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Sulfur Dioxide Emission Rates from Kilauea Volcano, Hawai`i, an Update: 1998-2001

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INTRODUCTION

Sulfur dioxide (SO_2) emission rates from Kilauea 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). A compilation of SO_2 emission-rate and wind-vector data from 1979 through 1997 is available as Open-File Report 98-462 (Elias and others, 1998) and on the web at http://hvo.wr.usgs.gov/products/OF98462/. The purpose of this report is to update the existing database through 2001.

Kilauea releases SO_2 gas predominantly from its summit caldera and east rift zone (ERZ) (fig. 1), as described in previous reports (Elias and others, 1998; Sutton and others, 2001). These two distinct sources are quantified independently. The summit and east rift zone emission rates reported here were derived using vehicle-based Correlation Spectrometry (COSPEC) measurements as described in Elias and others (1998). In 1998 and 1999, these measurements were augmented with airborne and tripod-based surveys.

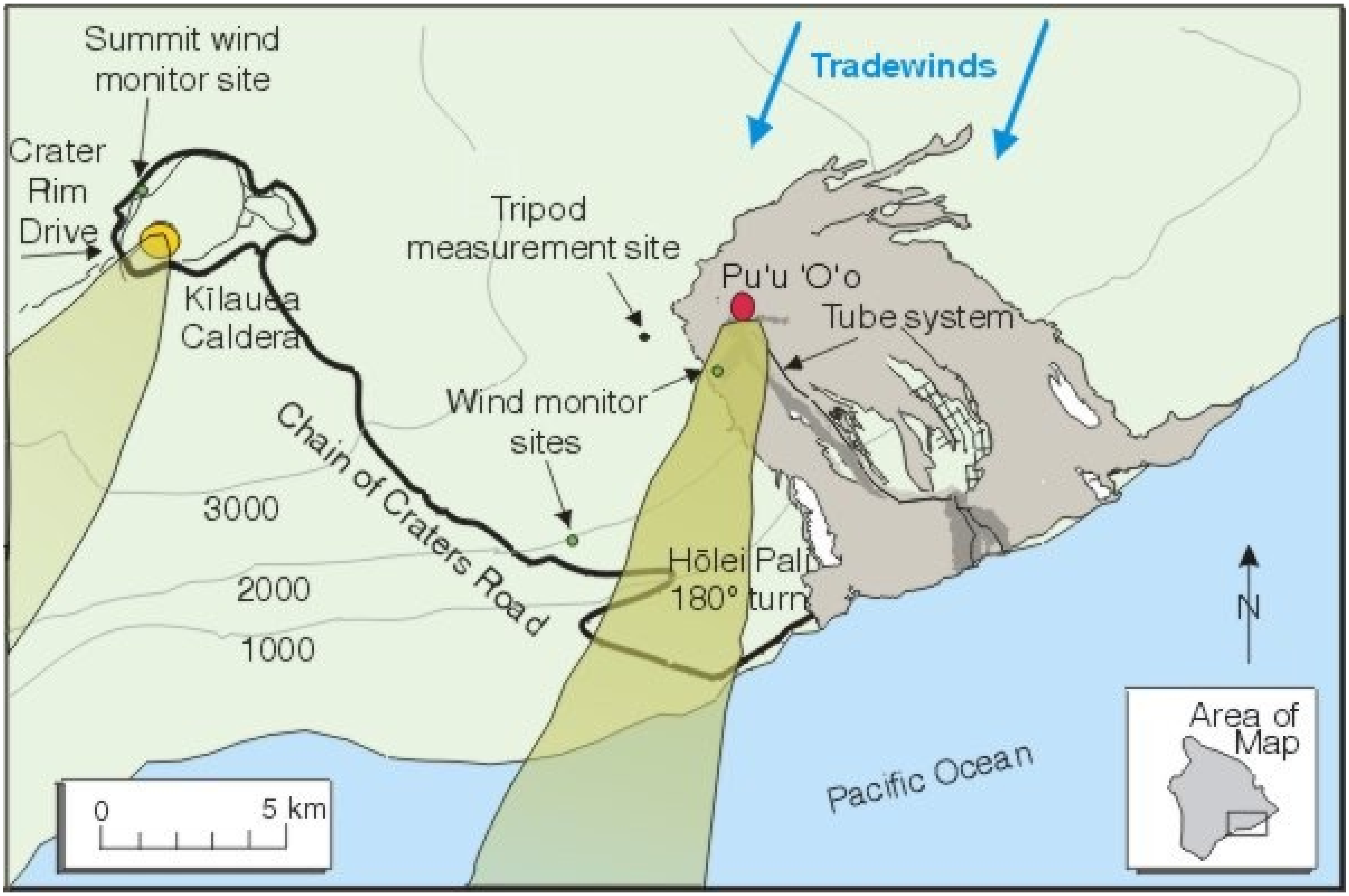


Figure 1. Summit and east rift zone of Kilauea Volcano. From 1979 through 2001, most of the SO_2 at Kilauea was released from the summit caldera and east rift zone. Vehicle-based COSPEC measurements were made on Crater Rim Drive and along Chain of Craters Road during trade-wind conditions to quantify summit and east rift zone SO_2 emissions respectively. In 1998 and 1999, airborne and tripod-based surveys made near Pu`u `O`o augmented the vehicle-based studies.

ACKNOWLEDGEMENTS

We are particularly grateful to the gas geochemistry volunteers at the Hawaiian Volcano Observatory (HVO), who contributed to these 4 years of data, including more than 350 days of measurements and 2300 plume traverses. These measurements were funded under the Volcano Hazards and Global Change Research Programs. Also, many thanks to the University of Hawai'i, Center for the Study of Active Volcanoes, for the extended use of their newly acquired COSPEC V. The timing of the acquisition was impeccable, as our COSPEC IV, which had faithfully made measurements at HVO for 22 years, began experiencing increasing amounts of instrumental problems.

METHODS AND UNCERTAINTIES

Instrumentation

From 1979, when regular COSPEC measurements began at HVO, through February 27, 2001, SO_2 measurements at Kilauea were made using a COSPEC IV correlation spectrometer, manufactured by Barringer Research Ltd., Toronto, Canada. During the period covered by this report, it was fitted with a high concentration disc assembly, calibration cells of 402 ppm and 1447 ppm, and a Cassegrain telescope.

Beginning on 3/13/01, measurements were made using a COSPEC V, manufactured by Resonance Ltd., which purchased rights to produce the instrument from Barringer in 2000. The COSPEC V is also fitted with a Cassegrain telescope, high concentration disc assembly, and has calibration cells of 410 ppm and 1395 ppm. The newer instrument has several advantages over the COSPEC IV, including a better signal-to-noise ratio, reduced sensitivity to light polarization, and an onboard data-acquisition system.

From 3/13/01-5/3/01, data were collected simultaneously with the COSPEC V and the COSPEC IV. Forty-three traverses were made over 7 days from a vehicle at the summit and ERZ to compare the data from the two COSPEC instruments. The two instruments were run side-by-side, looking either out the side door of a van, or from a vehicle tailgate.

We found no systematic difference in measurements made with the instrument oriented perpendicular vs. parallel to the line of travel of the vehicle. Since our COSPEC IV was experiencing increasing amounts of instrumental noise and baseline drift as 2001 progressed, the comparison of the two instruments was compromised by the poor data quality of the IV. Data collected at the summit were particularly prone to large discrepancies, as the low summit emissions (average=120 t/d) yielded a poorer signal to noise ratio compared to the ERZ data. Individual emission rate measurements for the COSPEC V and IV at the summit had a mean difference of 11 percent, standard deviation (sd)=21 percent, while ERZ measurements had a mean difference of -6 percent, sd=12.6 percent. We attribute the high variability between the instruments in part to the increasing baseline noise, drift, and offset in the COSPEC IV signal that occurred as 2001 progressed.

Figure 2 shows the average SO_2 emissions measured by the two instruments on a given day. The vertical bars, which represent the standard deviation of all traverses on a single day, reflect the variability in emission rate, as well as the effects of short-term changes in atmospheric and wind conditions. In contrast to individual traverse comparisons, we note that the difference in the average emission rates for each day of measurements are within the variability of the emissions themselves. Although the COSPEC V produced slightly higher average emission rates than the IV for the ERZ measurements for our comparison runs, no systematic difference between the two instruments was observed for individual traverses. The COSPEC V does yield slightly more variability in emission rates for the ERZ measurement set, as shown by the larger standard deviations measured by the V. No systematic difference between the instruments was observed at the summit, but the emission rates measured by the IV are generally more variable than those measured by the V, at least in part due to the lower signal-to-noise ratio of the IV data.

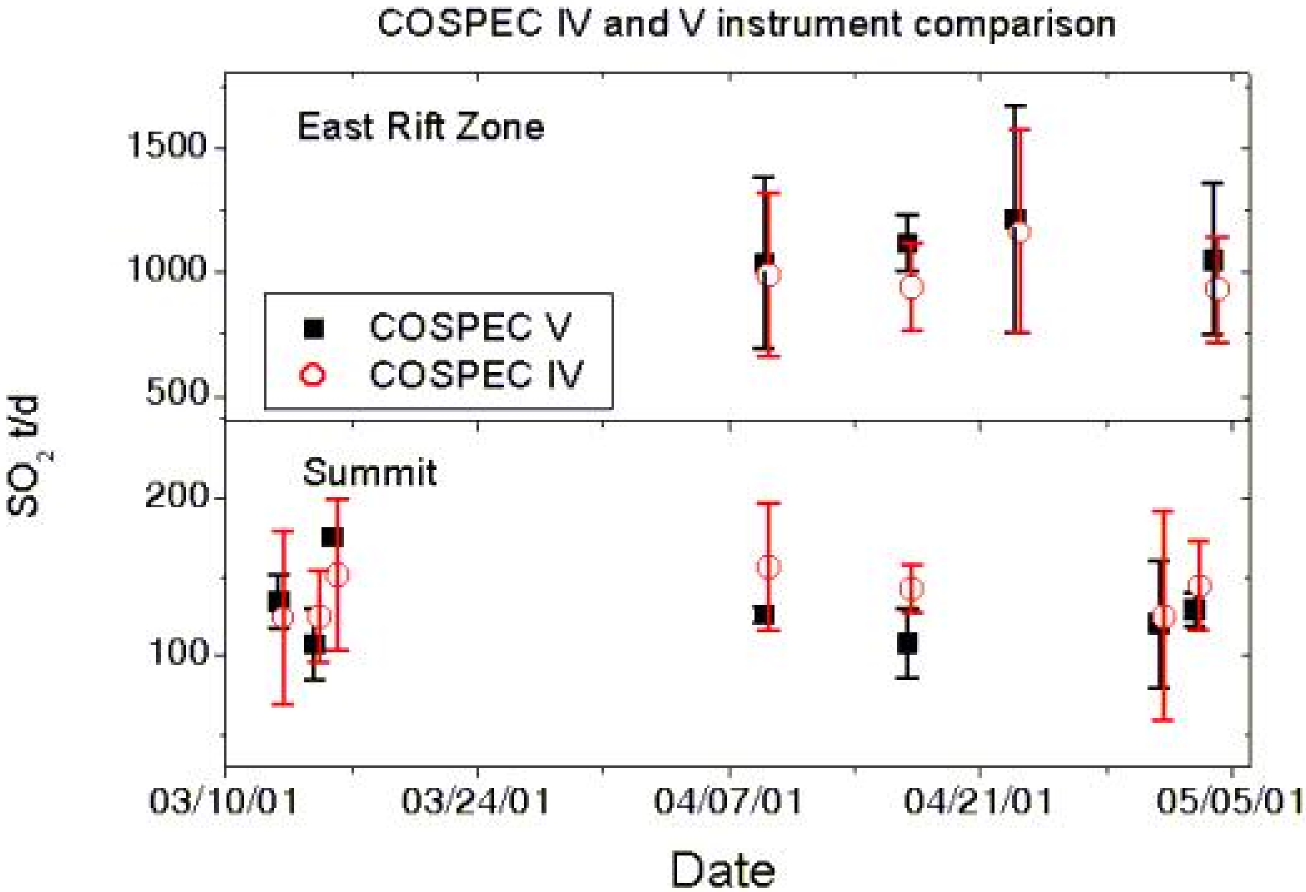


Figure 2. Average SO_2 emissions measured by the COSPEC IV (circles) and COSPEC V (squares). The vertical bars represent the standard deviation of all traverses on a single day. Although the COSPEC V and IV traverses were contemporaneous, the data are presented here with a slight temporal offset so that they can be viewed more easily.

