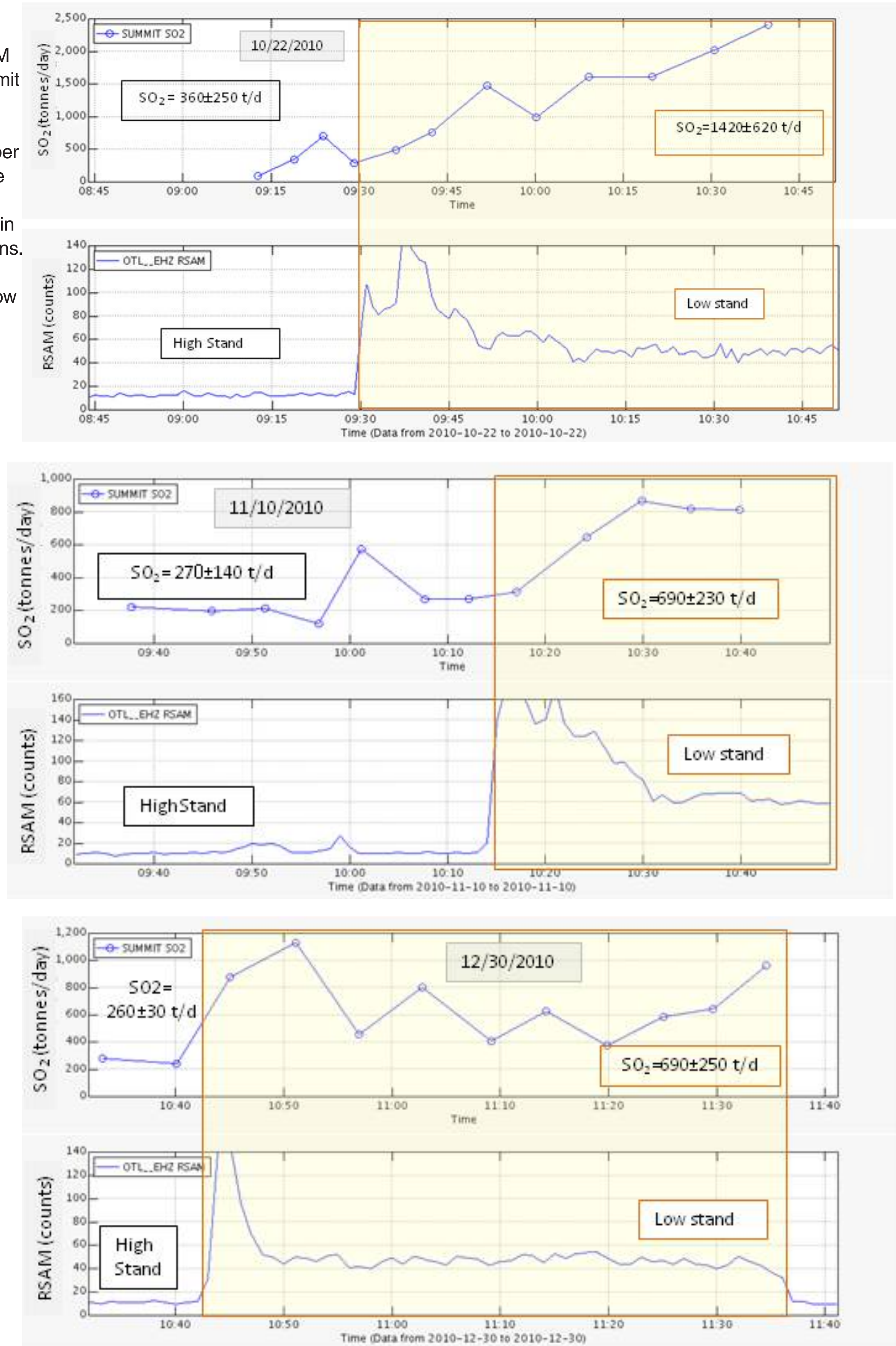

Figure 21. Individual SO_2 traverses and RSAM examples from the summit of Kīlauea during drain and fill event in October, November, and December 2010. During 2010 these events were clearly accompanied by a drop in RSAM and SO_2 emissions. The energetic draining event and subsequent low lava stand were marked by an RSAM and SO_2 increase. SO_2 data are presented without SRT-DOAS adjustments.

