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Separate Quantification of Volcanic Gas Fluxes from Showa and Minamidake Craters at Sakurajima Volcano, Japan

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We conducted SO_2 flux measurements at Sakurajima volcano, Japan during 2007−2010 to ascertain differences in the degassing activity at two craters of the volcano: Minamidake and Showa craters. Recent developments in SO_2 visualization techniques using a UV camera observation system enabled us to quantify the SO_2 flux from each crater. SO_2 flux reflects conditions of the volcanic conduit. Therefore, a separate estimate of the gas fluxes from different vents is useful to gain insight into conditions within the volcano. Sulfur dioxide flux from Showa crater ranged from a few hundred to several thousand ton/day. In contrast, sulfur dioxide flux of 100−500 ton/day from Minamidake crater remained at a lower level. These results suggest that degassing conditions (i.e. permeability of the conduit or the amount of degassing magma) of Minamidake crater have remained stable. In contrast, the degassing activity of Showa crater is probably variable and sensitive to volcanic activities in the crater. The difference implies that drastic variations of Sakurajima volcano's SO_2 flux data, observed using a conventional traverse method with a UV spectrometer, resulted from the Showa crater's SO_2 flux, not the Minamidake crater's SO_2 flux.

Key words: volcanic gas, UV camera, SO_2 flux, remote sensing

1. Introduction

Volatile components are dissolved in magma under pressure. As magma ascends to the shallow region of a volcanic edifice, the magma begins to decompress, thereby causing exsolution of volatiles, which provides a driving force for explosive eruptions. Therefore, measurements of volcanic gas emissions provide reliable information related to the state of the magma and contribute to the monitoring of volcanic activity.

Sulfur dioxide (SO_2), a major volcanic gas constituent emitted from active volcanoes, can be detected using ultraviolet (UV) light absorption. Sulfur dioxide flux observations are used to monitor the variation of volcanic activity. The instrument used most widely to measure SO_2 flux is a correlation spectrometer (COSPEC; Stoiber *et al*., 1983). At the beginning of the 21st century, cheaper and more compact UV spectrometer systems (*e. g.*, mini-DOAS; Galle *et al.*, 2002; COMPUSS; Mori *et al.*, 2007) were developed to replace COSPEC. These advancements have facilitated data collection and have increased the number of observations. Although these developments have been innovative, the production of high temporal resolution SO_2 flux measurements remains challenging as UV spectrometers scan volcanic plumes. Recently developed UV camera observation systems (Bluth *et al.*, 2007; Mori and Burton, 2006) can provide images of the SO_2 column amount and measure SO_2 flux at high frequencies (up to 2 Hz). Recent studies using this new tool have revealed links between volcanic gas emissions and seismic signals (*e.g.*, Kazahaya *et al.*, 2011; Nadeau *et al.*, 2011).

Sakurajima volcano is an active volcano in southern Kyushu, Japan. This stratovolcano consists of two adjoining edifices: Kitadake and Minamidake. Previously, the main active crater had been Minamidake crater, which generated numerous eruptions since 1955. After the 1990s, the volcanic activity subsided to moderate levels. Showa crater, located east of Minamidake crater, awakened from about 60 year dormancy in June 2006. The main volcanic activity shifted from Minamidake crater to Showa crater. In contrast to the now active Showa crater, few explosions have occurred at Minamidake crater since 2006 (JMA, 2007, 2008, 2009, 2010).

The two craters are the major degassing source of Sakurajima volcano since June 2006. Sulfur dioxide flux is controlled by the several degassing parameters. One candidate is permeability of a volcanic conduit (*e.g.* Edmonds *et al.*, 2003). Because these two craters have different eruptive behaviors, as described above (*e.g.* number of erup-

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tions), their degassing activities are expected to be different. However, it is difficult to measure the volcanic gas flux from each crater because the two craters are close to each other and volcanic plumes from the two craters mix near the craters. Conventional observation techniques using a UV spectrometer can only acquire a mixture of volcanic plumes emitted from multiple craters.

