

Sulfur dioxide flux monitoring using a regular service ferry after the 2014 eruption of Kuchinoerabujima Volcano, Japan

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Abstract

The volcanic island of Kuchinoerabujima recently erupted on Aug. 3, 2014 and on May 29, 2015. After the 2014 eruption, a gradual increase of sulfur dioxide (SO₂) flux from the volcano was observed. In response to the increase, we built a UV spectrometer system that can be operated semi-automatically without an experienced observer for repetitive flux monitoring. The monitoring was carried out based on a traverse method using a regular service ferry as a carrier. With the repetitive measurements, we detected a sudden flux increase to over 2500 ton/day at the end of Nov. 2014, a high and variable flux after mid-March to early-May 2015, and a continued decreased flux (< 500 ton/day) before the May 29, 2015 eruption. The detected SO₂ flux variations showed that a large amount of magma was involved in gas emissions at the volcano, the conduit system became unstable from mid-March, and the conduit system became partially sealed about one week before the 2015 eruption, which was probably the turning point toward the eruption. The repetitive SO₂ flux monitoring using a regular public transportation made it possible to detect important changes of flux before the eruption and was very effective for understanding the process toward the 2015 eruption.

Keywords: volcanic eruptions, Kuchinoerabujima Volcano, volcanic gas, sulfur dioxide flux

1. INTRODUCTION

Eruptive activities of volcanoes have a strong impact on the local population around volcanoes. In particular, on volcanic islands, eruptive activities might lead to full evacuation of the island, which we have experienced three times (Izu-Oshima, Miyakejima, and Kuchinoerabujima eruptions) in the last 30 years in Japan (Iguchi et al., this issue), to avoid serious disasters due to possible changes in eruptive activities. Considering the conditions of volcanic islands, the monitoring of volcanic activities is especially important to understand contemporary conditions and to estimate future activities.

Together with various monitoring methods of the volcanoes, sulfur dioxide flux monitoring is important for an early-warning of eruptive activity changes (Young et al., 1998). Sulfur dioxide is a major volcanic gas component and is considered an indicator of magmatic influence (e.g., Oppenheimer et al., 2014). In particular, high SO₂ fluxes from volcanoes are considered important signals showing that the degassing activity is related to magma beneath the volcanoes (Symonds et al., 2001; Oppenheimer et al., 2014). Many studies have revealed the importance of SO₂ flux in volcanic activity monitoring (e.g., Symonds et al., 1994; Oppenheimer et al., 2014) and reported the flux variations before and after the eruptions (e.g., Malinconico et al., 1979; Casadevall et al., 1994; Daag et al., 1996; Zapata et al., 1997; Fischer et al., 2002; Kazahaya et al., 2003, Mori and Kato, 2013). In fact, the SO₂ flux monitoring had been used for disaster prevention decisions prior to the eruptions of Pinatubo Volcano, Philippines (Daag et al., 1996) and Merapi Volcano, Indonesia (Surono et al., 2012).

Kuchinoerabujima is a volcanic island about 70 km south of Kyushu Island, Japan (Fig. 1a) and is about 15 km from Yakushima Island (Fig. 1c). Kuchinoerabujima Volcano suddenly erupted on Aug. 3, 2014 after years of unrest (Iguchi et al., this issue). The eruption was a phreatomagmatic eruption with a plume height of 800 m from the crater rim (Iguchi et al., this issue). All the monitoring instruments such as seismometers, tilt meters and GNSS stations within 1 km of the crater were destroyed by the eruption (Iguchi

et al., this issue), thus the monitoring level of volcanic activities of the volcano became significantly low compared to that before the eruption. About 10 months after the 2014 eruption, on May 29, 2015, a larger scale phreatomagmatic eruption occurred again at the volcano. The plume went up higher than 10,000 m and pyroclastic flow traveled down the flank near to the shoreline on the northwestern side of the volcano (Iguchi et al., this issue). Soon after the eruption, the Japan Meteorological Agency upgraded the Volcanic Alert Level to 5 (evacuation) and the local government decided to fully evacuate the island on the same day of the eruption (Iguchi et al., this issue). The evacuation continued for about 5 months until the end of 2015.

In this study, we report probably the first repetitive monitoring of SO₂ flux using regular public transportation at Kuchinoerabujima Volcano, Japan. Our repetitive measurements using a regular service ferry for the traverse measurements of SO₂ flux revealed degassing unrest after the 2014 eruption toward the 2015 eruption of the volcano, which clearly showed a strong magmatic influence during the period.

