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Variation in Sulfur Dioxide Emissions Related to Earth Tides, Halemaumau Crater, Kilauea Volcano, Hawaii

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Variation in SO_2 emissions from Halemaumau crater, Kilauea volcano, Hawaii is analyzed using a set of techniques known as exploratory data analysis. SO_2 flux was monitored using a correlation spectrometer. A total of 302 measurements were made on 73 days over a 90-day period. The mean flux was 171 t/d with a standard deviation of 52 t/d. A significant increase in flux occurs during increased seismic activity beneath the caldera. SO_2 flux prior to the this change varies in a systematic way and may be related to variation in the tidal modulation envelope.

INTRODUCTION

Daily SO_2 flux is considered to reflect the state of activity of a volcano and increases by orders of magnitude during and often prior to eruptions [*Menyailov*, 1975; *Malinconico*, 1979; *Stoiber et al.*, 1980]. Most studies of daily variation of SO_2 flux describe a constant flux with random departures from the mean. Changes in activity are denoted by nonrandom departures [*Greenland et al.*, 1985; *Stoiber et al.*, 1986]. In this study, SO_2 flux was measured several times daily at Halemaumau crater, Kilauea volcano, Hawaii, over a period of several months (Figure 1). Exploratory data analysis techniques [*Tukey*, 1977; *Cleveland and Kleiner*, 1975; *Kleiner and Graedel*, 1980] reveal systematic variations in SO_2 flux that are smaller than changes attributable to changes in the level of volcanic activity. The departures from the mean flux can be correlated with oscillation in stress induced by Earth tides. Other observed changes in SO_2 flux during the time interval of the study can be related to concomitant changes in seismic activity.

Many authors have noted a correlation between volcanic eruptions and Earth tides [*Eggers and Decker*, 1969; *Hamilton*, 1973; *Johnston and Mauk*, 1972; *Mauk and Johnston*, 1973; *Golombek and Carr*, 1978; *Mauk*, 1979] and volcanic earthquakes and tides [*Mauk and Kienle*, 1973; *McNutt and Beavan*, 1981]. *Stoiber et al.* [1986] related nonrandom variation in SO_2 flux from Masaya volcano, Nicaragua, to gas bursts triggered by tides. *Sugisaki* [1981] noted a correlation between tides and variation in He/Ar in gas bubbles along active faults. A correlation between Earth tides and the frequency of geyser eruptions has also been identified [*Rhinehart*, 1976]. At Kilauea volcano, *Brown* [1925] discovered that the level of Halemaumau lava lake, present earlier this century, rose and fell in response to lunar tides. *Dzurisin* [1980] found that eruptions of Kilauea tend to occur at fortnightly tidal maxima. *Dzurisin et al.* [1984] found that tilt measurements at the volcano had a pronounced oscillation corresponding to fortnightly tidal period over several months in 1980. Therefore we hypothesized that Earth tides may cause variation in SO_2 flux from Kilauea.

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METHODS AND RESULTS

Remote correlation spectrometry is commonly used to estimate SO_2 flux from volcanoes [*Stoiber and Jepson*, 1973; *Malinconico*, 1979; *Haulet et al.*, 1977; *Stoiber et al.*, 1983; *Williams et al.*, 1986]. SO_2 measurements were made at Halemaumau crater on 73 days between June 10 and September 12, 1979, using a Barringer COSPEC IV following the methods of *Malinconico* [1979]. A total of 302 measurements were made during this time. Data were collected between 0900 and 1500 local time; usually four measurements of flux were made per day.

The mean flux between June 10 and September 12 was 171 t/d with a standard deviation of 52 t/d. This flux is typical for Kilauea [*Stoiber and Malone*, 1975; *Stoiber et al.*, 1979; *Greenland et al.*, 1985; *Gerlach and Greaber*, 1985], although it is relatively small for an actively degassing volcano [*Stoiber and Jepson*, 1973; *Williams et al.*, 1986; *Stoiber et al.*, 1987]. According to the model of *Gerlach and Greaber* [1985] for the degassing of Kilauea, this SO_2 is a constituent of "chamber" gas, representing volatile loss as a parental magma equilibrates with reservoir magma between 1 and 6 km beneath the caldera, as opposed to degassing associated with eruptive activity.

Because variance in SO_2 flux is greater on days having a higher mean flux, the $\ln(SO_2)$ was calculated; a scatter plot of $\ln(SO_2)$ over time is given in Figure 2. Moving statistics [*Cleveland and Kleiner*, 1975] were adopted to search for structure in this data set. This method is used because it provides a robust/resistant method of assessing data in which noise is high compared to the signal and the density of sampling points varies with time [*Kliener and Graedel*, 1980]. Both of these features are present in the SO_2 flux data.