To measure the SO_2 flux from each of the three craters at Mt. Etna, Italy, Aiuppa *et al*. (2008) performed walking traverse measurements around the craters. However, this technique is not applicable to Sakurajima volcano because of its frequent explosive eruptions. High spatial resolution of SO_2 imaging data provided by UV camera observation systems enable estimation of SO_2 fluxes from multiple sources as shown at a fumarolic field of Vulcano, Italy (Tamburello *et al.*, 2011). The evaluation of SO_2 flux from each crater is crucial to investigate the similarity and dissimilarity of an individual crater's degassing activity, which is quite important information for the understanding of eruptive mechanisms. The SO_2 flux of each crater enables us to compare the degassing activity and other geophysical data related to the eruptive activity. This report describes the observation of SO_2 fluxes from the two active craters at Sakurajima volcano using the UV camera observation system, and presents discussion of the degassing activities of Showa and Minamidake craters.

2. Observations

We conducted SO_2 flux measurements using a UV camera observation system (Bluth *et al.*, 2007; Mori and Burton, 2006) at Sakurajima to measure the SO_2 flux separately from each crater. The observational site was Arimura (Fig. 1). The distance between the craters and Arimura was 2.7 km. Measurements were conducted on 7 June 2007, 7 May 2008, 1 December 2009, and 14 September 2010.

The measurement on 7 June 2007 was made with one UV camera and two UV band pass filters (Mori and Burton, 2006), which were switched alternately by manual operation. The SO_2 images were obtained every 3 s. After 2008, measurements were conducted using two UV cameras and a UV spectrometer (USB2000/2000＋; Ocean Optics Inc.). The UV cameras were synchronized. The time resolution of the system was 0.5 Hz. The UV scattering between a volcanic plume and an instrument engenders underestimation of the SO_2 amount (Kern *et al.*, 2010; Mori *et al.*, 2006). The SO_2 column amount on the images was corrected by the SO_2 column amount, which was calculated using UV spectra of the same volcanic plume observed using the UV spectrometer. A conventional traverse SO_2 flux measurement using a compact UV spectrometer system (COMPUSS; Mori *et al.*, 2007) was also made on 1 December 2009 simultaneously with the UV camera observation to compare the SO_2 flux data obtained using the UV camera and those of the traverse method.

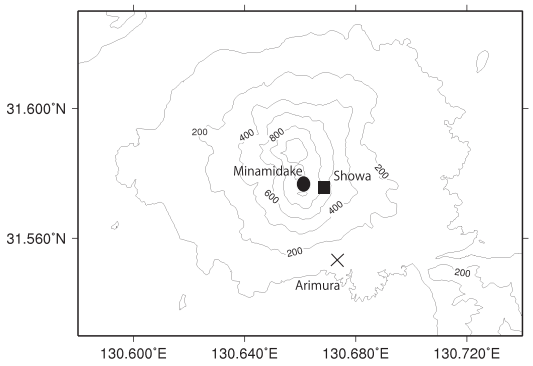

Fig. 1. Map of Sakurajima volcano. The black circle and square respectively show the locations of Minamidake crater and Showa crater. The observation site, Arimura, is shown as the black cross.

3. Separate SO_2 flux quantification of multiple craters

3−1 SO_2 flux calculation

Principle techniques for SO_2 flux calculation of the UV camera observation system were described in earlier reports (Bluth *et al.*, 2007**;** Mori and Burton, 2006). Each SO_2 amount of a point on an image represents the SO_2 column amount, which is the integrated SO_2 concentration along the CCD line of sight. The sulfur dioxide column amount profile on a line of an SO_2 image that is perpendicular to plume-flow direction corresponds to the SO_2 column amount profile of a cross-section of the volcanic plume. The SO_2 amount within the cross-section is calculated by integrating the SO_2 column amount on the line (hereinafter the "flux calculation line"). Sulfur dioxide flux is derived by multiplying the integrated SO_2 column amount within the cross-section by the plume speed. The plume speed is obtained from the plume motion. For practicality, a time lag among integrated SO_2 column amount time series of two parallel cross-sections of the plume perpendicular to the plume-flow direction is calculated. The plume speed is ascertained by dividing the time lag from the distance between the cross-sections. These two cross-sections correspond to a flux calculation line and an arbitrary line parallel to the flux calculation line on the image. The time lag is examined using the cross-correlation method (*e.g.* Mori and Burton, 2006).