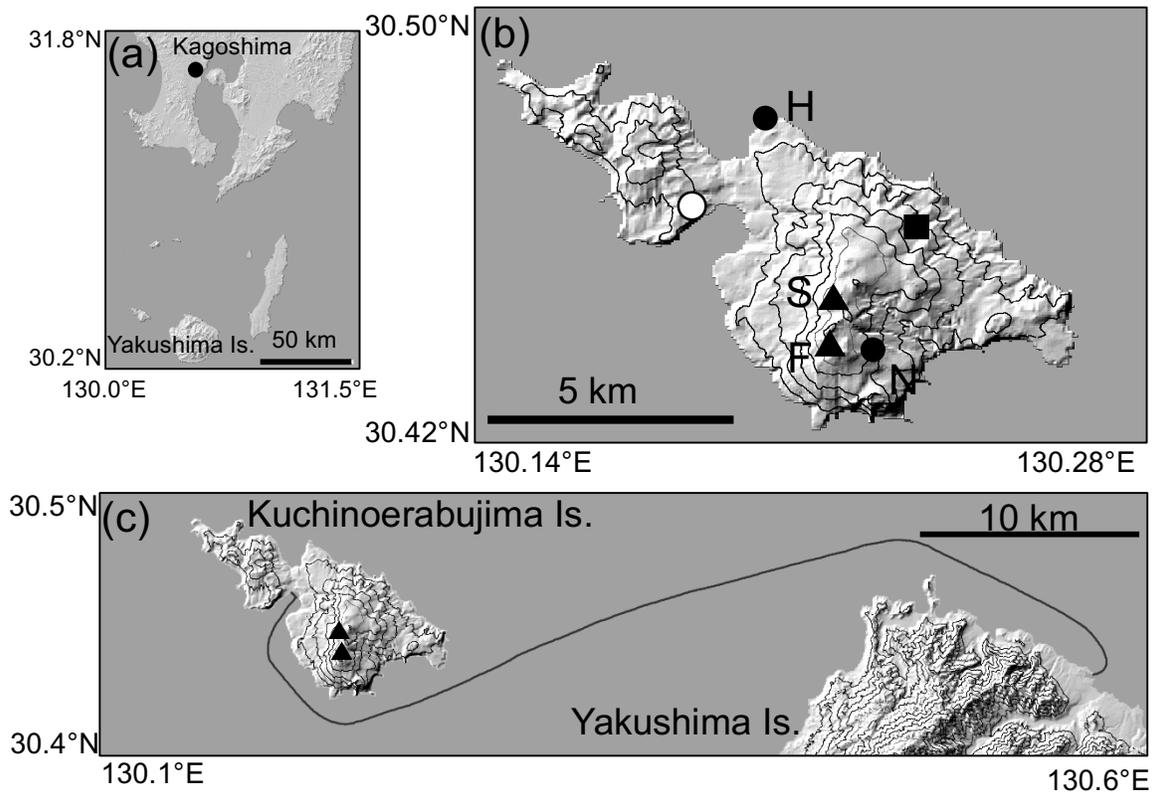


Fig.1 (a) A map of the southern part of Kyushu Island, Japan and showing the location of Yakushima Island about 70 km south of Kyushu Island. The solid circle corresponds to Kagoshima city. (b) A map of Kuchinoerabujima volcano showing the location of summit craters Furudake and Shindake (triangles), two GNSS stations, Nanakama and Heliport (solid circles) and a seismic station, Shindake-Hokuto-Sanroku (solid square) on the island. The open circle corresponds to Honmura Port which is the main port of Kuchinoerabujima Island where Ferry Taiyo stops. Contour lines are shown every 100 m. (c) A map of Kuchinoerabujima Island and northern part of Yakushima Island. The solid curve shows the typical route of Ferry Taiyo between the two islands.

2. SULFUR DIOXIDE FLUX BEFORE THE 2014 ERUPTION AT KUCHINOERABUJIMA VOLCANO

Kuchinoerabujima Volcano has fumarolic activity at two summit craters, Furudake and Shindake craters (Hirabayashi et al., 2007). At the volcano, the fumarolic activity in Shindake crater increased at the southern part and new activity at the bottom appeared in 2003, and the fumarolic activities increased furthermore after 2005 (Hirabayashi et al., 2007). Although the orifice temperature of the southern fumaroles was not of high temperature magmatic gas, high SO₂ and H₂ concentrations and the detectable amount of CO in the fumarolic gas supported the assumption that the volcanic gas at Shindake crater was of magmatic origin (Hirabayashi et al., 2007).

The first SO₂ flux measurement at Kuchinoerabujima Volcano was carried out using a correlation spectrometer (COSPEC) by traverse measurements from the observation vessel in 1977. The flux was below the detection limit of << 10 ton/day (Kamada et al., 1986). In response to the increased fumarolic activities observed as above, a new series of SO₂ flux measurements was started after the end of 2006 (Mori et al., 2009) using a compact UV spectrometer system (COMPUS; Mori et al., 2007). The flux continued at a level of several tens of ton/day until the beginning of Oct. 2008, and increased to over 200 ton/day coinciding with the increased seismicity and inflating deformation observed at the volcano (Mori et al., 2009). The flux decreased to several tens of ton/day after the inflating deformation. A similar flux increase was also observed at the time of another inflating episode in 2011, but the flux remained at several tens of ton/day for the period until the 2014 eruption (JMA, 2014a). After the 2014 eruption, the flux ranged from 200 to 400 ton/day for a few months, and increased to about 500 ton/day in mid-October and to 700 ton/day in mid-November (JMA, 2014b). As mentioned earlier, because most observation instruments near the summit area were destroyed with the 2014 eruption at the volcano (Iguchi et al., this issue), the observed increase of SO₂ flux after the 2014 eruption was considered very serious, and more frequent flux measurements were necessary at this remote island volcano for volcanic activity monitoring.

3. INSTRUMENTS AND MEASUREMENTS USING REGULAR SERVICE FERRY

At Kuchinoerabujima Volcano, most previous SO₂ flux measurements were carried out by car traverse measurements using the roads around the volcano (Mori et al., 2009). Soon after the 2014 eruption, a 2-km zone around the summit area became a restricted area and the road used for traverse measurements for the southern half of the volcano became unusable due to the restriction (JMA 2014a). Thus, flux measurements in winter when the northerly wind is predominant were expected to be difficult to perform. For this reason, we focused on using the regular service ferry, Ferry Taiyo (Fig. 2b), operated by the local town of Yakushima, which makes a round trip from Yakushima to Kuchinoerabujima Islands each day. As shown in Fig. 1, Ferry Taiyo runs off the southern coast of Kuchinoerabujima Island and arrives at Honmura Port on the island, which is located north-west from the active Shindake crater, thus traverse measurements were expected to be possible by using the ferry under northerly wind conditions.

In order to use the ferry for repetitive traverse measurements semi-automatically without an experienced observer for SO₂ flux measurements, we built a small UV spectrometer system. The system was based on a small UV spectrometer as used elsewhere in various volcanic fields (e.g., Galle et al., 2002; Mori et al., 2007). A USB2000+ (Ocean Optics Inc.) spectrometer with a 50- μ m slit was used in our system (later substituted to a FLAME S spectrometer of Ocean Optics Inc. in October 2015). A custom-made telescope with a 25-mm focal length quartz lens was directly attached to the spectrometer. For controlling the spectrometer as well as recording observed spectra and the location information, a single board computer, Raspberry Pi B+ (Raspberry Pi Foundation), with a GPS module (GT-723F, CanMore Electronics) and a USB Wi-Fi adapter (WLI-UC-GNM : BUFFALO Inc.) was used to make the system compact. The Wi-Fi adapter was used to upload the observed data through a mobile router (Aterm MR03LN, NEC Corp.) to a cloud storage server. The system was powered by a Li-ion mobile battery (CP-F2L, Sony Corp.). All the instruments above were set into a water-proof plastic box (135mm \times 185mm \times 100.5mm, BCAP131810 G,

Takachi Electronics Enclosure Co., Ltd.) with a filter window (50 mm x 50 mm, Hoya U330) to protect from sea spray and rainfall (Fig.2a).