We feel that the accuracy in the calculated SO_2 emission rates reported from Kilauea is not substantially affected by the change in instrumentation. Since we estimate our COSPEC measurements to have an associated uncertainty of 10-30%, the comparison shows that the emission rates calculated with the new COSPEC V are within the error of the measurements made with the old COSPEC IV.

Data collection and reduction

Since mid-1979, when regular COSPEC measurements began at HVO, data have been collected on an analog strip chart recorder and then manually digitized on a digitizing tablet; emission rates were calculated using a Fortran program. We began developing a digital data collection and reduction system in 2000 using a Handar 555 data logger. We wrote a program with a graphical user interface for calculating emission rates using the PC-based software application Origin (Originlab). Starting 3/13/01, all reported data were reduced using the PC-based program. From 4/20/00 to 4/3/01, during hardware testing and refinement and software development, data were reduced sporadically using both the analog strip chart/FORTRAN program and the new PC-based method. The average difference in individual emission rates between the two techniques is 1 percent, sd=11 percent. Average SO_2 emissions calculated for the Kilauea summit and ERZ using the two data reduction techniques are shown in figure 3. Several individuals reduced the data using the two techniques, so some error is attributed to individual differences, which is estimated at ~5 percent (Casadevall and others, 1987).

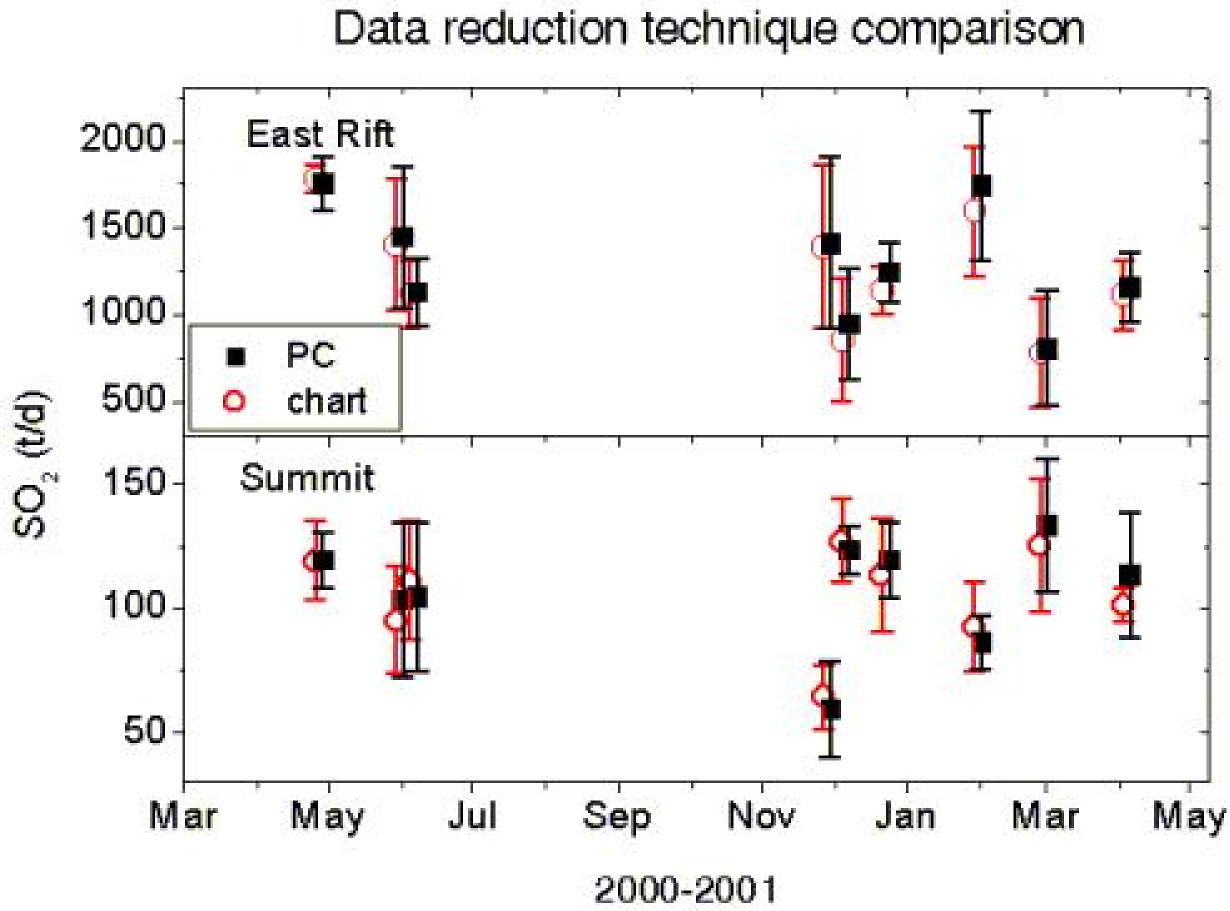


Figure 3. Average SO_2 emissions calculated for the Kilauea summit and ERZ from strip chart and PC-based data reduction techniques, as discussed in text. Although the data are contemporaneous, they are presented here with a slight temporal offset so that they can be viewed more easily.

Routine digital data collection was streamlined by the COSPEC V data-logging capability, which allows us to capture data directly using a palmtop or notebook computer. However, we continue to use an analog strip chart for in situ plume tracking and as back up in the event of computer failure in the field.

Summit vehicle-based data

The emission-rate measurements at the summit of Kilauea were made by vehicle-based COSPEC traverses within the summit caldera along Crater Rim Drive. We generally collect COSPEC data at Kilauea's summit when winds are greater than 3 m/s and from directions greater than 340° and less than 50°, as these conditions give rise to the best plume geometry and location. Casadevall and others (1987) and Elias and others (1998) describe details regarding this measurement technique. The data for 1998 through 2001 are shown in table 1 and figure 4.

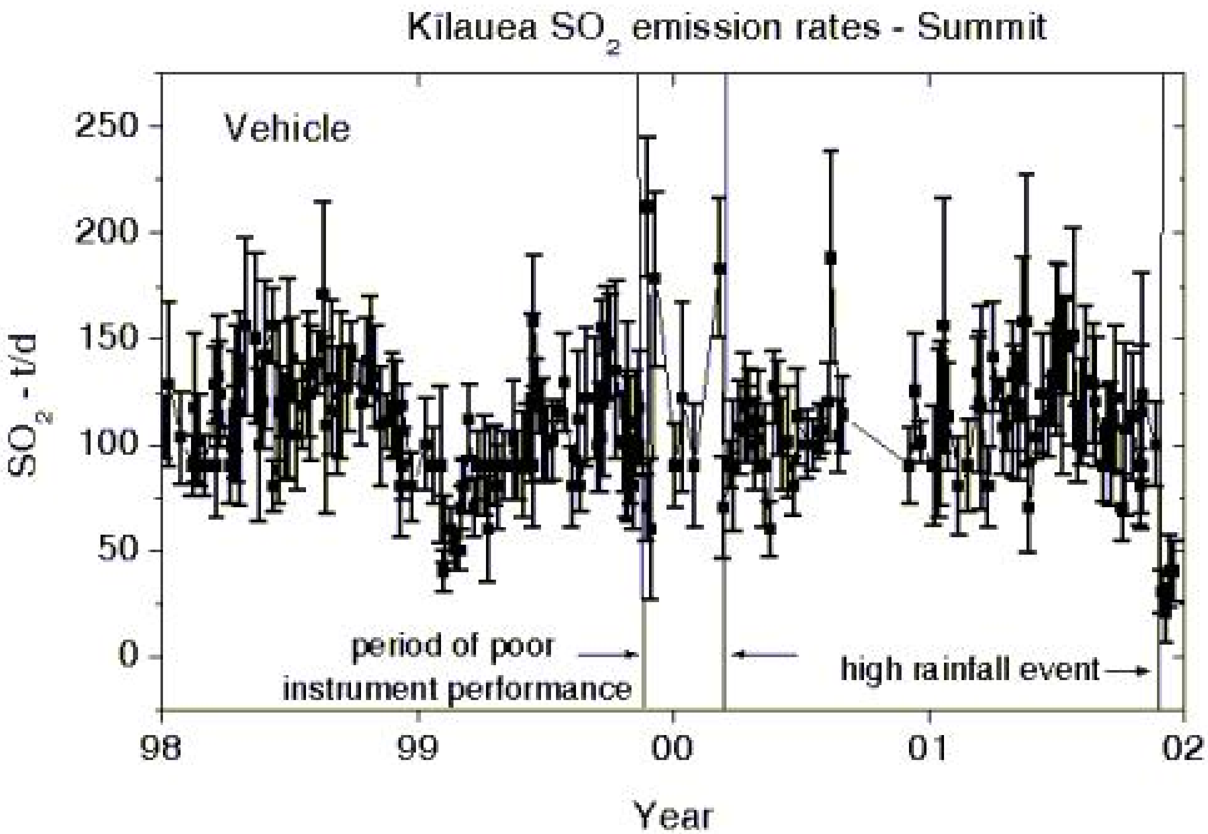


Figure 4. Averaged SO_2 emissions (t/d) from Kilauea's summit from January 1998 through December 2001. The black vertical bars represent the standard deviation of all traverses on a single day.

In order to quantify the copious amounts of SO_2 released regularly from the ERZ of Kilauea, the COSPEC is fitted with the high concentration disk assembly and associated calibration cells. This creates a challenge when quantifying the summit emissions, which are an order of magnitude lower than those from the ERZ. The low emissions at the summit cause any increase in background noise to introduce a high error to the measurements. From mid-November 1999 through March 7, 2000, a small but gradual increase in the COSPEC IV noise contributed to poorer quality summit data (fig. 4). The instrument optics and electronics sub-systems were tuned in early March 2000, restoring the COSPEC IV to good working order. The rest of the summit data for 1998 through 2001 are judged to be of good quality.