To measure the SO_2 flux for each crater separately, the flux calculation line is selected for each crater (Fig. 2a). When plumes from multiple sources flow apart without mixing, separate measurements of SO_2 flux from the different sources can be determined using UV image analysis of the flux calculation lines. Each flux calculation line is used to measure each crater's flux. Even though plumes from the two craters mix at a distance, sulfur

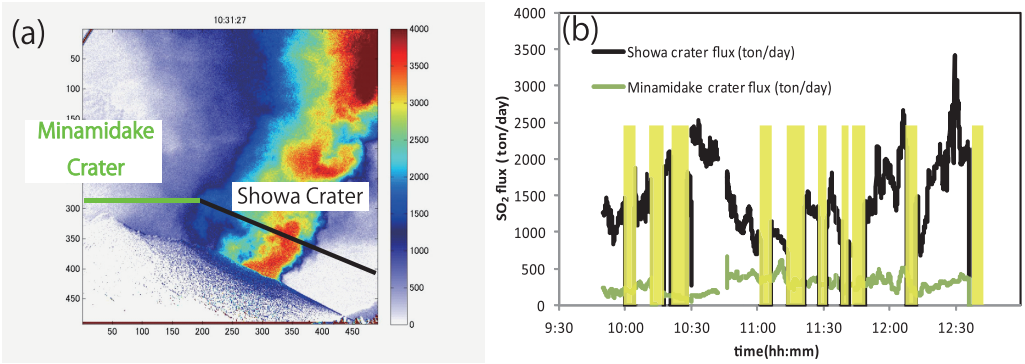

Fig. 2. Sulfur dioxide visualization image and calculated SO_2 flux time series of the two craters. (a) Sulfur dioxide visualization image taken by the UV camera observation system on 1 December 2009. The colors present the SO_2 column amount as shown in the color bar set on the right. The image was taken from Arimura. Sulfur dioxide flux calculation lines are set above the two craters to calculate the SO_2 flux of each crater. The green line above Minamidake crater is used to calculate Minamidake crater's SO_2 flux. The black slanted line is for Showa crater's SO_2 flux. (b) Variation of SO_2 fluxes of two craters on 1 December 2009. The black and green curves respectively show the SO_2 fluxes of Showa and Minamidake craters. Periods filled with yellow correspond to occurrences of eruptions.

dioxide flux of each crater can be measured before mixing occurs. The mixed plume's flux can also be estimated using flux calculation lines on the image by setting the flux calculation line to get a cross-section of the mixed plume. When SO_2 flux from one crater cannot be measured directly because of the mixing and the other can be measured, the missed flux can be derived by subtracting SO_2 flux of other crater from the mixed plume's flux.

Wind direction affects SO_2 flux measurements. When images are taken from a leeward location, the plume moves upward on the images. For that reason, distinguishing fluxes from multiple craters is easy. In contrast, when images are taken from a windward location, the plume remains above the source in the images, making it difficult to measure SO_2 flux. When some part of a plume misses the field of view (FOV) of an instrument (*e.g.*, being behind a volcanic body), the SO_2 flux might be underestimated or it might not be measurable.

With a weak wind from the northwest, from Arimura, the plumes from Showa crater and Minamidake crater are visible as rising separately. Under such conditions, the SO_2 flux from each crater can be quantified separately (Figure 2a). With strong winds, the volcanic plume moves laterally and SO_2 flux estimation is impossible because parts of the volcanic plume are outside the FOV of the instrument.