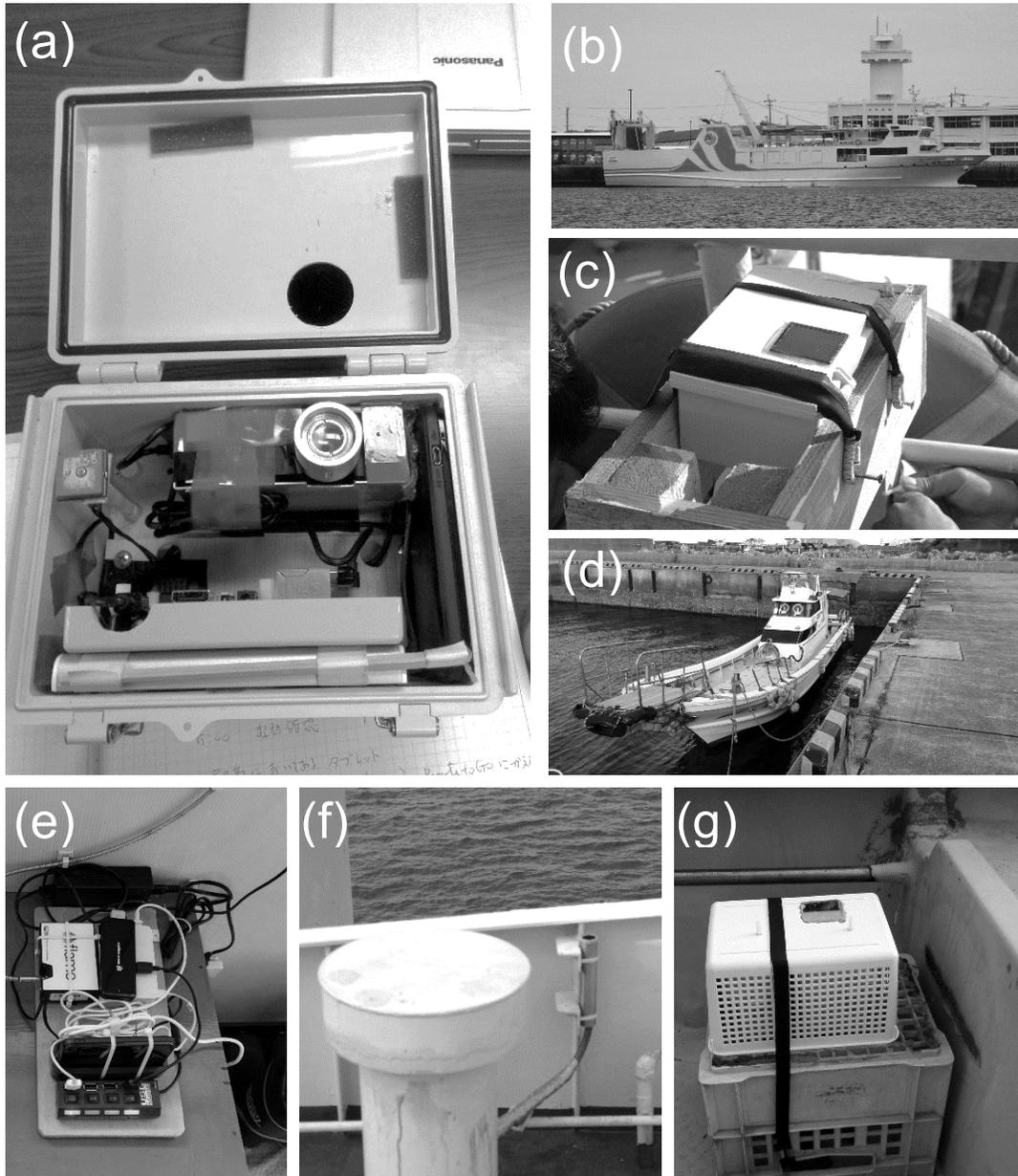


Fig.2 (a) A photo of the first UV spectrometer system used at Ferry Taiyo and Fumimaru. The waterproof box is opened to show the instruments inside. (b) A photo of Ferry Taiyo at the port in Yakushima Island. (c) A photo showing the box fixed on the top deck of Ferry Taiyo. (d) A photo of Fumimaru at the port in Yakushima Island. (e) A photo of the UV spectrometer system installed inside the wheelhouse of Ferry Taiyo. The gray line toward the top is an optical fiber connected to the telescope on the top deck. The black cable toward the right is of the GPS module set by the window. (f) A photo of the telescope on the top deck of Ferry Taiyo connected to the optical fiber. (g) A photo of the UV spectrometer system set on the deck of Fumimaru. The UV spectrometer system in (a) is covered by a plastic basket with UV transparent window to avoid direct sunlight on the box.

A Python (a programming language developed by Python Software Foundation) based program on Raspbian (Linux based operating system for Raspberry Pi), which automatically starts measurement, decides the integration time of the spectrometer, uploads the observed data and halts according to the ferry's timetable, was made and used in the measurements, so that the captain or crew of the ferry could start the measurements by one push of a switch of the mobile battery. The system was set on an upper deck of the ferry (Fig. 2c) before departure and recovered after arrival at Yakushima Island. The mobile battery and the mobile router were charged overnight for measurements the next day by the ferry crew.

From April 2015, the observation system was upgraded and permanently installed on Ferry Taiyo. A telescope with a 60-mm focal length quartz lens with a Hoya U330 filter window was set up on the upper deck (Fig. 2f). Another part of the system was installed inside the wheelhouse of the ferry (Fig. 2e). The telescope and the spectrometer were connected by a 3m-long single quartz optical fiber (600- μm diameter). The system was operated by the on-off power switch of the system installed in the wheelhouse.