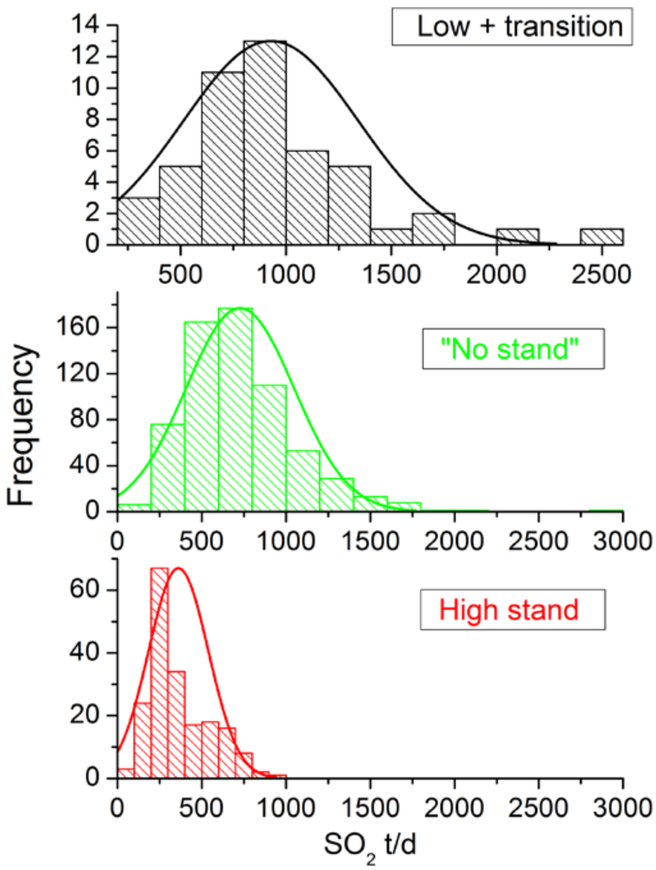

Figure 22. Frequency distributions of Kīlauea SO_2 emission-rate values during high-stand, low-stand, and “no-stand” conditions for July-December 2010 confirm that emission rates are higher during periods when the lava pond is at a low stand. The solid line is the normal curve calculated using the mean and standard deviation of the datasets. SO_2 data are presented without SRT-DOAS adjustments. Abbreviation: t/d, tonnes per day.

during “no-stand” conditions (that is, no rise and fall cycle during data collection) was 720 t/d, σ=325. A clear and repeated seismic signature accompanies the drain/fill cycles, with a drop in RSAM coincident with a high lava stand, a spike during the vigorous drain event, and a return to a moderate level for the lava low stand (fig. 21). Figure 22 shows the frequency distribution of emission-rate values during high- stand, low-stand, and “no-stand” conditions. Although the amount of data collected is unequal for the three conditions, the distribution of values confirms that emissions decline during high-stand events. A two sample independent t-test using the low- and high-stand means confirms that the means are different at the 0.05 significance level. The drop in SO_2 emissions during a high-stand event may be related to a decrease in the circulation of material within the shallow conduit, and (or) a constraint on degassing due to the formation of a crust on the pond surface (Patrick and others, 2010).

Changes in rainfall effects

Because of the high water solubility of SO_2, extreme rainfall events can contribute to the shallow subsurface scrubbing of SO_2 and historically have caused a decrease in measured emissions (Elias and Sutton, 2007). In late 2007, a heavy rainfall event resulted in SO_2 levels dropping below the detection limit of our technique for a period of several days (fig. 23). However, since the opening of the Overlook Vent, emissions have been virtually unaffected by high rainfall events. While a rainfall event in early February 2008 caused a short disruption in the steady increase in SO_2 emissions prior to the Overlook Vent opening, by year’s end a comparable rainfall event had no discernible scrubbing effect on SO_2 (fig. 24). The presence of magma likely dries out the gas pathway, minimizing the scrubbing effect. This is consistent with observations at the ERZ, where fresh, gas-charged magma is also close to the surface, and the hot, dry subsurface conditions have resulted in little scrubbing for the ERZ SO_2 signal. An open vent configuration provides a pathway from the magma to the atmosphere with no storage zone for water to scrub the magmatic gases.