3−2 Elimination of volcanic ash effect for SO_2 amount quantification

Volcanic ash causes underestimation of the SO_2 flux (Andres and Schmid, 2001) because the ash does not let UV light penetrate through. Even during passive degassing stages, volcanic plumes sometimes contain ash, which affects the estimation of the SO_2 flux in the column. This effect lessens with distance because dispersion and precipitation of ash lowers the ash concentration. To eliminate the ash effect, we quantified the SO_2 flux at several distances from the crater by elaborating the flux calculation lines on SO_2 images (Fig. 3). We set the five flux calculation lines on the UV image (Fig. 3b) and compared the calculated flux on each line (Fig. 3a). Figure 3a shows the temporal fluctuation of SO_2 flux of the flux calculation lines. The absolute values of the timelines differ because of the ash effect. The lower lines show lower SO_2 fluxes. Each timeline has a time lag because of the positions of the lines. The upper two lines show similar SO_2 fluxes to the time averaged values to within a 5 % difference (Fig. 3a). Therefore, we concluded that the ash effect is cancelled for the two lines. To compare the SO_2 flux timeline with eruptive activity and other geophysical data, the calculation line should be set up as close to the crater as possible. However, if the flux calculation line is set up close to the crater, then the amount of ash is higher in the volcanic plume near the crater, which means that the calculation of SO_2 column amounts will be an underestimate. We examined the effect as described above and selected the aqua flux calculation line, which is unaffected by the ash, but which is the nearest to the crater (Fig. 3).

Accuracy of the SO_2 flux estimated using this procedure was examined by comparison with the SO_2 flux obtained using the conventional traverse method. Figure 4 presents a comparison of the traverse method with the UV camera observation. Results show that the SO_2 fluxes obtained using the two measurement techniques agree well except for data obtained during eruptions (Fig. 4). Underestimation of SO_2 flux caused by the volcanic ash is cancelled out by elaboration of the flux calculation lines.

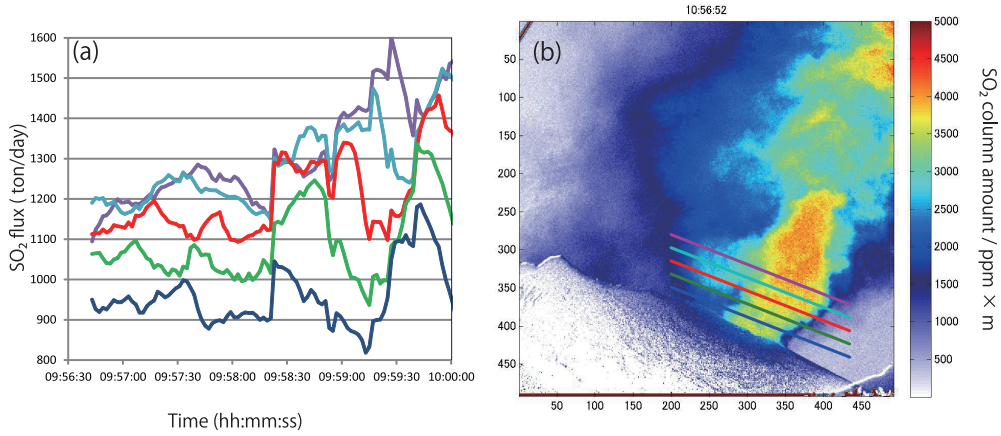

Fig. 3. Difference of SO_2 fluxes obtained with different five SO_2 flux calculation lines on the UV images. (a) Variation of SO_2 fluxes of multiple SO_2 flux calculation lines above Showa crater. (b) A SO_2 image with five SO_2 flux calculation lines above Showa crater. The colors of the lines on the SO_2 image correspond to those of the lines on the left graph. In this case, we calculated the SO_2 flux using the aqua line, which is the second highest one.