The uploaded observed data from the ferry after each day of measurement were downloaded at the University of Tokyo from the cloud storage server. The data were then analyzed by normal DOAS technique (e.g., Platt et al., 1994; Galle et al., 2002, McGonigle et al., 2002) for retrieval of the SO_2 column amount for each spectrum, and then the integrated SO_2 column amount for a transect of the plume was calculated (e.g., McGonigle et al., 2007) for two traverses, namely the out-bound and in-bound trip of the ferry. For the SO_2 flux calculation, the wind speed from the grid point value (GPV) data estimated from numerical weather prediction by the Japan Meteorological Agency (JMA) was used as the plume transport speed (Mori and Kato, 2013; Mori et al., 2016). The GPV wind speed data for 925 hPa corresponding to the altitude of Kuchinoerabujima Volcano was mainly used but the speeds from different heights were also used when the plume height was available by live video camera images and was apparently different from the altitude of the volcano. When the GPV wind direction was significantly different (more than 45°) from the plume direction estimated from the maximum SO_2 column amount location during the traverses, the flux calculation was rejected to preserve the quality of flux data. The flux calculation was also rejected for the measurements during rainy conditions.

For the errors in SO_2 flux estimation, Galle et al., (2010) discussed dividing errors into four components; "spectroscopy," "Atmospheric Scattering," "Measurement Geometry" and "Wind speed" for their scanning instruments. We assumed that the effect of error sources is basically the same for our traverse measurements and used the values for the error estimation except for the "Measurement Geometry" error, which is typical of scanning instruments. Instead of the "Measurement Geometry" error (Galle et al., 2010), we utilized error components intrinsic to traverse measurements considered by Mather et al., (2006), which was about 10% and arose from geometrical relations between the plume direction and the traverse route. The largest source of errors in the SO_2 flux estimation was considered to be the plume speed in previous studies (e.g., Stoiber et al., 1983; Mather et al., 2006; Burton et al., 2009, Galle et al., 2010), and even assessment of plume speed uncertainty is considered difficult due to the complex wind fields surrounding volcanoes (Mather et al., 2006). A plume speed uncertainty of 20-30% has been used in previous studies using meteorological wind models (Galle et al., 2010; Conde et al., 2014) and we adopted that uncertainty in our flux estimation. As a total, we assumed the errors of our flux calculations for two conditions following Galle et al., (2010) as "Good" and "Fair" and estimated the error of our flux measurements as 26% and 46%, respectively.

After the 2015 eruption on May 29, 2015, the regular service of Ferry Taiyo between Yakushima and Kuchinoerabujima Islands was stopped until the full evacuation of the residence of Kuchinoerabujima Island had been called off on Dec. 25, 2015. During this period, the first box type observation system, which had been used on Ferry Taiyo, was deployed for repetitive measurements by a fishing boat, "Fumimaru" (Fig. 2d). The observation method with Fumimaru was basically the same as that for the Ferry Taiyo. The captain of Fumimaru set and started the system near Kuchinoerabujima Island after departure from Yakushima Island. To avoid direct sunlight on the instrument box during the measurements, a plastic basket with a UV transparent window was used as a sunshade (Fig. 2g). The boat made several traverses off the downwind side coast of Kuchinoerabujima Island and returned to Yakushima Island. The UV spectroscopic measurements were started and observed data were sent to the cloud storage server automatically by the

system four to five hours after the system was turned on.

4. RESULTS AND DISCUSSION

Figure 3 shows examples of the SO₂ column amount time series of the measurements by Ferry Taiyo and Fumimaru. Figures 3a-c show two peaks of SO₂ corresponding to plumes during out-bound and in-bound traverses. Figure 3c corresponds to an example of low SO₂ flux on Apr. 15, 2016, about a year after the 2015 eruption. Figure 3d is an example of the southerly wind condition when the plume flew on the other side of the island from the ferry's route. Figure 3e is an example of the easterly wind condition when the plume flew over Honmura Port on Kuchinoerabujima Island. In this case, Ferry Taiyo was not able to cross beneath the plume and was detecting SO₂ while stopping at the port (The Ferry Taiyo is scheduled to stop at Honmura Port at either 9:50 – 10:30 or 14:40 – 15:10). In these two cases, the SO₂ flux cannot be calculated. Figure 3f is an example of Fumimaru measurements making 4 traverses (two round-trips) under the plume. By integrating by the distance observed SO₂ column amount time series as above, and multiplying by the appropriate wind speed from the GPV wind data, we calculated the SO₂ flux of Kuchinoerabujima Volcano.

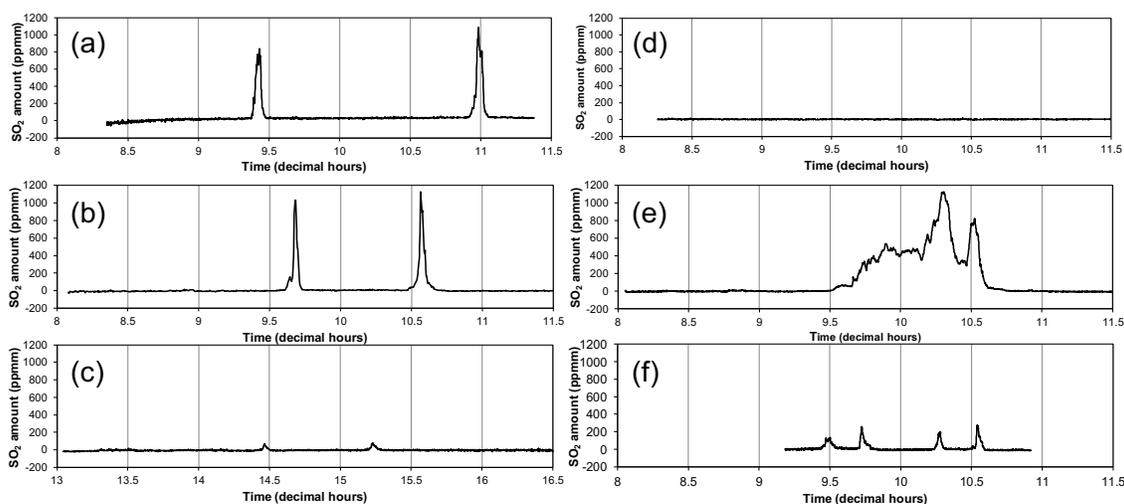


Fig. 3. Examples of SO₂ column amount time series observed during the traverse measurements. Horizontal axes are time in decimal hours. (a) – (e) were measured by Ferry Taiyo. (f) was measured by Fumimaru. (a) Dec. 30, 2014; (b) May 10, 2015, (c) Apr. 15, 2016; (d) Apr. 6, 2015; (e) May 10, 2015 and (f) Sep. 9, 2015. See text for the details.