The low emission rates measured at the end of 2001 (fig. 4) are attributed to a high rainfall event at the summit of Kilauea (>590 mm over 48 hours on November 27-28). Since SO_2 is extremely water soluble, heavy rainfall can lead to the scrubbing of SO_2 gas as it rises to the surface through the water-saturated ground. By early January 2002, summit emission rates had returned to more typical values.

Wind velocities at the time of the summit COSPEC measurements were measured using a continuously recording wind monitor located 3.5 meters above the ground and 30 m northwest of the edge of the summit caldera (fig.1). We believe that data from this site give a reasonable representation of wind conditions at the elevation of the plume and contributes to an accurate estimate of the SO_2 released from the summit of Kilauea. Wind parameters were measured 4 m above the ground at several locations along the measurement path in the caldera to confirm that the data from the wind-monitor site were representative. From 1/1/98 through 9/7/01, wind data were collected using a bearing-based wind monitor (RM Young-model 05103). This conventional, helicoid propeller-vane type sensor is an industry standard used by the National Weather Service and other agencies nationwide to monitor wind speed and direction. In December 1999, we co-located an ultrasonic wind sensor (Handar-model 425A) with the conventional sensor on the northwest edge of the caldera. The ultrasonic sensor has no moving parts and thus may prove more consistent and durable in an acidic volcanic environment than the conventional sensor, which uses metal bearings and other parts susceptible to corrosion and wear.

Wind data from the period 1/1/01-9/12/01 show that the ultrasonic sensor yields wind speeds an average of 9.6 percent (sd=1.5 percent) higher than the conventional propeller-vane wind sensor (Fig. 5). However, our wind characterization experiments (Elias and others, 1998), as well as other Kilauea emission rate studies (Andres and others, 1989; Casadevall and others, 1987), report wind-speed uncertainties between 10% and 20- 30%; therefore, we incorporate the SO_2 measurements calculated with ultrasonic wind data into the ongoing 23 year Kilauea database without further correction. Mean wind direction difference between the sensors was 1.5 percent, sd=3.5 percent. Wind direction has much less impact on calculated emission rates than wind speed, and the variation in emission rates due to wind direction is insignificant.

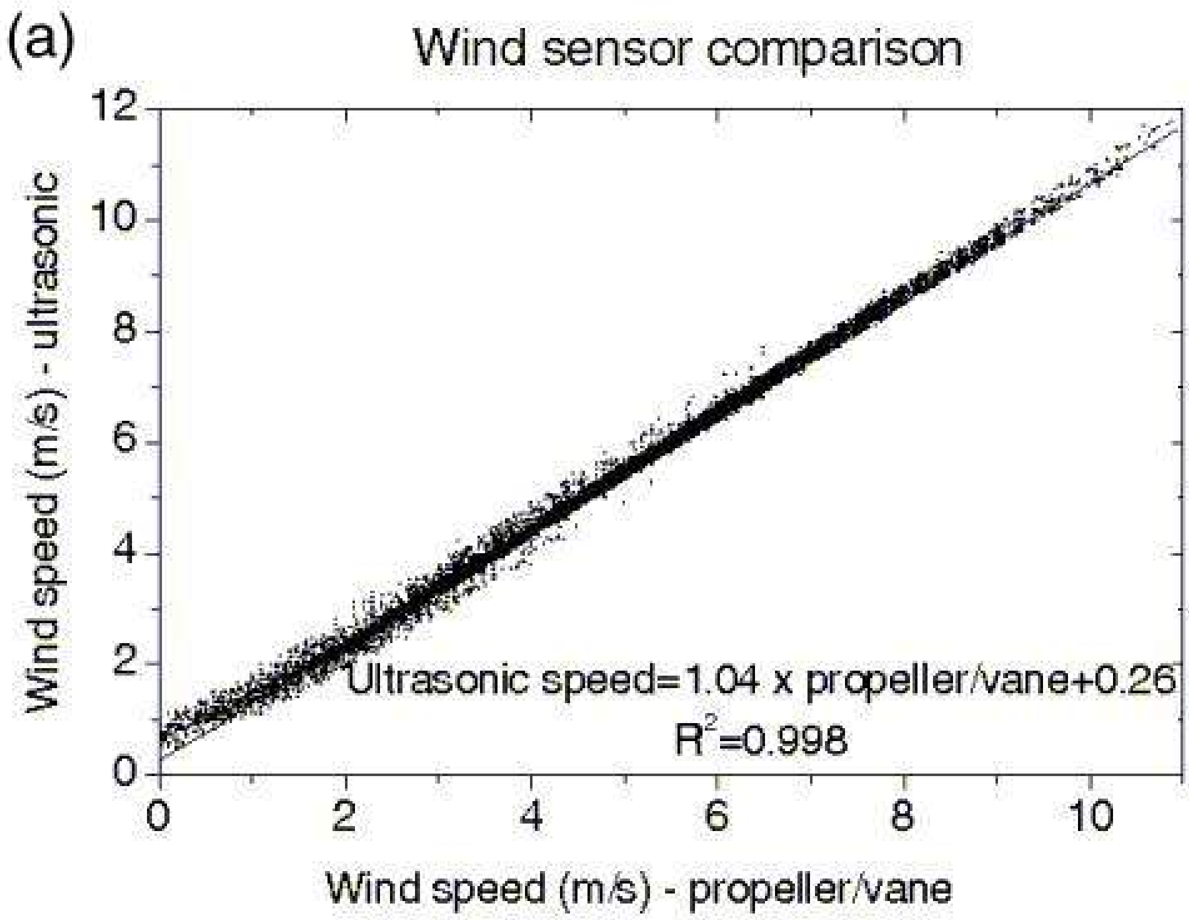
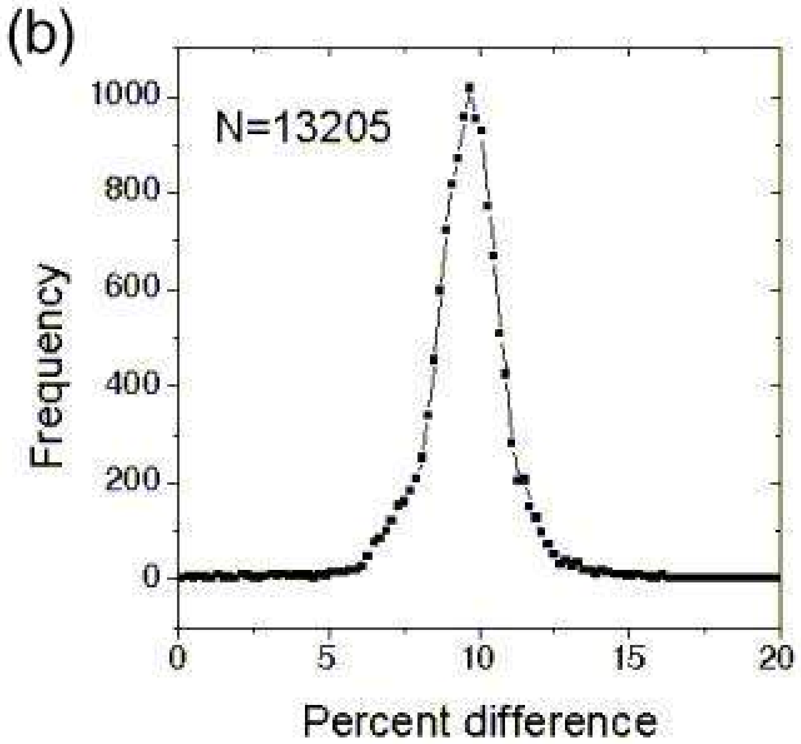


Figure 5. Comparison of RM Young propeller/vane-based wind sensor and Handar ultrasonic wind sensor. (a) Wind data from 1/1/01 to 9/12/01 show that the two sensors are linear for all wind speeds. (b) Frequency distribution of the percent difference in wind speed from the two sensors [(WSultrasonic-WSRMYoung) /WSRMYoung x 100] for 13205 data points with speeds greater than 3 m/s. The mean increase from the ultrasonic sensor is 9.6 percent, sd=1.5



percent.

East rift vehicle-based data

For wind with speeds greater than 5 m/s and directions between 25º and 40º east of north, gases from Pu'u 'O'o typically form a compact plume that crosses Chain of Craters Road above the 180º turn at Holei Pali (fig. 1). This turn marks the beginning of a steep section of the road that traverses down the pali (cliff). Vehicle-based COSPEC data obtained under these conditions typically provide the best-integrated estimate of Kilauea's ERZ SO_2 release (Elias and others, 1998; Sutton and others, 2001). When wind conditions at Pu'u 'O'o are sufficiently northerly, the entire ERZ plume crosses the Chain of Craters Road below Holei Pali. Often, these conditions yield a plume that clears the pali traveling toward the south, and then is turned toward the west by the easterly along- shore winds. Under these conditions, the plume, at times, lofts high above the road, because of the relief of the steep, 300-m pali. We do not report emission rates when the plume is widespread, with sections both above and below the 180º turn at Holei Pali, because traversing the same section of plume in two directions and at two elevations introduces added uncertainties. East rift zone vehicle-based data is presented in table 2 and figure 6. Figure 7 shows the averaged SO_2 emission rate for each day of measurements for the ERZ and summit, as well as the data after it was processed using a non-parametric digital filter and then smoothed using an FFT algorithm. A discussion of the data treatment is presented in Sutton and others, 2001. The low emission rates measured at the summit toward the end of 2001 attributed to high rainfall, were not mirrored in the east rift emissions.