An interesting dynamic of the Overlook Vent was observed in December 2008, when collapses of the vent produced a rubble-filled cavity, which, along with a decrease in vent temperature, and an increase in rainfall, fostered more chemically reducing conditions within the vent. H_2S emissions from the Halema‘uma‘u area, which are typically less than 1 t/d, increased by an order of magnitude, while the molar SO_2/H_2S dropped from typical values of around 1,000

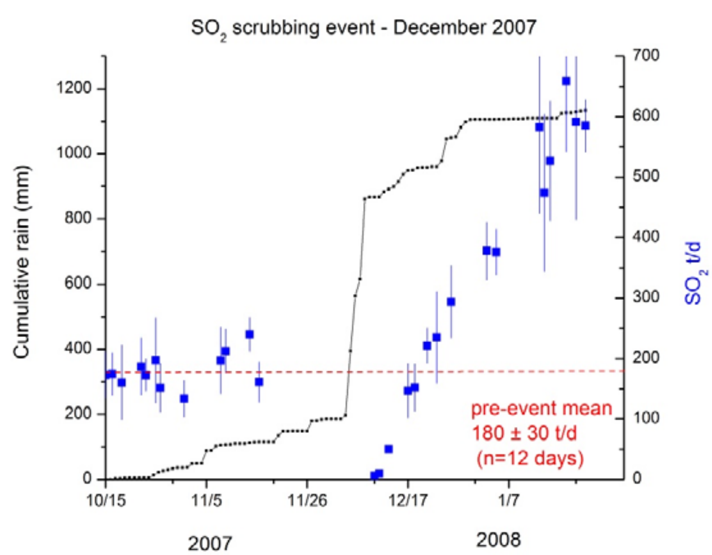

Figure 23. SO_2 in tonnes per day (t/d) and rainfall in millimeters (mm) as a function of time, Kīlauea summit. The 700-mm rain event in late 2007 effectively scrubbed SO_2 emissions. It took between 9 and13 days for the emissions to recover to the pre-event mean of 180 t/d. SO_2 data are presented without SRT-DOAS adjustments.

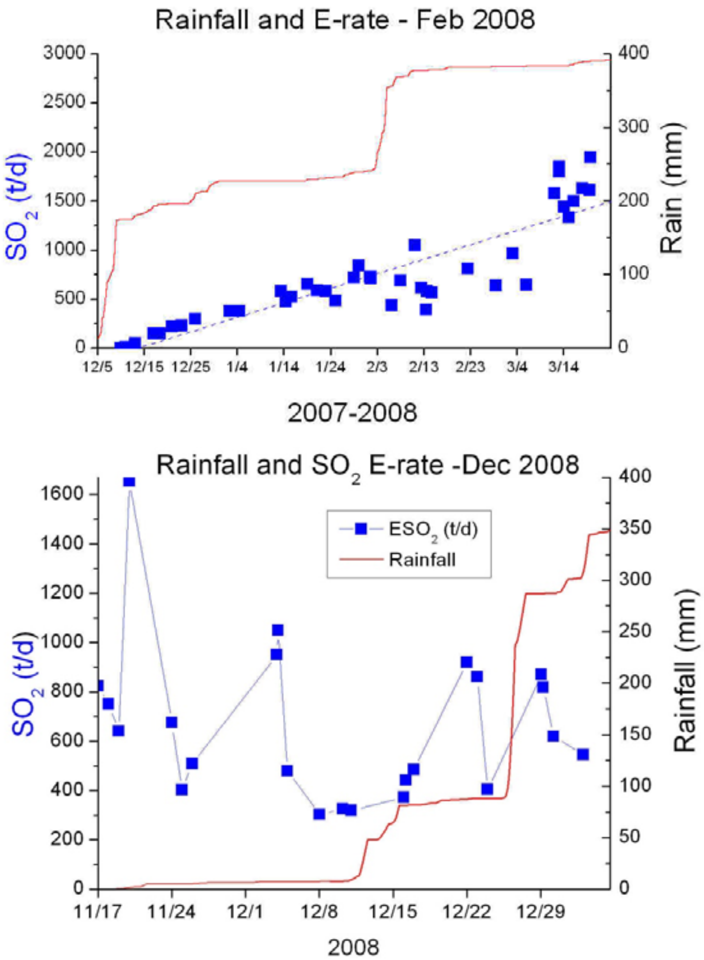

Figure 24. SO_2 in tonnes per day (t/d) and rainfall as a function of time, Kīlauea summit. While the steady increase in emissions in February 2008 (upper) was disrupted by a strong rainfall event, SO_2 did not appear to be affected by a similar-magnitude event in December 2008 (lower). SO_2 data are presented without SRT-DOAS adjustments.