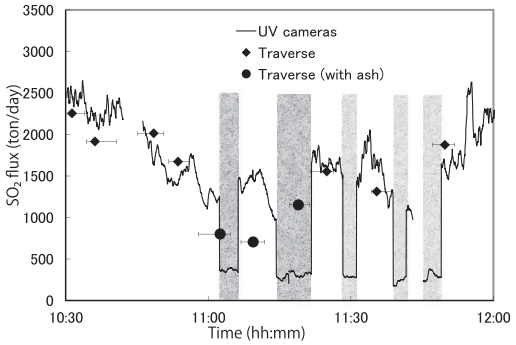

Fig. 4. Sulfur dioxide fluxes obtained using the UV camera observation system and the traverse method. Variation of SO_2 flux time series obtained using the UV camera observation (solid line) and the traverse measurement using the COMPUSS (squares and circles). Filled regions correspond to the period of an eruption during which we cannot measure the SO_2 flux because of the great amount of ash with the UV camera observation. The circles show data points including uncertainty because of volcanic ash emitted by explosive eruptions and direction change of eruptive plume. Horizontal error bars of the traverse data points show the observational period of each traverse measurement. The UV camera observation system was used to observe the plumes just above the two craters. The traverse measurement observed the plume 2.4–5 km away from the craters. A time difference prevailed between SO_2 timeline of the traverse method and the UV camera observation system. We corrected the time lag of the traverse measurement using a simple calculation with the wind speed and the average distance between the crater and the route of traversal.

Table 1. Observation conditions for each day.

Date (dd/mm/yyyy)	separation†	ash‡	traverse*
07/06/2007	×		
07/05/2008	×		
01/12/2009	○	v	v
14/09/2010	○		

(†) If each crater's SO_2 flux could be observed separately. The two craters' fluxes would be calculable by subtraction even if separate observations were to fail.

(‡) If the plume contains a significant amount of ash.

(*) If the traverse measurement was conducted at the same time with the UV camera observation.

3–3 Observational conditions of each day

The observational conditions of each day are presented in Table 1. On 7 June 2007 and on 7 May 2008, the plume emitted from Showa crater flowed westward and mixed with the plume from Minamidake crater. In this case, we cannot calculate the SO_2 flux from Minamidake crater separately because of the mixing. Two lines were set on the images to calculate the flux from Showa crater and the total flux. We calculated Minamidake crater's flux by subtracting Showa crater's flux from the total flux. The volcanic plume did not contain a substantial amount of ash. It was not necessary to have an arrangement of flux calculation lines.

On 1 December 2009, volcanic plumes from Minami-

Table 2. Sulfur dioxide flux of each crater at Sakurajima volcano, Japan, 2007−2010.

date (dd/mm/yyyy)	Showa crater's SO_2 flux (ton/day)	Minamidake crater's SO_2 flux (ton/day)	number of eruptions at Showa crater per month	number of eruptions at Showa crater on each day
07/06/2007	150 (80–220)	310 (210–510)	14	0
07/05/2008	900 (400–1700)	300 (100–800)	27	1
01/12/2009	1880 (1000–3100)	270 (80–580)	143	4
14/09/2010	190 (90–290)	100 (20–210)	47	0

Range of estimated SO_2 flux on each day is shown in parenthesis.

dake and Showa craters rose vertically. We were able to measure the fluxes separately. In this case, we set two flux calculation lines above the respective craters on the UV image (Fig. 2). Volcanic ash in the plume was abundant on this day. Therefore, the flux calculation lines were arranged to reduce the ash effect.

On 14 September 2010, the ash-free volcanic plume rose vertically. Because of slow movement of the plume and the very low SO_2 column amount, it was difficult to estimate the speed of the plume from Minamidake crater using either cross-correlation analysis (Mori and Burton, 2006) or analysis of the plume movement viewing video image. We assumed that Minamidake crater's plume speed was equal to that of Showa crater's plume. The SO_2 flux of each crater was quantified separately.

4. Results and discussion

The SO_2 flux was measured from each crater on four separate days (Table 2). The variation of Showa crater's SO_2 flux was considerable (100−2000 ton/day on average). In contrast, the SO_2 flux of Minamidake crater was constant at around 300 ton/day. Large SO_2 flux was observed when the eruption frequency was high on 1 December 2009; the number of eruptions at Showa crater might be related to the SO_2 flux measured at Showa crater (Table 2). Minamidake crater's SO_2 flux data were stable. Therefore, the total flux from the two craters is expected to correlate with the number of eruptions at Showa crater. In this regard, Mori *et al*. (2008) conducted traverse measurements intensively after 2003 and reported that the total SO_2 flux increased with the Showa crater activity. This study further supports that inference. Mori *et al*. (2008) were unable to distinguish the SO_2 fluxes from the two craters, but measured their sum.