Figure 4 shows the SO₂ flux time series of the volcano between Aug. 2014 and Jun. 2016. The black circles correspond to the data observed by repetitive measurements by Ferry Taiyo and Fumimaru. The white circles are data of the Japan Meteorological Agency (JMA) mostly obtained by car traverses until Nov. 2014 and boat traverses afterward. The circles show the average flux value of the day. The high and low values correspond to the maximum and minimum values of the day. In the case of Ferry Taiyo measurements, the average value corresponds to the average of two traverses.

The first Ferry Taiyo measurement was carried out on Nov. 26, 2014. Between the first day and the day of the 2015 eruption on May 29, 2015, the SO₂ flux was retrieved for 57 days out of 185 days by Ferry Taiyo. Considering until the end of June 2016 including both Ferry Taiyo and Fumimaru measurements, the SO₂ flux was retrieved for 121 days out of 583 days. There were several reasons for missing flux data. The major reason for the missing data was bad weather conditions (raining and the ferry cancellations due to strong wind or high waves), inappropriate wind direction as shown in the traverse data in Figs. 3d and e. Other major reasons were related to instrumentation problems such as data transfer and PC failures, and

were periods when Ferry Taiyo was in dry dock for periodic vessel inspections.

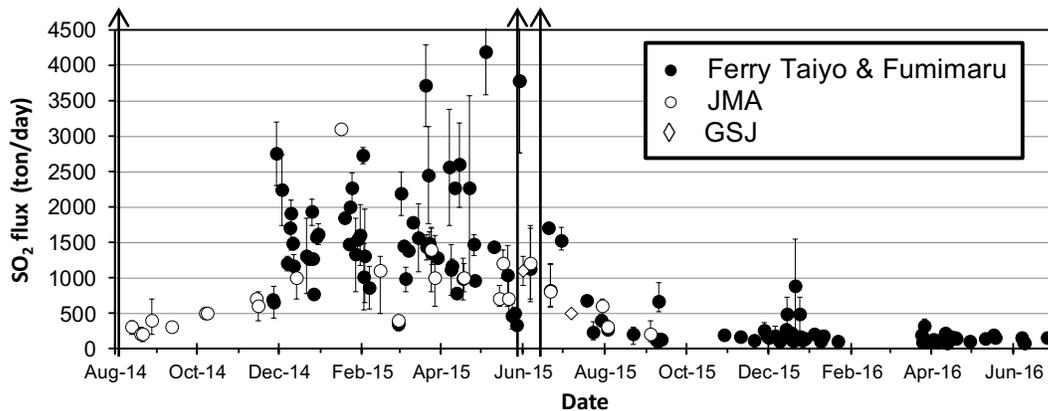


Fig.4. The SO₂ flux of Kuchinoerabujima Volcano between August 2014 and June 2016. Vertical arrows from the left correspond to eruptions on Aug. 3, 2014, May 29, 2015 and Jun. 18, 2015, respectively. GSJ data are unpublished data observed and provided by the Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (Kazahaya, personal communication, October, 2016).

After the 2014 eruption, the SO₂ flux gradually increased from several hundred ton/day to 700 ton/day until the first Ferry Taiyo measurements on Nov. 26 (Fig. 4). The flux suddenly increased to over 2500 ton/day on Nov. 29, 2014 and ranged from 1000 to 2500 ton/day with an average of about 1600 ton/day until the 2015 eruption on May 29, 2015 (Fig. 4). About 4 to 6 hours after the May 29 eruption, the flux measurements were available because Ferry Taiyo went to Kuchinoerabujima Island to evacuate the residents and recorded about 3800 ton/day. The flux rapidly decreased to the 100-200 ton/day range by early Sep. 2015 and remained in that range until the end of June 2016 with some exceptionally high fluxes of over 500 ton/day in mid-September and mid-December 2015 (Fig. 4).

The gradual increase of the flux for several months and the sudden increase of the flux at the end of Nov. 2014 indicated that the eruptive activity of Kuchinoerabujima Volcano after the 2014 eruption was not heading toward quiescence but a large amount of magma was engaged in the degassing activities, because high SO₂ flux values strongly suggest the presence of magma beneath a volcano (e.g., Symonds et al., 2001, Oppenheimer et al., 2014). Figure 5 shows the SO₂ flux between the 2014 and the 2015 eruptions together with the daily maximum plume height, daily number of earthquakes and ground deformation observed by GNSS. There were three notable SO₂ flux features during this period: (i) A sudden increase of the flux at the end of Nov. 2014, (ii) Frequent high (>2500 ton/day) and highly variable fluxes between mid-March and early May 2015, and (iii) Continued low flux below 500 ton/day prior to the May 29, 2015 eruption.

The sudden flux increase occurred within a few days from 700 ton/day on Nov. 26 to over 2500 ton/day on Nov. 29, 2014. Increase of SO₂ fluxes prior to eruptions are commonly observed phenomena elsewhere (e.g., Malinconico et al., 1979; Daag et al., 1996, Olmos et al., 2007). Such flux increases are often accompanied by increased seismicity. Prior to the Oct. 1, 2005 eruption of Santa Ana Volcano, El Salvador (Olmos et al., 2007) and the Jan. 5, 2010 eruption of Turrialba Volcano, Costa Rica (Conde et al., 2014), clear increases of the flux together with an increase of RSAM (Real-time Seismic Amplitude Measurements; Endo and Murray, 1991) signals were observed and up-rises of magma to shallower levels were suggested based on their observations. In contrast to the observations above, the flux increase at Kuchinoerabujima Volcano occurred aseismically and even without apparent change in plume height (Fig. 5). As explained above, almost all the monitoring instruments were destroyed by the 2014 eruption (Iguchi et al., this issue) and the seismic station used was about 2.2 km north-east from Shindake crater (Fig.1c).