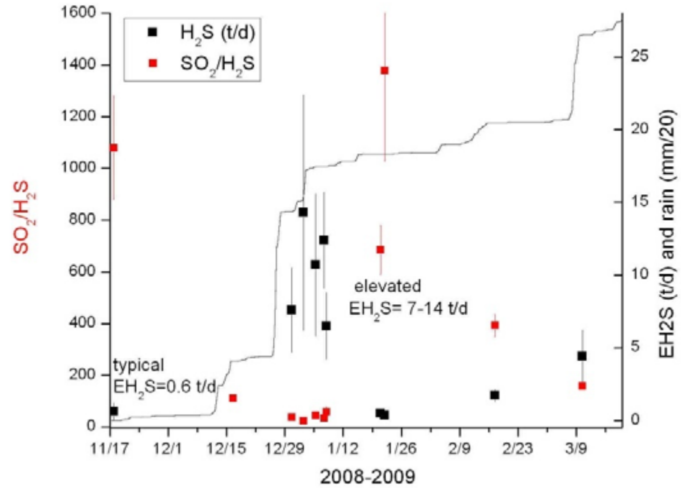

Figure 25. H_2S emission rate (EH_2S), rainfall, and SO_2/H_2S ratio time series, Halemaʻumaʻu area. An increase in H_2S emission rate (black) and decrease in SO_2/H_2S (red) was measured in mid-December 2008 and to a lesser extent in March 2009. Abbreviations: t/d, tonnes per day; mm, millimeter.

to less than 40 (fig. 25). The process of forming H_2S through the chemical reduction of SO_2 occurs at slight expense to the prodigious SO_2 emissions. Since a tonne of SO_2 converts to ~2 t of H_2S, the 7 t of H_2S measured on December 30 resulted in a decrease in SO_2 emissions of only ~3.5 t, or 0.5 percent on this day. The SO_2/H_2S ratios were measured with electrochemical gas detectors (Interscan Corporation) in ambient air along Crater Rim Drive directly downwind of Halemaʻumaʻu . H_2S emission rates are calculated using the integrated H_2S/SO_2 ratio as measured along Crater Rim Drive, their molecular weights, and the SO_2 emission rate, analogous to the CO_2 measurement technique detailed by Gerlach and others (2002).

East Rift Zone SO_2 emission rates and eruptive changes

East rift vehicle-based data

During 2007–2010, we continued to measure Kīlauea's integrated East Rift Zone (ERZ) SO_2 release by collecting emission-rate data along Chain of Craters Road as we routinely have done since 1992 (table 5 and fig. 26). These data have not been adjusted using SRT-DOAS. The original and SRT-DOAS adjusted ERZ SO_2 emission rates for 2007-2010 are presented in figure 27, emphasizing the limited period in 2008 that high column amounts were measured on the rift . The Puʻu ʻŌʻō area, the July 21, 2007, vents, and gas released from various sources along the ~10-km-long tube system were the main sources of SO_2 on the ERZ (fig. 1). The shifting vent locations resulted in different plume widths, densities, and locations as measured along Chain of Craters Road; however, the basic measurement technique was unaffected by the vent and eruptive changes manifested on the east rift. 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 on the order of 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). Changes in east rift emissions occurred with the pause after the Father's Day intrusion, the onset of the July 21 fissure eruption, the lead-up to the 2008 summit eruption, and the tilt inflection in mid-2008. A time lag is frequently observed for changes in gas emissions with observed eruptive and geophysical events. For instance, the July 2008 increase in

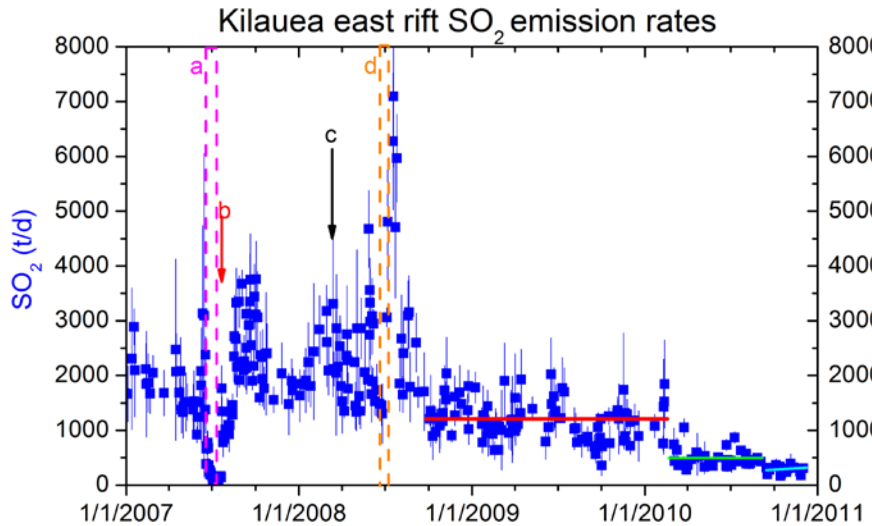

Figure 26. Average East Rift Zone (ERZ) SO_2 emission rates for 2007–2010. Vertical bars represent the standard deviation for all traverses on a single day. Letter codes: a, 12-day eruptive pause following Father's Day ERZ intrusion/eruption. b, onset of July 21 ERZ fissure eruption. c, summit Overlook Vent opens. d, summit tilt inflection indicates magma supply pulse. Horizontal red, green, and cyan lines indicate average SO_2 emission rates for September 2008 –February 2010, March 2010–September 2010, and October 2010 –December 2010, respectively. These data have not been adjusted using SRT-DOAS. Abbreviation: t/d, tonnes per day.