The large variation of SO_2 flux of Showa crater (100−2000 ton/day average) implies a considerable change in the amount of degassing magma or variation of degassing mechanism under Showa crater. In contrast, the average SO_2 flux of Minamidake crater was constant at 100−500 ton/day. Those values are similar to the flux values reported for Minamidake crater during 2003−2006, before reactivation of Showa crater (Mori *et al.,* 2008). This fact suggests that the degassing conditions of the conduit (*e.g.* changes of conduit radius or permeability) under Minamidake crater did not change even after the extensive eruptions at Showa crater.

5. Concluding remarks

Sulfur dioxide flux measurements were conducted at Sakurajima Volcano during 2007−2010 using the UV camera observation system to quantify SO_2 fluxes separately from the two craters: Showa crater and Minamidake crater. Sulfur dioxide flux of Showa crater fluctuated with the eruptive activity of 100−2000 ton/day. In contrast, the SO_2 flux of Minamidake crater was 100−500 ton/day. Data were similar during 2007−2010. These values also resembled the data of 2003−2006, when Sakurajima volcano was in the more quiescent period before the activity of the Showa crater. This fact implies that the long-term SO_2 flux change after 2006 at this volcano results from Showa crater's activity. Correlation was found between the SO_2 flux and the number of eruptions at Showa crater, suggesting that the eruptions changed the amount of degassing magma and/or degassing conditions under Showa crater as described later. In contrast, the constant SO_2 flux of Minamidake crater implies that the conditions of Minamidake crater are stable, with few explosions at this crater.

When assuming degassing of a convecting magma column (Shinohara, 2008), the gas flux change is explainable by changes of the conduit radius, convection speed, change of magma column height, and the amount of volatiles in the

magma. However, the change of the amount of volatiles in the magma is unlikely because a change of that parameter might engender variation of Minamidake crater's activity as well as the Showa crater's activity if assuming that magma convections within the two conduits are driven by the same magma. It is possible that the variation of SO_2 flux of Showa crater shows changes of the conduit radius and/or magma column height of that crater.

The separate quantification techniques used to ascertain SO_2 flux from multiple craters enables the evaluation of different degassing activities at multiple craters at one volcano. In the case of Sakurajima volcano, because Showa crater has undergone many eruptions, this separate quantification technique will be useful to examine the SO_2 flux fluctuation occurring before and after eruptions at this crater using high temporal SO_2 flux measurements. Comparison of the SO_2 flux of Showa crater with other geophysical data is another challenge that lies ahead.

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(Editorial handling Takeshi Nishimura)

桜島における南岳・昭和火口からの二酸化硫黄放出率の分離

風早竜之介・森　俊哉・山本圭吾

桜島火山にて紫外線カメラ観測装置を用いてガス観測を行い，南岳火口及び昭和火口から放出される二酸化硫黄放出率の分離を行った．二酸化硫黄放出率は各火口の状態を反映していると考えられるため，複数火口が存在する火山でそれらの放出率を個別に測定する事は噴火活動を理解する上で非常に有用である．観測は 2007 年から 2010 年に行われた．その結果，昭和火口の放出率は数百トンから数千トンレベルで大きく変動したが，南岳火口の放出率は 100–500 トン程度でほぼ一定だった．これより，観測期間中，南岳の火道の状態は安定したままほとんど変化していないと考えられる．また，昭和火口の火道状態は昭和火口の噴火活動・回数に応じて大きく変動している事が示唆される．桜島火山において長期的に行われている COMPUSS を用いた二酸化硫黄放出率観測データは二つの火口の放出量の合計である．南岳のガス放出率がほとんど変わっていないことから，COMPUSS を用いたガス放出率観測で見出されている放出率変動は主に昭和火口による寄与が大きく，南岳の放出率変化はほとんど寄与していないと考えられる．