Three moving statistics are used to enhance the scatter plot. These are the midmean [*Tukey*, 1977] and the lower and upper semimidmeans [*Cleveland and Kleiner*, 1975]. For a given flux value X_r the midmean is the average flux for the r samples collected closest in time to X_r and which fall between the upper and lower quartiles of the probability distribution for these r flux values. The lower and upper semimidmeans are means calculated using flux values less than and greater than the median flux of r samples, respectively. As with all moving average techniques, the degree of smoothing depends on r, the number of adjacent points used to calculate the moving statistics. There is no set criteria for selecting r, and in practice, several values of r are used [*Cleveland and Kleiner*, 1975]. Structure in the data is enhanced using these moving statistics because, for example, the midmean resists variation produced by extreme values and rapid flucutations.

We chose values of r ranging from 4 to 40 sample points. Rapid fluctuations in SO_2 flux dominate the time series when little

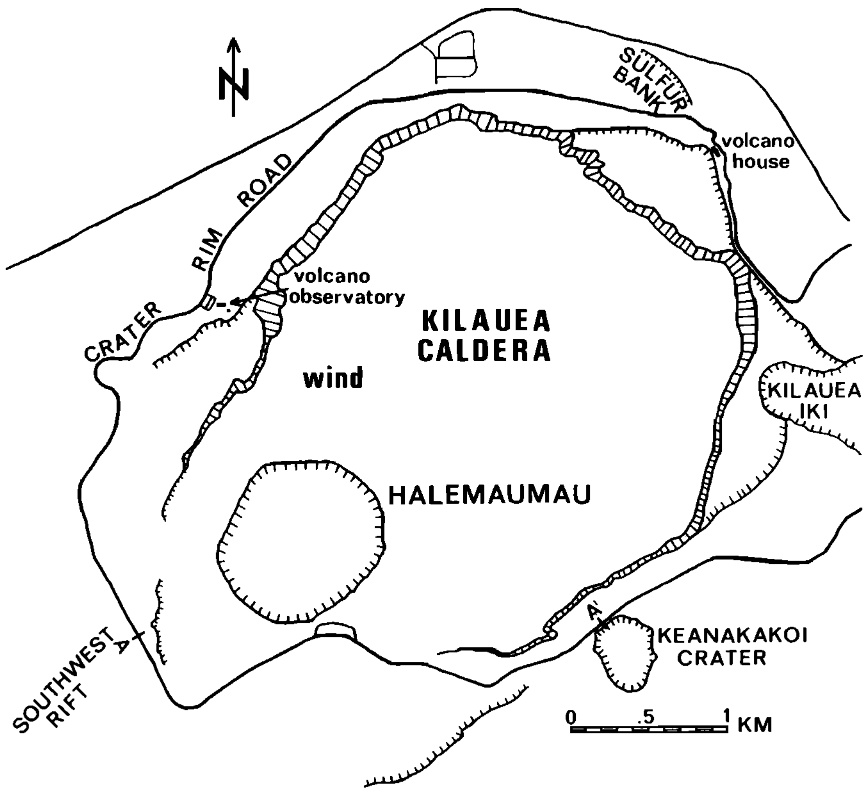

Fig. 1. Kilauea caldera and associated structures. SO_2 flux from within Halemaumau crater and the immediately surrounding areas was measured. Fault scarps and crater rims are indicated by hachured lines; wind direction is indicated by the shaded arrow. Measurements were collected along the crater rim road between A and A'.

smoothing is done (e.g. $r = 12$). Variation is characterized by spikes, and little or no long-wavelength variation can be discerned. The spikes disappear when a slightly larger smoothing factor is used ($r = 18$) (Figure 2). At this level of smoothing, several longer-wavelength variations are clear, such as a broad peak in flux around day 30, with two smaller peaks on either side, and a rapid increase in flux near day 52. Following day 52, the midmean $\ln(SO_2)$ is generally larger than it was earlier in the time series. The upper semimidmean also increases during this period. The lower semimidmean is not consistently larger, indicating that after day 52,

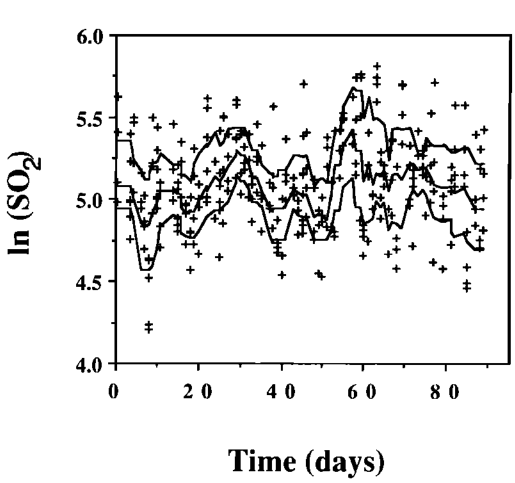

Fig. 2. Scatter plot of $\ln(SO_2)$ over time with the moving statistics (r=18) superimposed: top curve, upper semimidmean; middle curve, midmean; bottom curve, lower semimidmean. Time is in days since June 10, 1979.