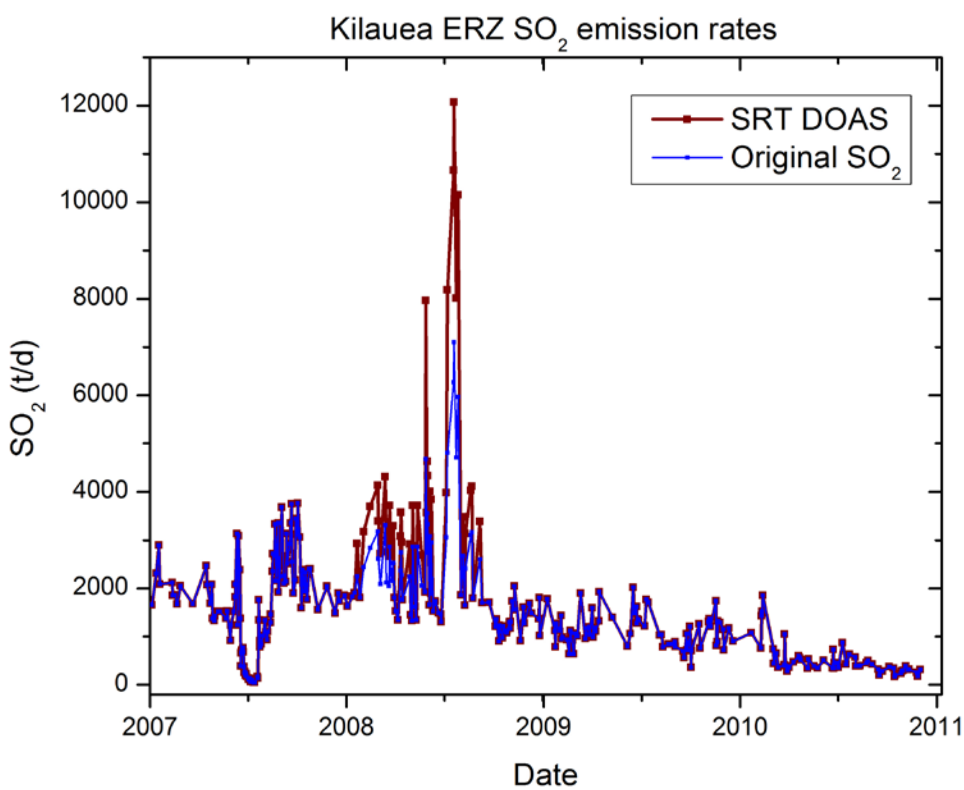

Figure 27. Original and SRT-DOAS corrected East Rift Zone SO_2 emission rates for 2007-2010. High column amounts were limited to values in 2008, thus only these were adjusted. Abbreviation: t/d, tonnes per day.

