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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 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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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, $SO_2$ 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...
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The range of tidal acceleration was determined by differencing the maximum and minimum acceleration occurring over 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 ellipse, $N_2$. 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, $r = 0.60$, 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 |
|-----------------|---|---|---|---|---|
|                 | $N$ | $T_1$ | $T_2$ | $T_3$ | $T_5$ |
| $ln(SO_2)$      | 302 | 0.06 | 0.13 | 0.20 | 0.16 | 0.18 |
| Midmean $ln(SO_2)$ | 0.17 | 0.26 | 0.36 | 0.32 | 0.31 |
| $ln(SO_2)$      | 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 |
| $ln(SO_2)$      | 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 ($T_1$), range of tidal acceleration over the previous 6 hours ($T_2$), 12 hours ($T_3$), 24 hours ($T_4$), and the range of magnitude of the total vector of acceleration over the previous 24 hours ($T_5$). $N$ is the number of samples. The midmean is calculated for a smoothing factor of 18 samples.
SO2 flux from Halemaumau crater does emerge through the use of exploratory data analysis techniques (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(SO2) 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(SO2) flux (r = 0.8) and the daily tidal oscillation is not statistically significant, but a relationship is suggested by 1) the persistence of variation in the midmean ln(SO2) to large smoothing factors, 2) the tendency for SO2 flux to increase when the tidal modulation envelope is large, and 3) the decrease in this correlation when the midmean ln(SO2) is lagged with respect to tidal oscillation. Degassing increased significantly during the second half of the observation period, associated with an increase in seismicity. These observations suggest that monitoring SO2 degassing can, under some circumstances, provide valuable information concerning the relative movement of magma.

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