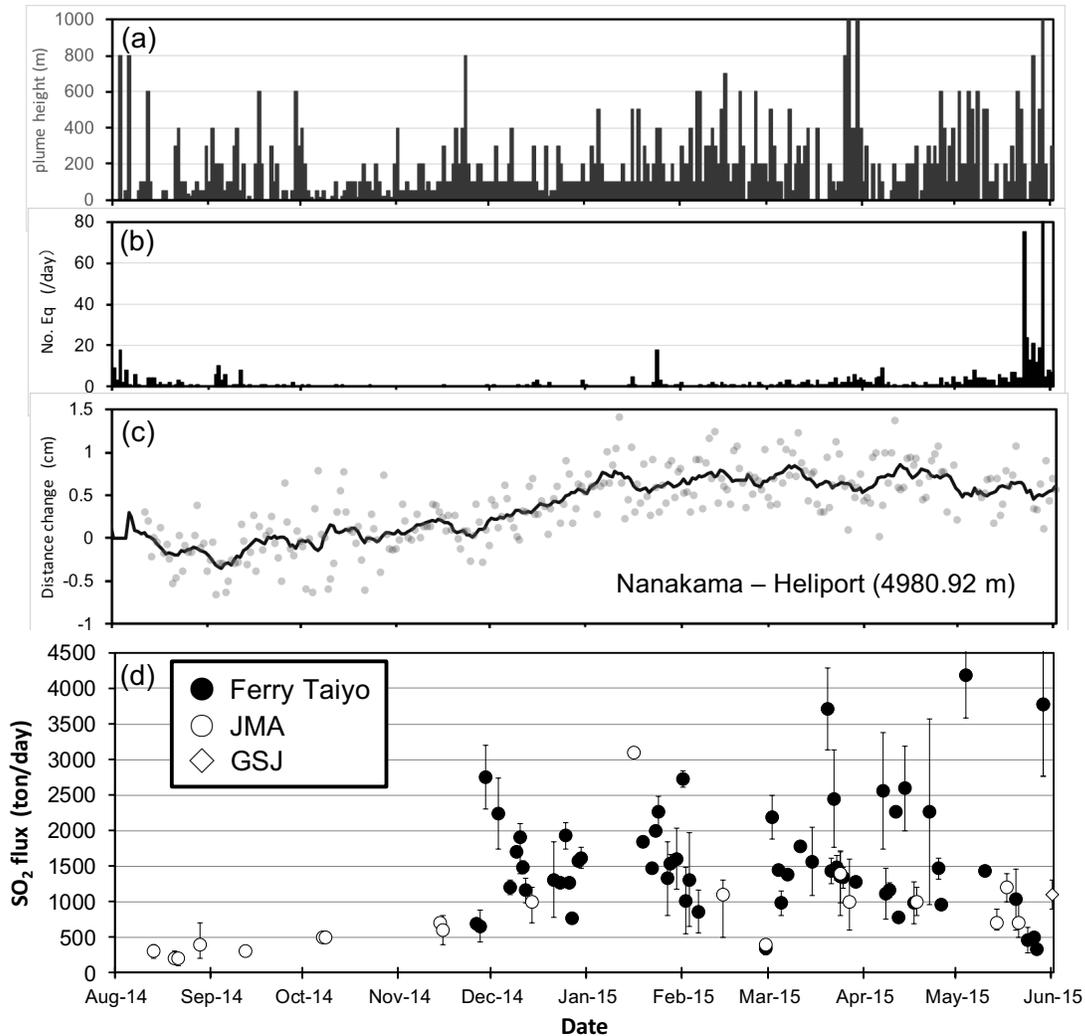


Fig.5. Various observations between August 2014 and June 2015. (a) Daily highest plume height. (b) Daily number of earthquakes at Shindake-Hokuto-Sanroku seismic station (Fig. 1b). (c) Distance change between Nanakama and Heliport GNSS stations (Fig. 1b). The dots are daily values and the curved line corresponds to the moving average of one week. (d) The SO_2 flux.

This may partly explain the aseismic flux change, since the distances of the station from the crater were much shorter: about 1 km at Santa Ana (Olmos et al., 2007) and Turrialba (Conde et al., 2014). Figure 5c shows the baseline change between the two GNSS stations located on the flanks of opposite sides of Shindake crater (Fig. 1b). This baseline showed an increase probably corresponding to the inflating deformation of the volcanic edifice from the beginning of Dec. 2014 for an about two-month period (JMA, 2015). The start of the deformation corresponds to the sudden increase of the flux, implying some kind of pressure increase as well as upward migration of magma and/or volcanic fluid beneath the volcano. Increase of the SO_2 flux can be expected not only by an uprise of magma but also by drying out of the hydrothermal system, which had been absorbing SO_2 (Daag et al., 1996), increasing the permeability of the conduit system (Edmonds et al., 2003) and/or increasing the convection rate of magma in the volcanic conduit (Kazahaya et al., 1994, Shinohara, 2008). Shinohara et al. (2011) revealed the decreasing influence of the shallow low temperature hydrothermal system on the high temperature magmatic gas of Kuchinoerabujima Volcano during the five years of their repetitive surveys. Considering this, the drying out of the hydrothermal system

may be due in part to the sudden flux increase observed at the volcano, however, it is difficult to clearly suggest the mechanism of the change only with our flux data and limited available geophysical data after the 2014 eruption.

Frequent high flux (>2500 ton/day) and highly variable fluxes were observed between mid-March and early-May 2015. The highly variable fluxes included a large difference between consecutive observation days and also a huge variation over 1000 ton/day between fluxes of two traverses, which were an hour to a few hours apart in time. Thermal camera observations for the western rim fumaroles of the Shindake crater showed a clear increase from around March 2015 and a high sensitivity video camera frequently observed the volcanic glow at night time after Mar. 24, 2015 (JMA, 2015). This evidence suggests high temperature gas emissions at the vent with sufficient flux to maintain the glow, which is consistent with the high SO₂ flux observed during this period.