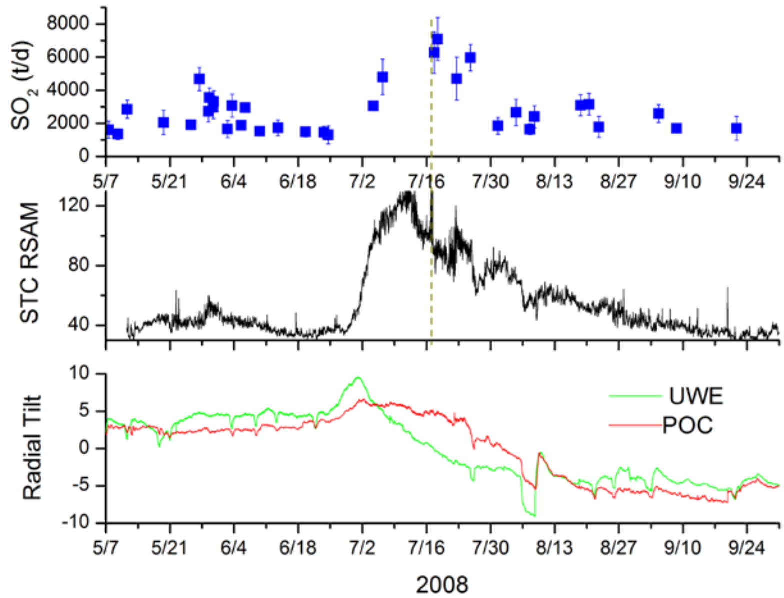

Figure 28. Daily average East Rift Zone (ERZ) SO_2 and standard deviation, 1-hour Steam Cracks (STC) RSAM, and Uwekahuna (UWE) and Pu‘u ‘Ō‘ō cone (POC) tilt, May-September, 2008. The increase in SO_2 emissions lagged behind the pulse in summit tilt, consistent with an increase in magma throughput of the summit reservoir to the ERZ. The SO_2 data have not been adjusted using SRT-DOAS. Abbreviation: t/d, tonnes per day.

ERZ SO_2 emissions was correlated with a spike in ERZ RSAM (Steam Cracks station) but followed the pulse in summit tilt and RSAM. This behavior is consistent with increased magmatic throughput of the east rift system (fig. 28). The July 2008 pulse is further supported by the observed dramatic increase in eruption vigor from the Thanksgiving Eve Breakout (TEB) vents, manifested as new, large tube breakouts and huge littoral explosions at the coast (Orr and others, 2008).

East rift emissions began to decrease in the fall of 2008, following the tilt inflection, likely due to dilution of magma bound for the east rift by material previously degassed at the summit. From October 2008 through February 2010, east rift emissions averaged ~1,200 t/d, σ =350 t/d, or approximately half the average measured between August 2007, following the Father’s Day eruption, through September 2008. Another significant decrease occurred in March 2010, with emissions from March through mid-September 2010 averaging ~500 t/d, σ =160 t/d. A further drop in emissions occurred in mid-September 2010, and emissions from September through the year’s end averaged only ~300 t/d, σ =70 t/d (fig. 26). East rift emissions have not been this low during periods of lava effusion since the Pu‘u ‘Ō‘ō–Kupaianaha eruption began in 1983. Significant effusion of lava from the ERZ continued (Tim Orr, HVO, written commun., 2010) during this unprecedented drop in emissions, supporting the idea of pre-eruptive degassing at the summit.

East rift scanning data

In November 2007 we quantified the emissions from the July 21 vent and Pu‘u ‘Ō‘ō to confirm the relative contributions from the two sources. Calculated emission-rate values indicated that Pu‘u ‘Ō‘ō remained the chief source of SO2 release, with the July 21, 2007, vent discharging only about 10 percent the amount of the Pu‘u ‘Ō‘ō emissions. This finding is consistent with data from the Infrasound Laboratory University of Hawai‘i (ISLA), which shows the TEB vent as a minor source of infrasound (Fee and others, 2011). Scanning measurements were also made in 2008 and 2010 from looking at individual degassing sources along the tube. Results confirmed that vents down tube of Pu‘u ‘Ō‘ō were minor emitters of SO_2. The 2007-2008 east rift measurements were made by scanning through the plume manually with the FLYSPEC mounted on a tripod, and the data reduced using a series of spreadsheets. The 2010 measurements were made using the FLYSPEC with an automated scanning mirror attachment and reduced using ScanCalc software. ERZ scanning results are presented in table 6. These data have not been adjusted using SRT-DOAS.

Total Kīlauea SO_2 emissions

Table 7 provides an estimate of the total integrated yearly SO_2 emissions for Kīlauea Volcano from 1992, when regular ERZ vehicle-based measurements began, through 2010. A revised estimate based on preliminary SRT-DOAS corrected data is included. Annual emissions were calculated by summing daily emission rates generated using a non-parametric digital filter (NPFD) (Peakfit software version 4, Jandel Scientific, San Rafael, California) for the summit and east rift datasets. This data treatment is discussed further in Sutton and others (2001). In addition, in order to examine the overall effect of variable emissions during summit lava pond cyclical rise/fall events, we calculated a summit emission rate for the last half of 2010 (when these events were frequent) taking into consideration the average drop in emissions during lava high-stand events, the average increase in emissions during the transition and subsequent low stands, and the documented occurrence of high-stand events, using local RSAM data. Summit emissions for July-December 2010 calculated using the high/low values are ~5 percent higher than those calculated using the NPDF treatment to calculate the annual budget presented above. The revised amount is well within the uncertainty of our measurement and data treatment methods.