SO_2 flux is generally greater but occasional readings are low. Long-wavelength variation persists even at large smoothing factors (e.g. $r = 36$); the broad peak around day 30 and the increase in SO_2 flux initiated by the rapid increase in flux around day 52 are still evident.

Temporal variation in the midmean $\ln(SO_2)$ flux, calculated vertical tidal acceleration, and the frequency of earthquakes beneath Kilauea caldera are compared in Figure 3. Although Kilauea did not erupt during the sampling period, there was a dramatic increase in seismic activity in early August (day 52), which has been interpreted to be related to the intrusion of a dike at depth (*R.W. Decker*, personal communication, 1987). As noted above, there is an increase in SO_2 flux during this same period. The flux prior to day 52 was less than after day 52, inclusive, with >99% confidence.

High SO_2 values, however, do not always occur on the same day as earthquake swarms. This results in a relatively low correlation between SO_2 flux and earthquakes; $r = 0.21$ for short-period earthquakes and $r = 0.26$ for long-period earthquakes. These correlations do not improve by lagging the midmean $\ln(SO_2)$ with respect to earthquakes or vice versa. This change is seismicity effectively subdivides the data set into flux values collected prior to the onset of seismic swarms and measurements collected after the onset of seismic swarms on day 52.

The $\ln(SO_2)$ and the midmean of $\ln(SO_2)$ flux were each compared with several aspects of Earth tides. These include the magnitude of the total vector and the vertical component of tidal acceleration at the time of measurement and the range of these measures over the previous 6, 12, and 24 hours. The derivatives of the horizontal components of tides across the caldera at azimuths

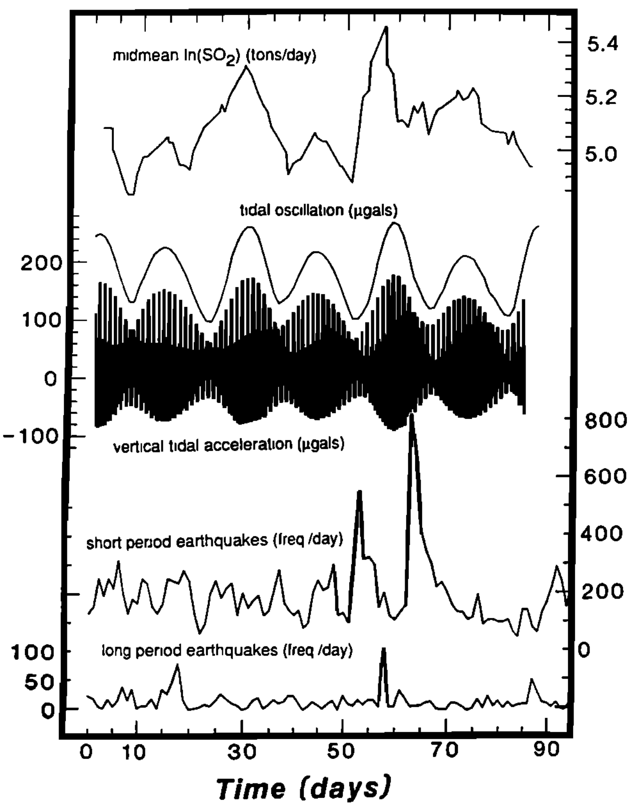

Fig. 3. Comparison of the midmean ln(SO_2) for $r = 18$ with tidal oscillation, calculated by differencing the largest and smallest upward tidal acceleration during the tidal day, the total upward acceleration, calculated at hourly intervals, and short- and long-period earthquakes. Time is in days since June 10, 1979.

ranging from east-west to north-south at 2° intervals, and the ranges of these were also compared with SO_2 flux. These calculations were made for the entire time series, the time series prior to day 52, and the series from day 52 onward. All tidal calculations were made following the methods of *Longman* [1959] and *Pollack* [1973].