Huge variabilities in SO₂ fluxes in a short time are quite common at many volcanoes (e.g., Caltabiano et al., 1994). High variable fluxes prior to the eruptions have been reported for the July 16, 1992 and the June 7, 1993 eruptions of Galeras Volcano, Columbia (Zapata et al., 1997), and for the Oct. 1, 2005 eruption of Santa Ana Volcano (Olmos et al., 2007). These variations were explained by periodic fracture of rocks that were partially sealing inside the conduit system (Zapata et al., 1997; Olmos et al., 2007). Similar conditions likely occurred within the conduit system of Kuchinoerabujima Volcano during the period, which may suggest instability of the conduit as a gas pathway and a sealing process was likely to occur in the conduit.

About one week before the May 29, 2015 eruption, the flux showed considerably low values of below 500 ton/day (Fig. 6d). A low value below 500 ton/day was once observed at the end of February 2015 after the end of November 2014. Since Ferry Taiyo was in dry-dock for inspection before this measurement for about 20 days, we are not certain of the duration of the low flux. Nevertheless, a decreasing trend from mid-May and the continuous low flux at the end of May were significant features of the flux measurements by Ferry Taiyo. At Kuchinoerabujima Volcano, low SO₂ fluxes below 500 ton/day were observed on May 24, 26 and 27. A decrease of the volcanic plume was clearly observed from several days before the May 29, 2015 eruption by officers of JMA and local people (Uhira and Toriyama, 2016) as well as by the captain of Ferry Taiyo (Personal communication with Captain Ohki of Ferry Taiyo). Imminent decreases of gas fluxes prior to explosive eruptions are very common and reported elsewhere with a variable duration of decreased periods (e.g., Harris et al., 1981; Casadevall et al., 1994; Zapata et al., 1997; Yokoo et al., 2013). A SO₂ flux decrease of two days was observed at Redoubt Volcano with a coinciding increase of the hourly number of earthquakes prior to the Mar. 23, 1990 eruption (Casadevall et al., 1994). Precursory flux decreases are generally considered due to sealing (or partial sealing) of the conduit, which results in pressurization of the magmatic system and further results in eruptions (Casadevall et al., 1994). In fact, on May 23, a volcano-tectonic earthquake of M 2.3 occurred, which was felt by local people on the island (Uhira and Toriyama, 2015; Iguchi et al., this issue), and the number of daily earthquakes increased after that until the eruption (Fig. 6b). The seismic increase observed simultaneously with the SO₂ flux decrease was considered due to a pressure buildup of the shallow magmatic system at Redoubt Volcano (Casadevall et al., 1994). It is very likely that pressure build up at the depth was in progress due to the sealing of the main conduit at Kuchinoerabujima Volcano, which probably lead to the May 29 eruption. The high variable SO₂ flux since mid-March 2015 and the sudden and prolonged observed low flux were probably clear precursors, and could have been used for early warning of the coming eruption.