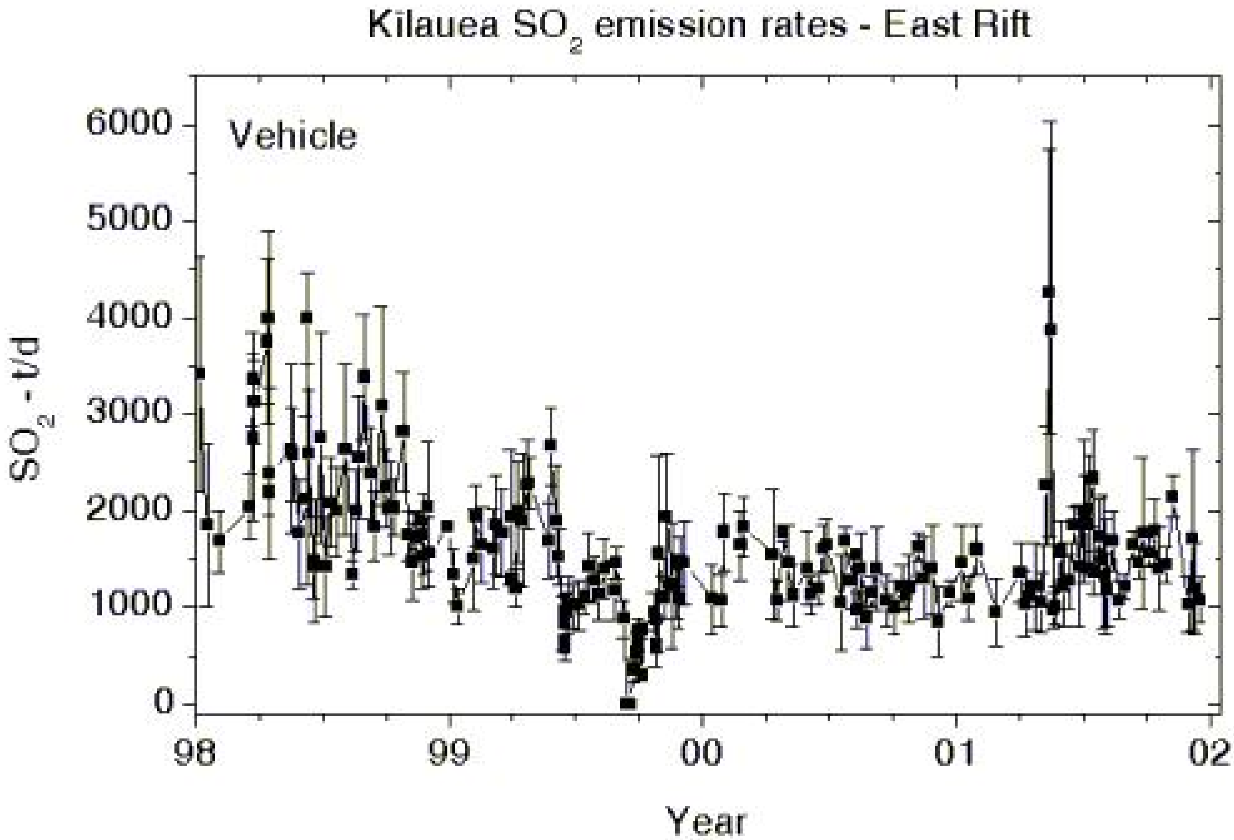


Figure 6. Averaged SO_2 emissions from Kilauea's east rift zone (ERZ) as measured by vehicle-based COSPEC along Chain of Craters Road, 1998 through 2001. The black vertical bars represent the standard deviation of all traverses on a single day.

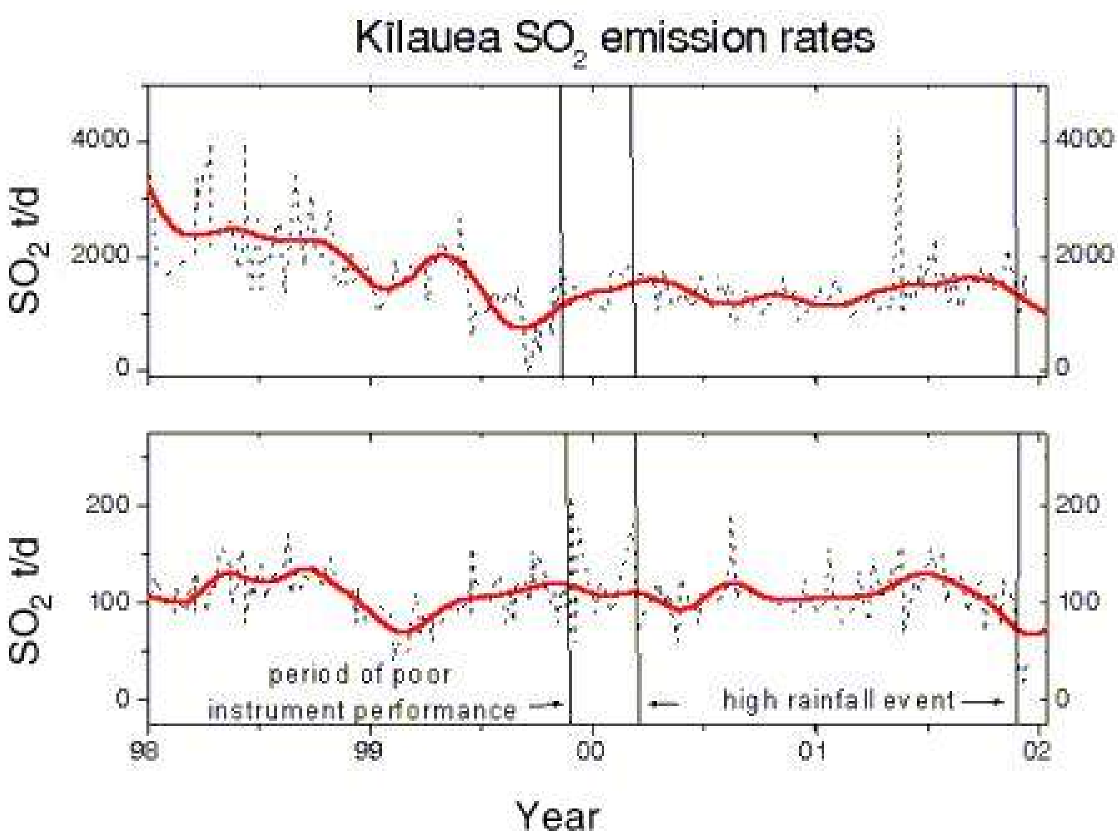


Figure 7. Kilauea summit and ERZ emissions for 1998-2001. Averaged SO_2 emission for each day of measurements is shown by the light, dotted line. The solid line represents FFT smoothing after data were processed with a non-parametric digital filter.

COSPEC measurements on Chain of Craters Road are made ~9 km downwind of the vent; therefore, some of the SO_2 gas has been converted to sulfate aerosol before reaching the measurement site. Porter and others (2002) used aerosol sun photometry, lidar, and COSPEC measurements along Chain of Craters Road to estimate a SO_2 half-life of 6 hours in the atmosphere. For wind speeds of 5-15 m/s, this suggests that ~3-8 percent of the SO_2 released from the vent would have converted to aerosol on its journey to the measurement site and would go undetected by the COSPEC.

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 180º turn on Chain of Craters Road (fig. 1). We believe that these data reasonably represent plume velocities above Holei Pali, because under these conditions the east rift plume is frequently close to the ground as it crosses Chain of Craters Road. For measurements made below Holei Pali on the coastal flats, wind conditions were determined using a combination of methods including 1) a portable continuous wind monitor located ~5.7 km below the 180º turn on Chain of Craters Road, 2) 5-minute wind-counter measurements made 4 m above ground level before and/or after a day's COSPEC traverses, and 3) continuous data from the wind station above the 180º 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.

On three occasions of brisk kona wind conditions (winds with a southerly component), gases from Pu'u 'O'o formed a reasonably compact plume that crossed Highway 11 between Volcano and Kurtistown, ~20 km downwind (north to north-northeast) of Pu'u 'O'o. For these traverses, wind speeds were measured using the 5-minute wind-counter 4 m above ground directly beneath the densest part of the plume. The uncertainty in wind speed measurements for east rift vehicle-based data is estimated to be 10-30 percent.

East rift tripod-based data

The few tripod-based measurements made during 1998 and 1999 are presented in table 3 and as filled circles in figure 8. A major collapse of Pu'u 'O'o in early 1997 (Heliker and others, 1998) contributed to an already diffuse degassing situation, with multiple vents, fissures, broad shields, tubes and skylights contributing to scattered degassing sources. The tripod-based measurements quantify parts of the plume from Pu'u 'O'o and the upper tube system but leave the contributions along the middle and lower tube system unquantified. These measurements provide important information on vent activity, but generally do not represent all of the east rift emissions.

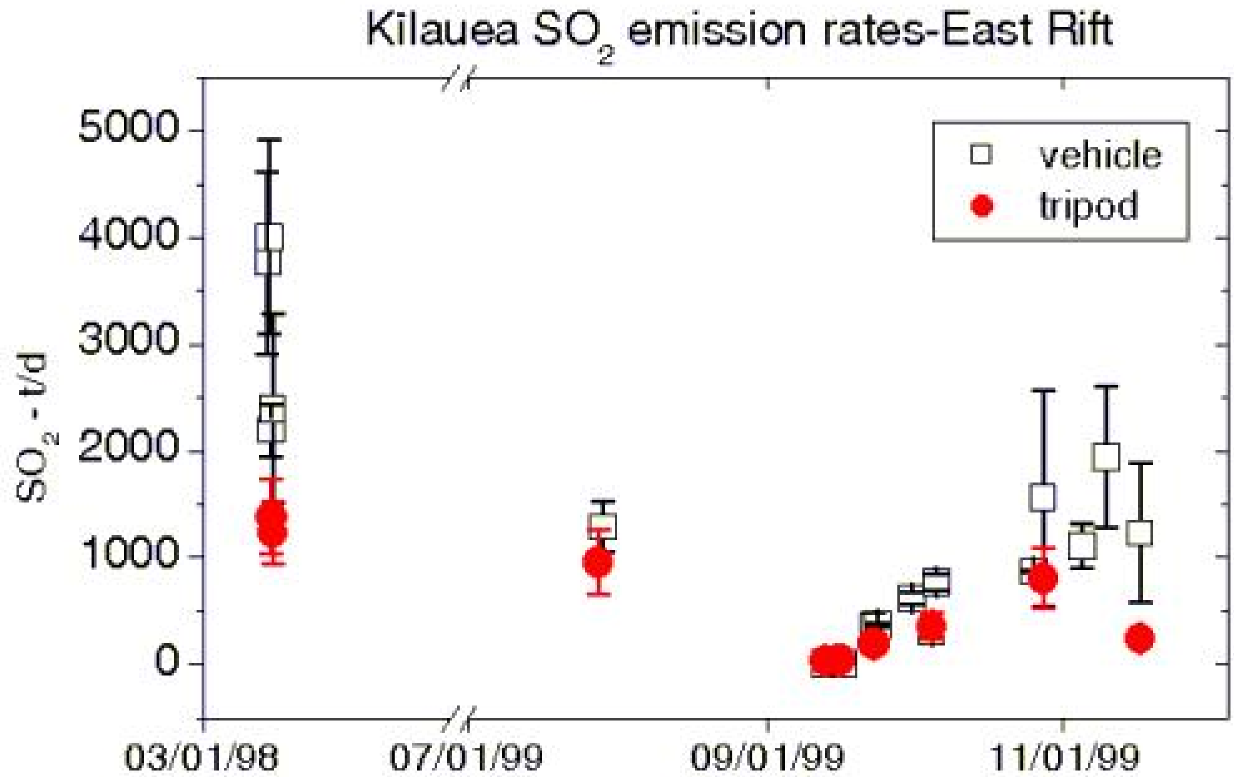


Figure 8. Averaged SO_2 emissions from Kilauea's east rift zone as measured by tripod- (filled circles) and vehicle-based (open squares) COSPEC for 1998-1999. The black vertical bars represent the standard deviation of all measurements on a single day.

Tripod-based campaigns during this time period were carried out primarily to support other studies (such as ground truthing for new SO_2 measurement techniques) or to provide data when emissions were too low to be quantified 10 km away on Chain of Craters Road. The measurements were made during periods of vigorous activity, eruptive pause, and variable pond activity. The April 1998 data are among the highest tripod-based measurements obtained during non-fountaining eruptive activity (Chartier and others, 1985; Elias and others, 1998; Sutton and others, 2001). The September-October 1999 measurements reflect the slow start-up of the eruption as it resumed on September 23 following an 11-day hiatus. The high variability in both tripod and road-based individual measurements on 10/28/99 coincides with periods of dynamic pond activity. Tripod measurements on this day ranged between 300 t/d and 1300 t/d, with a mean and standard deviation of 800 t/d and 290 t/d respectively, whereas measurements along Chain of Craters Road ranged between 700 t/d and 3300 t/d, with a mean and standard deviation of 1550 t/d and 1020 t/d respectively.