The range of tidal acceleration was determined by differencing the maximum and minimum acceleration occurring within a given interval. The tidal oscillation is modulated at approximately 14-day wavelengths but is not produced by the M_f and M_m tidal waves, which are fortnightly and monthly lunar waves, respectively [*Melchoir*, 1978]. Generally, the tidal modulation envelope is out of phase with M_f and M_m, and M_f and M_m have very small amplitudes relative to the tidal modulation envelope. The modulation is produced by the addition of the M_2 and S_2 semidiurnal waves, and the semidiurnal lunar elliptic, N_2. Since M_2, S_2, and N_2 have slightly different frequencies, a long wavelength modulation develops. Although the modulation is approximately fortnightly, it is produced by semidiurnal variations in tidal acceleration.

McNutt and Beavan [1981] successfully related the frequency of earthquakes beneath Pavlof volcano to the orientation of the horizontal component of tides. In the present study it is found that the correlation between flux and the horizontal component of tides was low (r = 0.36) and did not improve with changes in orientation.

The coefficients for some of the correlations between SO_2 flux and vertical tides are given in Table 1. The largest correlation coefficients, $r \approx 0.60$, are found by comparing the midmean ln(SO_2) flux prior to the onset of earthquake activity with the scalar and with the vertical component of tidal oscillation over a 24-hour period. Lagging the midmean ln(SO_2) with respect to tidal oscillation rapidly reduces this correlation, until the curves are again in phase.

DISCUSSION AND CONCLUSIONS

Intermittency, turbulence, and puffiness in the plume [*Venkatram*, 1979; *Hanna*, 1984; *Sykes*, 1984] and variable wind speed and direction [*Stoiber et al.*, 1980] leads to random variations in estimates of SO_2 flux. Processes acting on the magma itself, such as the development of slugs of gas in the conduit [*Imai*, 1983], may also produce rapid fluctuations in SO_2 flux. Nonetheless, pattern in

TABLE 1. Correlation Coefficients Between SO_2 Flux and Calculated Tides

	N	T1	T2	T3	T4	T5
Total data set						
ln(SO_2)	302	0.06	0.13	0.20	0.16	0.18
Midmean ln(SO_2)		0.17	0.26	0.38	0.32	0.31
Data collected before day 52						
ln(SO_2)	183	-0.01	0.09	0.08	0.22	0.24
Midmean ln(SO_2)		0.23	0.45	0.41	0.60	0.61
Data collected after day 52						
ln(SO_2)	119	0.17	0.22	0.24	0.13	0.21
Midmean ln(SO_2)		0.25	0.15	0.34	0.18	0.28

Linear correlation coefficients for ln(SO_2) flux and the vertical tidal acceleration at the time of measurement (T1), range of tidal acceleration over the previous 6 hours (T2), 12 hours (T3), 24 hours (T4), and the range of magnitude of the total vector of acceleration over the previous 24 hours (T5). *N* is the number of samples. The midmean is calculated for a smoothing factor of 18 samples.

SO_2 flux from Halemaumau crater does emerge through the use of exploratory data analysis techiques (Figure 3).

Brown [1925] (also see *Shimozuru* [1987]) observed that the lava lake level of Halemaumau crater, molten earlier this century, varied with the lunar tide. Furthermore, variations as would be expected, increased as the width of the tidal modulation envelope increased. When the width of the tidal modulation envelope is small, the magma experiences little displacement over time, and any degassing which takes place is presumably related to other processes, such as the equilibration of parent and reservoir magmas or crystallization. When the modulation envelope is wide, daily tidal oscillation is high and the rate of change in tidal stress is maximum. Under these circumstances the conduit magma has been observed to be displaced by as much as 30-60 cm over a 24-hour period [*Shimozuru*, 1987] and changes in the rate of vesiculation probably occur [*Huppert et al.*, 1982; *Rymer and Brown*, 1987]. This, in turn, should increase the rate of degassing.

Changes in the midmean $\ln(SO_2)$ of the order of 40 t/d were observed near days 15 and 45, and 70 t/d on and around day 30 (Figure 3). The correlation between the midmean $\ln(SO_2)$ flux (r = 18) and the daily tidal oscillation is not statistically significant, but a relationship is suggested by 1) the persistence of variation in the midmean $\ln(SO_2)$ to large smoothing factors, 2) the tendency for SO_2 flux to increase when the tidal modulation envelope is large, and 3) the decrease in this correlation when the midmean $\ln(SO_2)$ is lagged with respect to tidal oscillation. Degassing increased significantly during the second half of the observaton period, associated with an increase in seismicity. These observations suggest that monitoring SO_2 degassing can, under some circumstances, provide valuable information concerning the relative movement of magma.

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