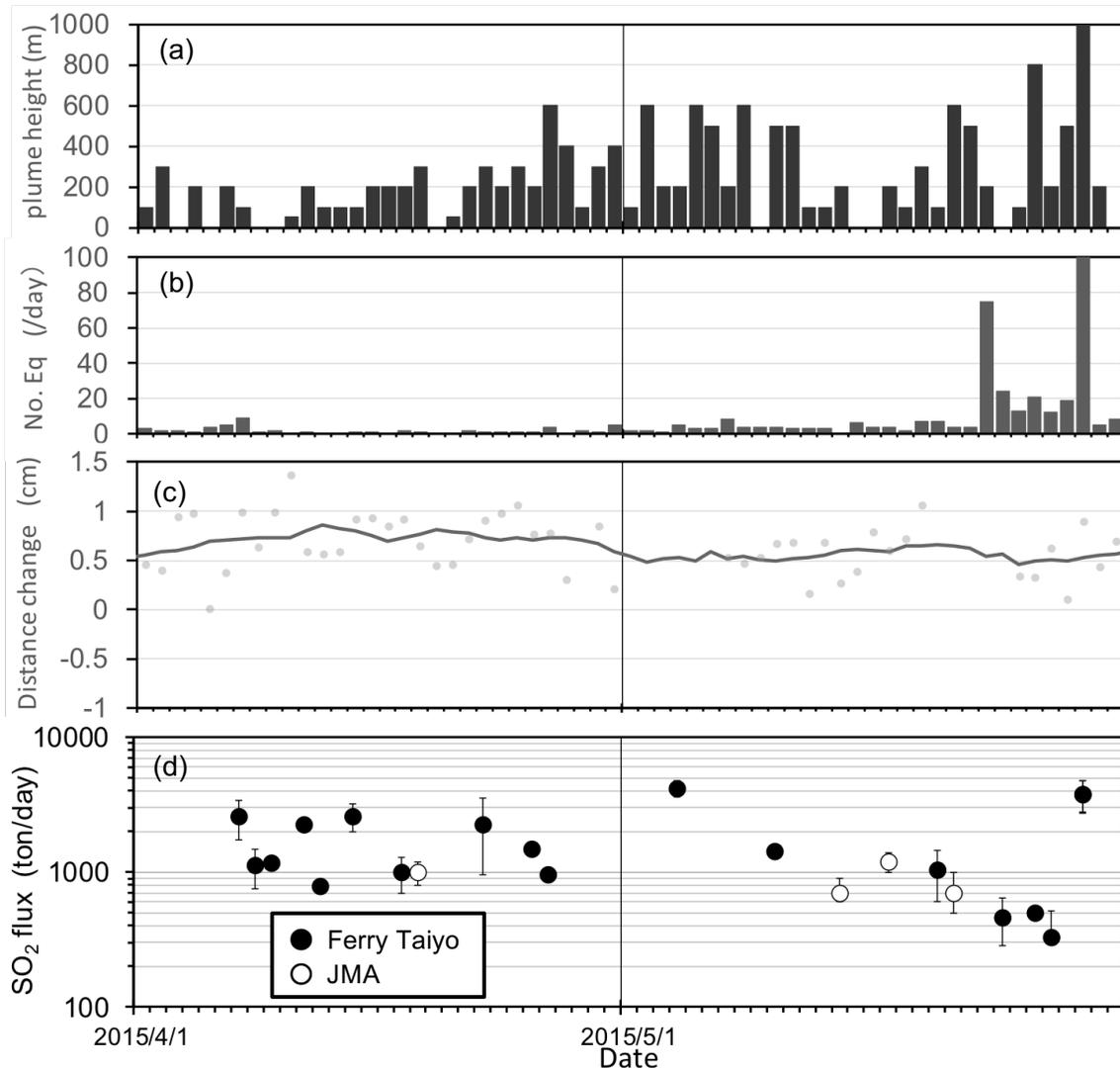


Fig.6. Various observations for April and May 2015. (a) Daily highest plume height. (b) Daily number of earthquakes at Shindake-Hokuto-Sanroku seismic station (Fig. 1b). (c) Distance change between Nanakama and Heliport GNSS stations (Fig. 1b). The dots are daily values and the curved line corresponds to the moving average of one week. (d) The SO_2 flux.

After the May 29, 2015 eruption, there was a vulcanian eruption on June 18 at Kuchinoerabujima Volcano (Iguchi et al., this issue). Although the degassing activity is still in progress, there has been no eruption to date. The SO_2 flux quickly decreased to the 100-200 ton/day range in the three months after the May 29 eruption (Fig. 4). Sulfur dioxide flux decrease after an eruptive activity is probably natural and a widely-observed phenomenon (e.g., Symonds et al., 1990; Casadevall et al., 1994; Zapata et al. 1997; Mori and Kato, 2013). At Augustine Volcano, Alaska, the SO_2 flux decreased exponentially after the 1986 eruption (Symonds et al., 2000) and the flux decreased below the detection limit in 1-2 years after eruptions including the 1986 eruption (McGee et al., 2010). After the 2011 Shinmoedake eruption at Kirishima volcanic complex, Japan, the SO_2 flux fell below the detection limit about one and a half years after the main subplinian eruption and about 9 months after the last phreatic eruption in September 2011 (Mori and Kato, 2013). At Ontake Volcano, the SO_2 first recorded over 1000 ton/day soon after the phreatic eruption on September 27, 2014. The flux went down to about 130 ton/day in two months and further decreased to

less than 7 ton/day in 8 months (Mori et al., 2016). These decreases of the flux are explained by stopping of the magma supply from the depths (Oppenheimer et al., 2014) of a degassed magma reservoir (Symonds et al., 2000) and/or scrubbing by hydrothermal waters (Symonds et al., 2001; McGee et al., 2010). In any case, if the gas supply from the magma system to the plumbing system is depleted and the influence of the hydrothermal system becomes significant, the flux would decrease to a negligible value. Kuchinoerabujima Volcano is still emitting 100-200 ton/day of SO₂ one year after the 2015 eruption (Fig. 4). Although the flux has significantly decreased compared to that soon after the 2015 eruption, the range of the flux is still sufficiently high to consider that there is still magma beneath the volcano degassing and supplying volcanic gas and that the conduit system is still not significantly affected by the hydrothermal system. Symonds et al. (2001) pointed out that a continuous SO₂ flux over 100 ton/day indicates the presence of magma in the plumbing system. We still need to monitor the SO₂ flux of Kuchinoerabujima Volcano carefully until the flux becomes well below 100 ton/day.

5. CONCLUDING REMARKS

In the last decade, repetitive SO₂ flux monitoring has been carried out at many volcanoes by automated scanning systems (e.g., Edmonds et al., 2003; Galle et al., 2010; Burton et al., 2009). Since the scanning method (e.g., McGonigle et al., 2003; Edmonds et al., 2003) does not need migration of the sensors beneath the plume and can be completely automated, it is more suitable for repetitive monitoring compared to the traverse method, which involves migration of the sensor beneath the plume. The scanning method carried out using a few scanners (e.g., Edmonds et al., 2003; Galle et al., 2010) is probably an adequate method for automated SO₂ flux monitoring at volcanoes at low latitude with a stable predominant wind direction by trade-winds. However, at mid-latitude volcanoes where the wind direction and wind speed are less stable, more scanners are needed and geometrical plume height estimation, which is fundamental for the SO₂ flux estimation using the scanners (Edmonds et al., 2003; Galle et al., 2010), is usually more difficult (Burton et al., 2009; Salerno et al., 2009). Volcanic plume grounding is reported for the downwind side of the volcanoes (e.g., Delmelle, 2003; Burton et al., 2009). In the case of the plume grounding and especially when one of the scanners was surrounded by the grounded plume, the plume height estimation by the geometrical method, which is fundamental in the scanning flux calculation, would not work properly because the method does not assume such conditions, and thus the flux measurements become impossible with the scanning method. In such cases the traverse method may become more robust and advantageous than the scanning method.

The repetitive SO₂ flux measurements carried out in this study were based on the traverse method and semi-automatic. However, our measurements were carried out without an experienced observer, which had been the case for the previous repetitive flux measurements based on the traverse method (e.g., Caltabiano et al., 1994), and was probably the first trial carrying out repetitive flux measurements using regular service transportation as the carrier for the traverse method. Considering the case of Kuchinoerabujima Volcano, in fact, environmental SO₂ monitoring carried out by Kagoshima Prefecture near Honmura Port sometimes recorded a SO₂ concentration over 0.1 ppm after the 2014 eruption (<https://www.pref.kagoshima.jp/ad05/kurashi-kankyo/kankyo/taikisouon/taikiosen/taikikannkyoujyouhou/kutinoerabu.html>). These SO₂ anomalies at ground level can be considered clear evidence for occasional plume grounding at the volcano and suggest that the traverse method was adequate for repetitive measurements of the volcano, although the measurements were limited to northerly wind conditions due to the route of Ferry Taiyo.

Conditions for using regular service transportation for the repetitive SO₂ flux measurements may be significantly limited due to fixed and unchangeable routes but have the advantage that the measurements can be made regularly using the traverse method. We believe the method applied at Kuchinoerabujima Volcano could become one of the choices for monitoring a SO₂ flux, especially when setting up routine monitoring in response to eruptions.

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