Wind velocities for the tripod-based data were measured with either a portable continuous wind monitor, a wind-counter mounted on a pole 4 m above the ground, or a continuous wind station located 1.5 km south-southwest of Pu'u 'O'o. We determined the distance to, and width of, the plume using helicopter-borne GPS or by visual estimation. All measurements were made from a site ~3 km southwest of Pu'u 'O'o, except for the 10/28/99 data, which were collected ~1.5 km north of our usual tripod site (fig. 1).

East rift and summit fixed-wing measurements

Airborne SO_2 measurements of gas emissions from the summit and east rift zone of Kilauea were made in May and June 1998 (table 4), the first such measurements for the summit and east rift zone since 1984 and 1995 respectively (Elias and others, 1998; Sutton and others, 2001). Wind speeds for the fixed-wing measurements were derived from continuous GPS position data taken during wind circle orbits (Doukas, 2002) and upwind/downwind traverses.

On the east rift zone, the vent geometry and multiple degassing sources give rise to a broad plume whose bottom is at ground level (McGee and Gerlach, 1998). Our orbits of Pu'u 'O'o, therefore, yielded SO_2 emission rates that represent minimum values, because some SO_2 was below the upward-looking COSPEC even on the lowest traverse, approximately 500 feet above ground level (agl). The ERZ airborne SO_2 emission rates are consistent with ERZ automobile-based emission rates from data collected on or about the same days.

Fixed-wing measurements flown 1 km downwind of Kilauea's caldera detected an unquantifiable amount of SO_2 in June, but in May, SO_2 was below the detection limit. Wind speeds were somewhat less during the June flight, causing the top of the plume to loft as high as 1525 m (520 m agl), whereas during the May flight, CO_2 measurements indicated that the top of the plume was at 1070 m (60 m agl).

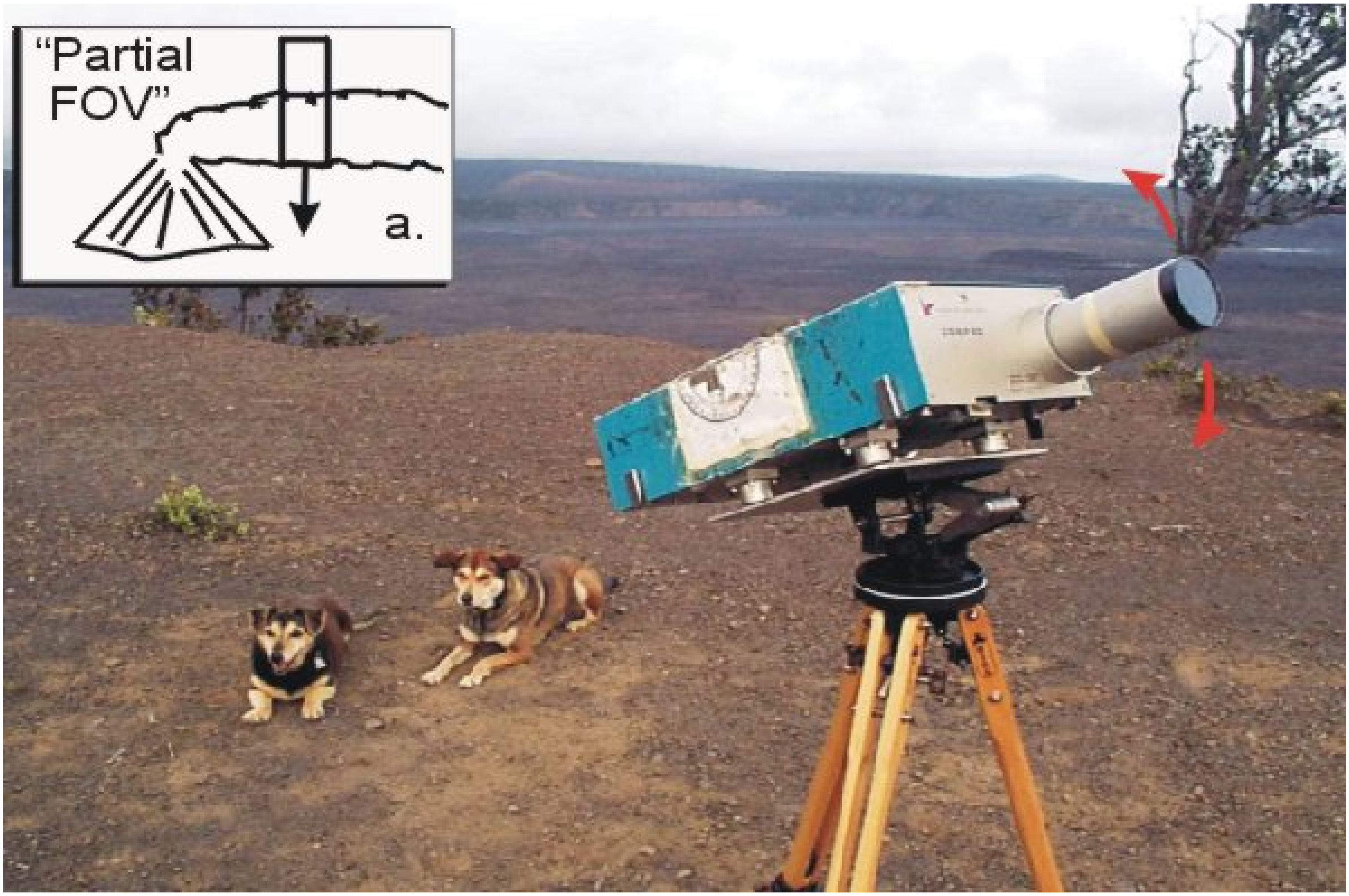
Total Kilauea SO_2 emission rates

Table 5 provides an estimate of the integrated yearly SO_2 emission rates for Kilauea during 1998-2001. Annual emission rates were calculated by summing the daily emission rates calculated using the filtered, FFT smoothed data for the summit and east rift.

Technique comparisons

As observed for earlier datasets (Andres and others, 1989; Elias and others, 1998; Sutton and others, 2001), Kilauea emission rates based on tripod measurements are generally lower than those based on vehicle measurements along Chain of Craters Road (fig. 8). An exception to this was observed as the eruption slowly resumed following the 11-day pause in September 1999. During this time, a thin wispy plume was released from Pu'u 'O'o, with minimal degassing from other locations. We were able to make measurements from a site relatively close to the plume, 100-800 m away, under varying conditions. The plume itself was reasonably compact at 150-600 m width. We found that tripod- and vehicle-based measurements agreed well when the plume was thin and emission rates were low, but the two techniques were less consistent once the plume increased in width and density.

Errors due to the COSPEC field of view (FOV) orientation can contribute to artificially low measured burdens (Millan and Hoff, 1978; Sutton and others, 2001). To determine the contribution of this effect, we made a series of measurements to compare scans collected with an instrument oriented flat, with the light entrance slits perpendicular to the horizontally moving plume, and with the COSPEC mounted on its side, so that the entrance slits were parallel to the plume axis (fig. 9). The flat configuration (fig. 9a) can result in a "partial FOV" effect; since the FOV has an aspect-ratio of 3:1, the COSPEC disproportionately combines radiant energy from clear sky with plume signal, effectively diluting the plume edges and resulting in artificially low measured burdens (Millan and Hoff, 1978). The original instrument manufacturer, Barringer, Ltd., recommends that the flat configuration be avoided when making tripod-based scans (Bob Dick, 1997, pers. com.).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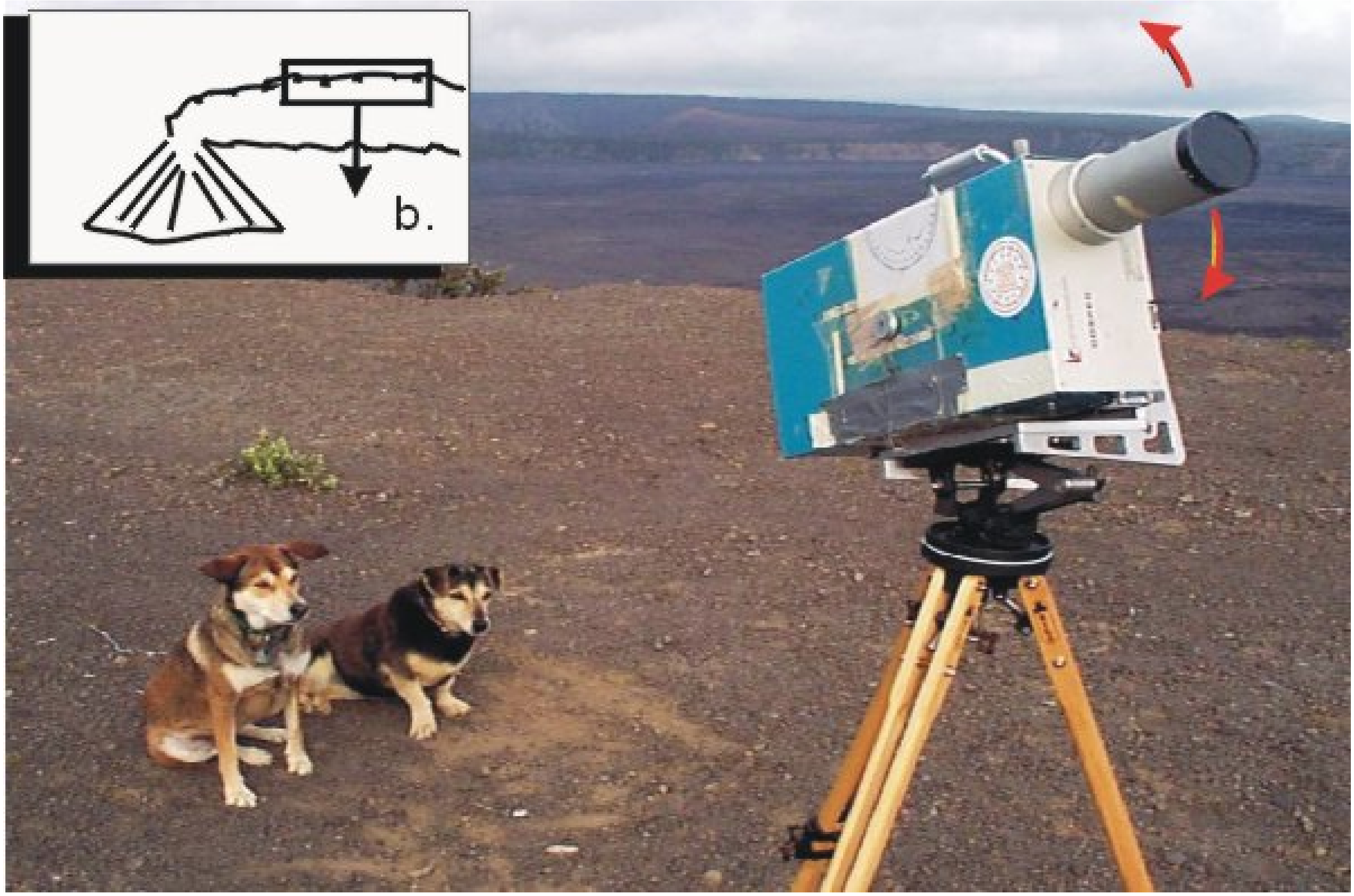

Figure 9. COSPEC IV oriented flat (a), with the light entrance slits perpendicular to the horizontally moving plume, and with the COSPEC mounted on its side (tipped) (b), so that the entrance slits are parallel to the plume axis. Red arrows indicate direction of plume scans.