Figure 29 shows the annual integrated SO_2 for Kīlauea since 1979, when emission-rate measurements began. The 2007-2010 time period includes the years with maximum and minimum annual SO_2 since the onset of the east rift eruption in 1983. Figure 30 shows the daily SO_2 emissions from Kīlauea's summit, east rift, and the combined emissions since 2002. By the end of 2010, sustained total emissions for Kīlauea were below pre-2002 levels. Figure 31 shows the relative contribution of the summit and ERZ on a daily basis as a percentage of the integrated amount of SO_2 from Kīlauea since 2000. The shift in relative contributions of SO_2 by the summit and east rift vent systems contributed to the increase in impacts on downwind communities (Longo and others, 2010a; b).

Based on Andres and Kasgnoc's (1998) inventory of global subaerial volcanic sulfur emissions, Kīlauea's 2007-2010 SO_2 average of 751,000 tonnes per year (0.75 teragram/annum, Tg/a) represents ~6 percent 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

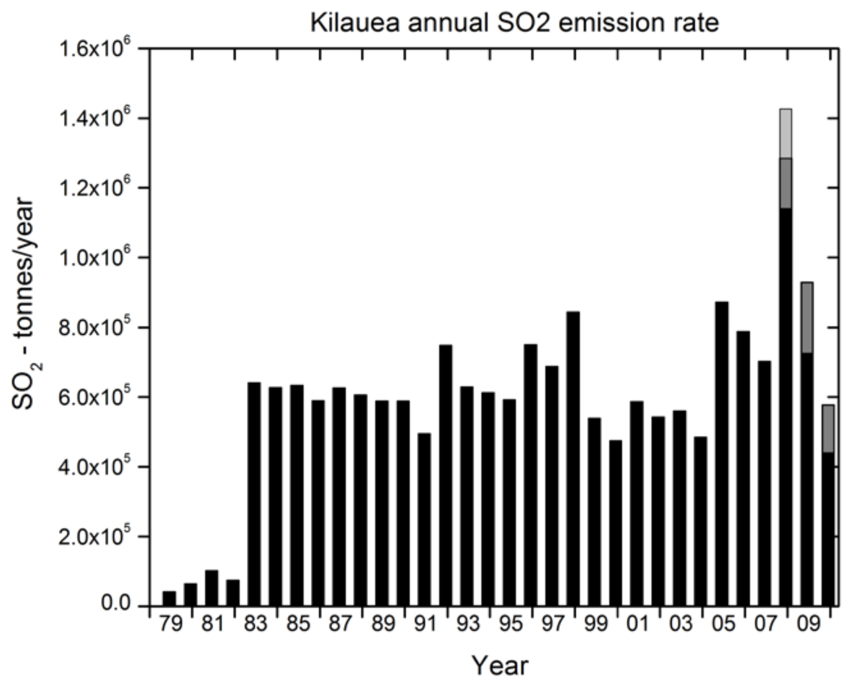

Figure 29. Kīlauea total annual emissions since measurements began in 1979, through 2010. The dark gray bars for 2008-2010 represent the additional annual emissions, taking into account preliminary SRT-DOAS adjustments for the summit. The light gray bar for 2008 (the only reported year likely to be significantly underestimated due to high column amounts) represents the additional annual emissions, taking into account preliminary SRT-DOAS adjustments for the East Rift Zone.