A total of 90 tripod-based measurements on three separate days showed that for the Pu'u 'O'o plume measured from 200-1200 m away, the variability in emission source and other technique variables were greater than the variability due to the COSPEC orientation (fig.10). There was no statistically significant difference in the data from the two distinct orientations.

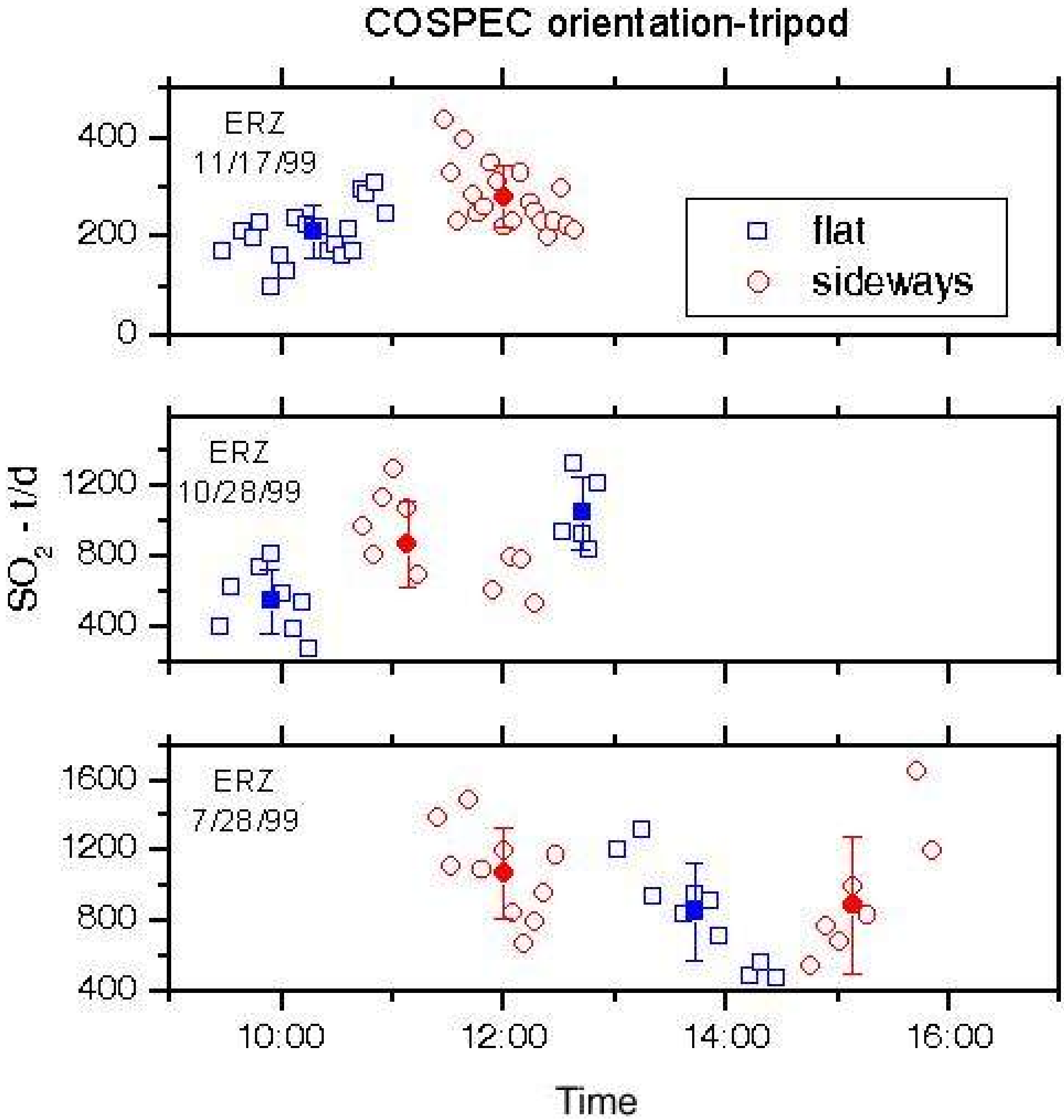

Figure 10. Individual SO_2 emission-rate measurements from Kilauea's east rift zone collected using a tripod-based COSPEC oriented flat (open squares) or sideways (open circles). Filled squares (flat), filled circles (sideways), and vertical bars represent averaged emission rate and standard deviation for a series of measurements.

A series of measurements was also made at the summit, where the SO_2 emission rate is more consistent, and the plume is closer. Forty traverses were made using a vehicle-based COSPEC oriented in the conventional flat, as well as the sideways, configuration. These results also showed that the difference in calculated emission rates using the two orientations was not statistically significant (fig. 11).

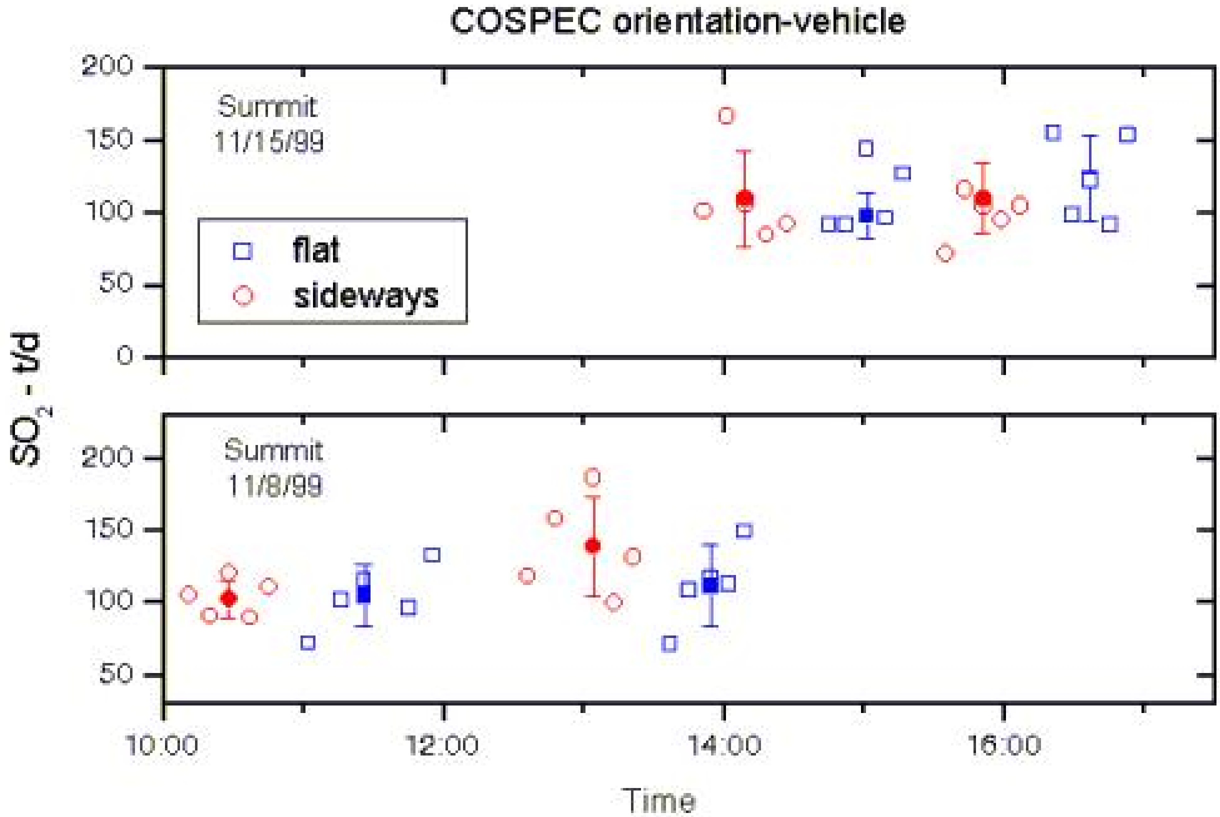

Figure 11. Individual SO_2 emission-rate measurements from Kilauea's summit as measured by vehicle-based COSPEC oriented flat (open squares) or sideways (open circles). Filled squares (flat), filled circles (sideways), and vertical bars represent averaged emission rate and standard deviation for a series of measurements.

REFERENCES

Andres, R.J., Kyle, P.R., Stokes, J.B., and Rose, W.I., 1989, SO_2 from episode 48A eruption, Hawaii: Sulfur dioxide emissions from the episode 48A east rift zone eruption of Kilauea Volcano, Hawaii: Bulletin of Volcanology, v. 52, p. 113-117.

Casadevall, T.J., Stokes, J.B., Greenland, L.P., Malinconico, L.L., Casadevall, J.R., and Furukawa, B.T., 1987, SO_2 and CO_2 emission rates at Kilauea Volcano, 1979-1984, chap. 29 in Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 771-780.

Chartier, T.A., Rose, W.I., and Stokes, J.B., 1985, SO_2 emission rates at Pu'u 'O'o vent, Kilauea between east rift zone phases 33 and 34 [abs.]: Eos, Transactions, American Geophysical Union, v. 66, no. 46, p. 1132.

Doukas, M.P., 2002, A new method for GPS-based wind speed determinations during airborne volcanic plume measurements. U.S. Geological Survey Open-File Report 02-395.

Elias, T., Sutton A. J., Stokes, J.B., Casadevall, T.J., 1998, Sulfur dioxide emission rates of Kilauea Volcano, Hawaii, 1979-1997. U.S. Geological Survey Open-File Report 98-462.

Greenland, P., Rose, W.I., and Stokes, J.B., 1985, An estimate of gas emissions and magmatic gas content from Kilauea Volcano: Geochimica et Cosmochimica Acta, v. 49, p. 125-129.

Heliker, C. C., J. P. Kauahikaua, J.P., Sherrod, D.R., Thornber, C.R. 1998, The rise and fall of Pu'u 'O'o cone, Kilauea Volcano, 1983-1998 [abs.]. Eos, Transactions, American Geophysical Union supp. v. 79(no. 45): p. F956.

McGee, K.A., and Gerlach, T.M., 1998, Airborne volcanic plume measurements using a FTIR spectrometer, Kilauea volcano, Hawaii: Geophysical Research Letters, v. 25, no. 5, p. 615-618.

Millan, M. M. and Hoff , R. M., 1978, Remote sensing of air pollutants by correlation spectroscopy - instrumental response characteristics. Atmospheric Environment v. 12: 853-864.

Porter, J. N., Horton, K. A., Mouginis-Mark, P. J., Lienert, B., Sharma, S. K., Lau, E., Sutton, A. J., Elias, T., Oppenheimer, C., 2002, Sun Photometer and Lidar Measurements of the Plume from the Hawaii Kilauea Volcano Pu'u 'O'o Vent: Aerosol Flux and SO_2 Lifetime. Geophysical Research Letters, 29 (16), 1783, doi:10.1029/2002GLO14744

Stoiber, R.E., and Malone, G.B., 1975, Sulfur dioxide emissions at the crater of Kilauea, at Mauna Ulu, and at Sulfur Banks, Hawaii [abs.]: Eos, Transactions, American Geophysical Union, v. 56, no. 6, p. 461.

Sutton, A. J., Elias, T., Gerlach, T.M., Stokes, J.B., 2001, Implications for eruptive processes as indicated by sulfur dioxide emission from Kilauea volcano, Hawaii, USA, 1979-1997. Journal of Volcanology and Geothermal Research v.108: 283-302.

Table 1.
Kilauea summit SO2 emission rates - vehicle-based

Date	SO2 (t/d)	SD	WS (m/s)	WD	N
01/06/98	110	20	5.5	32	5
01/12/98	130	40	4.1	30	6
01/29/98	100	20	7.0	27	6
02/13/98	90	10	4.3	28	6
02/17/98	120	40	4.0	30	6
02/24/98	100	20	5.0	35	6
03/03/98	90	10	4.6	28	6
03/18/98	130	20	6.6	34	6
03/19/98	90	30	3.2	40	6
03/23/98	130	30	6.5	30	6
03/24/98	120	30	5.9	30	6
04/08/98	90	20	3.7	35	6
04/14/98	110	30	7.9	30	5
04/15/98	110	20	6.2	35	6
04/18/98	120	40	5.2	21	6
04/22/98	120	50	6.4	30	6
04/29/98	160	40	6.2	16	6
05/15/98	150	40	4.6	31	4
05/19/98	100	40	5.5	36	6
05/27/98	120	20	5.0	25	6
05/29/98	140	40	6.8	35	6
06/08/98	160	20	6.1	17	8
06/10/98	80	10	5.3	39	4
06/17/98	120	40	5.5	35	6
06/21/98	120	20	6.4	41	6
06/26/98	110	20	6.5	33	6
06/30/98	130	50	5.3	35	6
07/06/98	140	20	9.1	26	6
07/13/98	100	30	5.4	39	6
07/21/98	120	20	5.4	30	5
07/30/98	130	30	6.4	40	6
08/02/98	120	30	5.2	27	6
08/13/98	140	10	6.7	35	4
08/19/98	170	40	9.3	32	6
08/24/98	110	40	6.9	40	6
08/31/98	130	40	6.8	38	6
09/08/98	120	30	4.4	35	6
09/14/98	130	30	6.4	30	6
09/24/98	130	20	3.8	34	6
09/28/98	140	10	5.6	34	6
10/13/98	120	20	7.0	34	6
10/20/98	140	20	4.5	23	5
10/26/98	150	20	8.0	35	6
11/02/98	130	20	5.4	33	6
11/09/98	110	30	4.5	36	6
11/18/98	110	10	3.9	37	6
11/27/98	120	30	6.1	29	7
12/01/98	120	20	5.9	42	6
12/09/98	80	20	5.0	39	6
12/10/98	90	20	5.8	28	6
12/11/98	120	10	6.7	37	6
12/24/98	80	20	3.4	33	6
01/13/99	100	20	3.8	34	6
01/25/99	90	20	7.4	47	6
02/04/99	90	40	5.8	21	6
02/08/99	40	10	6.0	32	6
02/09/99	60	20	6.0	37	6

02/17/99	60	10	3.1	34	6
02/23/99	50	10	4.4	42	6
03/03/99	50	10	3.1	40	6
03/05/99	70	10	4.6	35	6
03/08/99	80	10	5.0	45	6
03/09/99	80	10	6.8	36	6
03/16/99	110	20	6.0	42	6
03/23/99	70	10	6.0	30	6
03/30/99	90	20	7.2	14	6
04/07/99	90	20	5.2	43	6
04/12/99	60	30	3.5	43	6
04/16/99	90	20	7.5	27	5
04/23/99	90	20	6.0	38	5
04/27/99	80	20	5.0	40	6
05/06/99	90	20	4.2	37	8
05/19/99	100	30	4.5	38	6
05/25/99	90	20	9.3	35	7
06/01/99	90	30	5.2	32	6
06/07/99	100	20	5.2	37	6
06/14/99	120	40	3.9	31	7
06/15/99	90	30	5.5	45	7
06/17/99	160	30	9.5	12	7
06/21/99	130	10	5.9	38	6
06/24/99	120	10	6.8	37	7
06/29/99	110	20	9.2	36	6
07/06/99	100	20	6.0	38	7
07/14/99	100	20	4.3	30	6
07/21/99	120	5	8.1	30	6
07/30/99	130	20	5.8	38	6
08/10/99	80	20	3.9	39	7
08/19/99	110	30	4.2	38	6
08/23/99	80	10	6.8	49	6
08/30/99	120	30	6.6	37	6
09/13/99	120	30	6.9	30	6
09/17/99	100	20	5.8	43	6
09/20/99	100	30	6.3	38	6
09/23/99	160	10	6.8	36	3
09/24/99	120	30	7.7	45	6
09/29/99	150	30	6.5	46	6
10/04/99	150	20	6.1	40	6
10/12/99	140	40	5.4	37	5
10/22/99	100	20	4.3	39	6
10/25/99	100	40	4.3	49	6
10/28/99	110	50	4.8	45	3
11/01/99	100	30	5.0	45	6
11/05/99	80	20	6.3	40	6
11/08/99	110	30	4.5	38	20
11/15/99	120	30	4.9	38	20
11/24/99	70	20	5.2	47	6
11/26/99	210	30	8.1	33	5
12/01/99	60	30	2.9	33	6
12/07/99	180	40	5.8	41	6
01/04/00	90	20	5.6	46	7
01/14/00	120	50	7.1	21	3
02/01/00	90	30	7.0	26	5
03/07/00	180	30	4.9	46	6
03/13/00	70	20	4.9	37	2
03/23/00	90	10	6.7	34	6
03/28/00	90	30	6.6	37	4
04/06/00	110	20	4.8	33	6
04/12/00	120	30	8.2	29	6

04/19/00	110	20	7.8	37	7
04/20/00	120	20	8.1	27	4
04/26/00	100	20	7.0	38	6
05/03/00	110	20	7.3	38	6
05/10/00	90	30	6.7	38	6
05/19/00	60	10	4.3	63	6
05/24/00	130	20	3.6	34	6
05/30/00	120	20	5.8	41	6
06/05/00	100	20	6.3	42	6
06/13/00	100	30	5.3	33	6
06/21/00	80	10	5.5	33	7
06/27/00	110	20	6.0	20	6
07/10/00	100	20	3.5	28	6
07/19/00	100	10	4.9	35	6
07/28/00	110	10	5.6	34	5
08/03/00	110	10	6.1	38	6
08/10/00	120	20	6.2	24	6
08/14/00	190	50	4.5	30	6
08/25/00	100	20	6.9	39	6
08/31/00	110	20	6.3	40	6
12/05/00	90	20	3.8	43	6
12/13/00	130	30	4.8	35	8
12/20/00	100	10	5.7	34	2
01/08/01	90	30	3.4	35	6
01/16/01	110	40	3.0	27	10
01/18/01	110	40	4.8	33	5
01/22/01	160	60	7.6	13	5
01/29/01	110	30	4.5	38	8
02/13/01	80	20	4.7	41	5
02/27/01	90	20	5.6	39	6
03/13/01*	130	20	6.7	22	2
03/15/01	120	30	4.4	49	6
03/16/01**	120	50	6.5	52	2
03/27/01	80	20	4.4	15	6
04/03/01	140	30	11.1	20	5
04/09/01	130	5	5.5	25	5
04/17/01	110	20	6.0	30	5
04/23/01	110	10	5.7	27	5
05/01/01	120	40	4.5	29	8
05/03/01	130	10	5.3	30	5
05/08/01	110	30	5.2	29	4
05/10/01	120	20	5.2	31	6
05/15/01	160	30	5.5	36	7
05/21/01	160	70	2.8	25	11
05/23/01	70	20	3.4	15	3
06/04/01	100	10	4.1	29	4
06/11/01	120	30	5.9	19	8
06/21/01	110	20	6.4	6	6
06/26/01	130	20	9.0	8	5
07/03/01	150	40	5.0	5	5
07/06/01	160	30	8.0	7	5
07/11/01	130	40	6.2	24	9
07/17/01	150	20	7.8	21	6
07/26/01	150	50	5.1	10	6
08/01/01	100	20	6.5	33	6
08/03/01	100	20	5.9	23	3
08/06/01	120	30	6.3	14	5
08/13/01	130	40	7.8	20	5
08/23/01	130	30	6.4	15	5
08/28/01	120	30	5.8	12	6
09/07/01	90	20	5.0	12	6

09/12/01	110	20	6.8	30	5
09/17/01	100	30	7.7	30	6
09/25/01	120	30	8.3	32	6
10/04/01	70	20	4.3	30	6
10/09/01	110	40	8.3	20	6
10/18/01	110	30	7.8	26	6
10/29/01	80	20	8.3	31	6
10/31/01	90	30	8.7	10	3
11/01/01	120	30	9.2	16	6
11/01/01	120	60	8.5	19	6
11/21/01	100	20	3.7	25	5
11/29/01	30	10	4.5	28	6
12/06/01	20	10	6.2	32	6
12/11/01	40	20	6.0	27	6
12/17/01	40	10	8.1	23	6

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

*COSPEC V measurements begin
**COSPEC IV results (COSPEC V instrument problems)

Table 2.
Kilauea east rift zone SO2 emission rates - vehicle-based

DATA

DATE	SO2 (t/d)	SD	WS (m/s)	WD	N	LOCATION	CODE
01/06/98	3410	1210	6.8	12	6	L	C
01/16/98	1850	850	3.0	160	3	H	C
02/02/98	1690	320	7.9	11	4	L	C
03/19/98	2040	340	4.3	44	4	U	C
03/23/98	3360	490	9.4	11	6	L	C
03/24/98	2760	870	8.1	30	5	U	A
03/25/98	3130	440	9.9	25	3	U	C
04/14/98	3760	850	9.8	25	6	U	C
04/15/98	4000	900	7.3	35	6	U	B
04/16/98	2190	250	5.7	36	2	U	B
04/17/98	2390	890	7.6	35	7	U	A
05/18/98	2640	870	10.6	20	3	L	C
05/20/98	2580	480	4.9	66	2	U	C
05/29/98	1760	580	7.8	46	6	U	B
06/08/98	2110	870	7.3	35	8	U	C
06/10/98	4000	480	9.0	35	6	U	C
06/12/98	2590	670	7.7	25	6	U	A
06/19/98	1410	330	5.8	35	10	U	B
06/21/98	1480	630	7.9	40	7	U	C
06/30/98	2760	1100	7.0	38	7	U	C
07/06/98	1420	520	7.3	16	5	L	C
07/13/98	2080	460	7.7	33	6	L	C
07/21/98	1990	470	9.8	14	6	L	B
08/04/98	2630	880	9.4	30	9	U	A
08/14/98	1340	150	7.5	36	6	U	A
08/19/98	2000	430	10.2	20	6	L	A
08/24/98	2550	640	8.8	25	4	U	B
08/31/98	3390	640	9.2	20	6	L	B
09/08/98	2380	470	5.7	64	6	U	B
09/14/98	1840	350	6.9	47	6	U	B
09/25/98	3090	1040	5.4	50	4	U	C
10/01/98	2230	390	10.0	30	6	L	A
10/06/98	2020	480	8.7	18	4	UL	B
10/13/98	2030	280	10.0	20	6	L	B
10/26/98	2830	620	9.4	29	6	U	B
11/02/98	1740	260	6.0	54	6	U	B
11/09/98	1470	400	4.7	62	2	U	C
11/13/98	1710	260	7.9	47	8	U	B
11/19/98	1890	110	8.4	30	5	U	B
11/23/98	1520	340	8.2	38	3	U	B
11/25/98	1750	430	8.5	28	6	L	B
12/01/98	2040	670	8.6	30	2	U	A
12/02/98	1570	350	7.5	38	6	U	B
12/30/98	1830	0	5.0	190	1	H	C
01/07/99	1330	280	3.0	130	4	H	C
01/13/99	1000	190	5.2	50	6	U	C
02/05/99	1490	530	7.2	40	6	U	B
02/09/99	1940	320	7.4	23	6	U	B
02/17/99	1640	390	5.6	62	6	U	B
03/05/99	1600	410	4.2	55	5	U	C
03/09/99	1850	510	6.1	45	13	U	B
03/18/99	1770	460	9.1	32	8	U	C
03/30/99	1930	700	8.5	30	4	U	C
03/31/99	1300	0	7.0	58	1	U	C
04/02/99	1300	60	5.7	38	2	U	C
04/07/99	1190	200	6.4	63	2	U	C