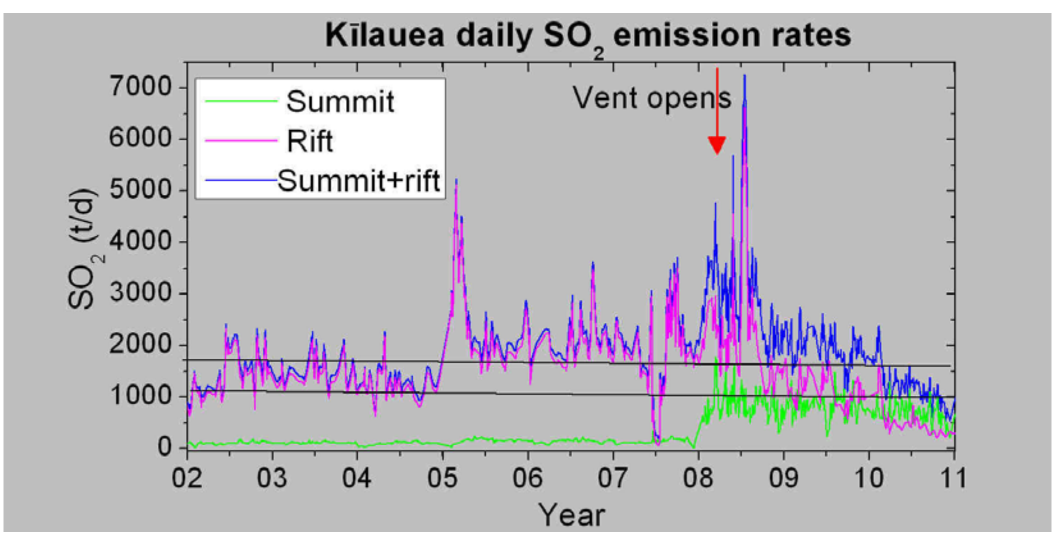

Figure 30. Daily SO_2 emissions from Kīlauea's summit, east rift, and the combined emissions since 2002. Daily values were derived by interpolating the field measurements using a non-parametric digital filter. The area between the horizontal lines indicates the typical range of values for 2002-2004. SO_2 data are presented without SRT-DOAS adjustments. Abbreviation: t/d, tonnes per day.

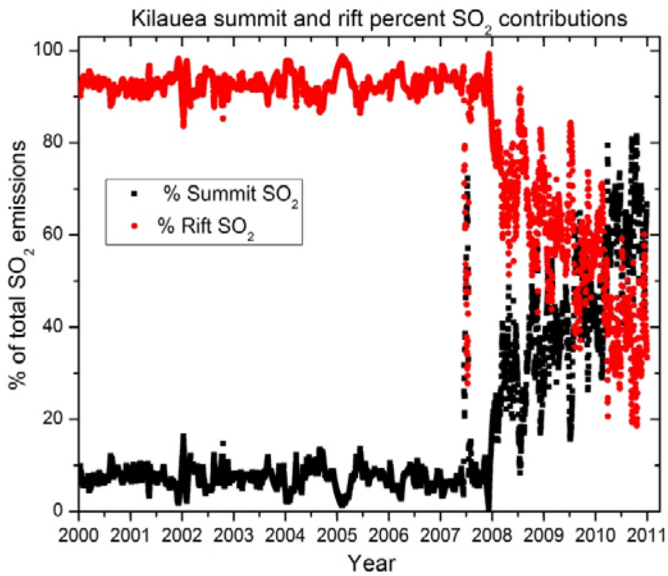

Figure 31. Summit and rift relative SO_2 contributions from 2000-2010 expressed as a percentage of Kīlauea's total SO_2 emissions. Daily values were generated using the non-parametric digital filter in peak-fit software. The data are presented without considering SRT-DOAS adjustments.

species present in the volcanic plume other than SO_2, we find that Kīlauea contributed <1 percent of the global sulfur emissions released through anthropogenic activities (Andreae, 1990; Bates and others, 1992; Spiro and others, 1992). The uncertainty in absolute emission rates due to unknown radiative transfer and other effects suggests that this value may change slightly upon more robust evaluation. Despite the relatively small proportion of Kīlauea's contribution to the atmospheric sulfur cycle, its emissions provide notable local and regional effects (Sutton and others, 1997; Longo and Yang, 2008; Longo, 2009; Longo and others, 2010a; b). The U.S. Environmental Protection Agency's 24-hour and 1-hour primary health standards for SO_2 were exceeded repeatedly on Hawaiʻi Island during 2007-2010 due to volcanic SO_2 (http://hawaii.gov/health/environmental/air/cab/index.html).

Future work

Areas for data improvement include incorporating radiative transfer model adjustments into the operational SO_2 retrieval algorithms, incorporating flexibility in analytical wavelength fit- window selection for more accurate fitting of wide ranging column amounts and expanded species quantification, measuring further downwind from the concentrated summit emission source, and developing a fixed, upward-looking spectrometer array for near real-time emission-rate monitoring.

Conclusions

The Kīlauea SO_2 emission rate dataset clearly showed the shallowing of magma in late 2007 and early 2008 heralding the eruption at the summit of Kīlauea. Kīlauea continues to be an excellent laboratory for developing gas study techniques and for examining how gas emission rates can be used with geophysical parameters to help constrain eruption dynamics. The recent dynamic activity at Kīlauea has highlighted the need for even higher frequency data acquisition and more flexible retrieval algorithms and robust analysis methods. For the 2008-2010 period, the uncertainty in absolute emission rates due to unknown radiative transfer and other effects is certainly larger than reported in previous years' data. While on first inspection it appears that the effect on Kīlauea's annual emissions is consistent with the generally reported uncertainty in these types of measurements, the errors systematically point to higher annual emission rates for 2008-2010. The errors in absolute emissions do not appear to mask short term changes to an extent that prohibits their usability for examining eruptive changes and degassing dynamics.

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