04/09/99	1980	530	8.6	37	6	U	A
04/16/99	1900	690	6.9	46	7	U	B
04/23/99	2270	470	9.0	24	6	U	A
04/27/99	2280	260	6.0	50	3	U	B
05/24/99	1690	400	10.2	41	7	U	A
05/27/99	2670	410	6.4	49	2	U	B
06/04/99	1890	580	6.6	37	7	U	A
06/08/99	1530	290	8.0	35	6	U	A
06/15/99	830	280	5.7	44	6	U	B
06/16/99	650	220	7.9	50	6	U	B
06/17/99	580	130	8.4	46	5	U	A
06/18/99	950	170	6.8	28	7	U	A
06/21/99	1020	130	7.7	45	2	U	A
06/22/99	1020	300	6.7	45	6	U	B
06/29/99	1010	230	7.1	34	7	U	B
07/07/99	1020	260	6.4	51	6	U	B
07/14/99	1100	180	6.6	48	6	U	B
07/21/99	1420	360	6.2	54	4	U	A
07/29/99	1280	240	6.8	42	6	U	A
08/05/99	1120	250	7.8	51	6	U	A
08/12/99	1400	310	8.5	36	6	U	A
08/26/99	1170	310	9.7	31	6	U	C
08/30/99	1460	170	8.8	29	5	UL	C
09/09/99	880	200	6.9	47	6	U	B
09/13/99	BDL	--	10.0	20	2	L	NA
09/17/99	BDL	--	5.7	80	2	UL	NA
09/23/99	350	120	7.3	40	7	U	B
09/24/99	360	20	6.3	53	3	U	B
09/27/99	540	200	7.0	25	4	L	C
09/30/99	750	140	7.0	30	3	L	B
10/01/99	610	60	7.6	70	5	U	C
10/05/99	300	60	6.8	64	5	U	C
10/06/99	760	80	7.6	67	4	U	C
10/22/99	950	200	6.5	30	5	L	C
10/25/99	600	220	6.5	58	6	U	B
10/26/99	870	1	8.7	38	2	U	C
10/28/99	1550	1020	6.0	50	6	U	C
11/05/99	1100	210	7.4	33	6	U	A
11/10/99	1940	670	7.5	28	6	L	C
11/17/99	1220	650	8.0	9	5	L	C
11/24/99	1220	330	7.2	44	6	U	C
11/26/99	1090	300	10.2	29	6	U	B
11/29/99	1460	260	12.9	50	6	L	B
12/06/99	1460	430	8.9	48	6	U	C
01/14/00	1080	360	9.0	25	5	L	C
01/27/00	1070	270	10.7	40	5	L	B
02/01/00	1780	400	5.6	35	6	U	B
02/24/00	1640	360	5.5	50	3	U	C
02/28/00	1830	310	9.0	35	5	U	C
04/10/00	1550	670	7.9	37	8	UL	B
04/17/00	1070	200	7.1	50	6	U	A
04/26/00	1780	80	7.1	30	6	L	A
05/03/00	1460	400	7.9	37	7	U	B
05/10/00	1120	320	6.7	31	6	U	B
05/30/00	1400	380	6.9	20	6	UL	B
06/05/00	1120	190	6.7	31	4	U	A
06/15/00	1190	170	5.6	28	5	U	A
06/22/00	1600	240	7.4	21	7	U	B
06/27/00	1640	270	6.8	13	5	U	B
07/19/00	1040	500	5.7	27	4	U	C
07/24/00	1680	150	8.1	22	7	U	A

08/03/00	1270	280	12.7	354	5	L	B
08/10/00	1540	0	27.0	7	1	U	C
08/11/00	960	180	21.0	6	4	U	B
08/16/00	1400	360	7.0	9	6	L	B
08/24/00	890	310	8.3	25	6	U	B
09/01/00	1160	160	6.2	25	5	L	C
09/08/00	1400	440	5.5	45	6	U	C
09/22/00	1070	260	8.3	30	6	L	B
10/03/00	990	270	6.2	30	8	U	B
10/13/00	1210	240	9.0	25	7	U	B
10/20/00	1110	130	9.0	50	4	L	B
10/24/00	1200	350	7.5	30	4	L	B
11/08/00	1620	140	7.2	22	6	U	A
11/14/00	1300	420	8.4	21	7	U	C
11/27/00	1390	470	7.9	19	9	U	B
12/05/00	850	350	4.9	44	6	U	C
12/22/00	1140	140	9.9	20	4	L	B
01/08/01	1470	400	9.9	18	7	L	C
01/18/01	1090	220	5.8	53	3	U	C
01/30/01	1590	260	6.4	17	6	U	C
02/27/01	950	340	5.6	50	6	U	C
04/03/01	1360	320	9.0	30	6	U	B
04/09/01	1040	350	8.0	21	7	U	B
04/17/01	1110	110	7.5	15	2	U	B
04/23/01	1210	460	7.5	15	5	U	C
05/04/01	1050	310	7.4	100	2	U	C
05/10/01	2260	610	6.7	32	7	U	B
05/15/01	4270	1480	7.5	30	6	U	C
05/16/01	3880	2150	7.0	19	5	UL	C
05/21/01	960	180	6.3	88	5	L	C
05/23/01	1010	200	5.0	22	4	U	C
05/31/01	1570	320	4.4	29	7	U	C
06/04/01	1220	430	5.1	39	7	U	C
06/11/01	1270	280	7.5	26	7	U	B
06/19/01	1850	180	10.5	357	8	L	C
06/26/01	1420	630	15.3	358	8	L	C
07/03/01	1990	740	7.1	22	9	U	B
07/06/01	1860	510	8.9	19	8	U	C
07/11/01	2010	560	5.8	32	6	U	B
07/16/01	2330	510	14.0	0	10	L	C
07/17/01	1360	230	7.5	21	6	U	B
07/26/01	1730	390	5.1	25	10	U	B
07/31/01	1470	700	8.5	15	10	U	A
08/03/01	1320	600	6.9	19	6	U	A
08/06/01	1180	390	8.2	16	5	U	B
08/13/01	1690	310	10.5	12	7	U	A
08/23/01	1080	190	6.8	25	5	L	C
08/30/01	1210	120	8.2	27	6	U	A
09/12/01	1640	140	8.0	15	4	UL	C
09/21/01	1460	160	6.4	33	6	U	A
09/25/01	1770	780	9.2	15	4	L	B
10/05/01	1570	160	11.5	14	6	U	B
10/12/01	1790	340	6.8	22	6	U	A
10/19/01	1400	430	8.5	39	5	U	A
10/30/01	1440	190	8.5	12	6	L	B
11/09/01	2150	220	11.5	17	6	L	C
11/30/01	1020	280	5.5	33	6	U	B
12/07/01	1700	930	6.3	31	4	UL	C
12/10/01	1190	470	7.1	34	6	U	C
12/18/01	1080	240	12.8	21	7	U	A

Data Quality Codes:
A - BEST QUALITY DATA -usually with strong, steady wind conditions, and a compact, consistent plume shape.

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.

C - ACCEPTABLE DATA - may have inconsistent plume location and shape. Wind speed and direction may be variable or poorly constrained. Some runs may measure a partial plume, representing minimum constraints on emission rates. Measurements with instrument inconsistencies are included in this category.

Location Codes:
U- Above the 180° turn at Holei Pali (upper Chain of Craters Road)
L- Below Holei Pali (lower Chain of Craters Road)
UL-traverses above the 180° turn at Holei Pali and below Holei Pali
H- Highway 11

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

Table 3.
Kilauea east rift zone SO2 emission rates - Tripod-based

Date	SO2 (t/d)	SD	WS	WD	N	plume distance by:	Data code
04/16/98	1380	340	6.7	24	16	flown under similar winds	A
04/17/98	1230	290	8.2	31	20	flown	A
07/28/99	960*	310	7.4	32	27	flown	A
09/13/99	40	10	8.3	25	11	estimated	C
09/16/99	40	5	5.0	35	2	estimated	C
09/23/99	190	80	8.6	14	14	flown	A
10/05/99	350	120	6.0	29	17	flown	C
10/28/99	800*	290	5.6	10	23	flown	B
11/17/99	240*	70	6.7	5	40	flown	B

Data quality codes:
A - Best quality data - with distance to plume less than 1 km, and good constraint on measurement of distance; steady wind direction resulting in COSPEC angle consistently orthogonal to plume.
B - Good quality data - somewhat longer distance to plume from measurement site; may have variable wind conditions resulting in COSPEC angle occasionally non-orthogonal to plume.
C - Acceptable data - may have used indirect method to estimate distance to plume; measurements may have been made under less consistent wind conditions. Local terrain and increased plume distance may compromise measurement geometry.

* - includes flat and sideways oriented scans

Table 4.
Kilauea SO_2 emission rates - Fixed-wing measurements

EAST RIFT ZONE

Date	SO2 (t/d)	SD
05/28/98	2400	520
06/08/98	2020	120

SUMMIT

Date	SO2 (t/d)	SD
05/28/98	none detected	xxx
06/08/98	<100	xxx

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

Table 5.
Estimate of total Kilauea SO_2 emission rates, 1998-2001

Year	Summit SO2 emission rate (t/y)	Days of summit data	East rift SO2 emission rate (t/y)	Days of east rift data	Total Kilauea SO2 emission rate (t/y)
1998	4.32E+04	52	8.32E+05	44	8.75E+05
1999	3.70E+04	57	4.98E+05	56	5.35E+05
2000	3.89E+04	32	4.90E+05	34	5.29E+05
2001	3.90E+04	53	5.25E+05	43	5.64E+05
Totals					
1998-2001	1.58E+05	194	2.35E+06	177	2.50E+06

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