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Analysis of High Volcanic Gas Concentrations at the Foot of Miyakejima Volcano, Japan

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ABSTRACT

Continuous measurement data of sulfur dioxide (SO_2) in 2001 at the foot of Miyakejima volcano is discussed in conjunction with upper wind data at Hachijyojima, NOAA/AVHRR satellite imagery, and ground observation of volcanic plumes from Mikurajima Island. The following results were obtained: (i) Fresh winds of more than 7 m/s produced high SO_2 concentrations in the area downwind of the plumes. (ii) In winter, steady north-westerly winds carried high SO_2 concentrations for many hours to the monitoring station located southeast of the volcano. (iii) In summer, winds were relatively calm due to the dominant Pacific high-pressure system over Japan, resulting in low SO_2 concentrations at ground level on the island, except when typhoons passed. (iv) Travelling high/low pressure systems that move eastward are characteristic of spring and autumn weather, and high SO_2 concentrations produced by strong, changeable winds were recorded at various stations as low pressure systems accompanying cold fronts passed near the island.

1. INTRODUCTION

Eruptions of Miyakejima volcano, about 160 km south of Tokyo (Fig. 1), have occurred at intervals of about 20 years; 1940, 1962, 1983, and 2000. The latest activity started on 8 July, with the ejection of enormous amounts of sulfur dioxide (SO_2) and continues as of June 2003. In 2000, the SO_2 flux, monitored by an airborne correlation spectrometer (COSPEC), averaged about 42000 tons/day, but has since decreased gradually. The flux had decreased from 40000 to 10000 tons/day, with fluctuation, in 2001 but still exceeded 5000 tons/day in June 2003 (Kazahaya et al., 2003). Large eruptions, recorded on 10, 18, and 29 August 2000, had respective cloud heights of about 8, 14, and 8 km (Japan Weather Association, 2000). All Miyakejima inhabitants have been evacuated since 1 September 2000. Since then, no notable eruptions have been recorded, and the volcanic clouds turned from ash-rich to white and vapour-rich since mid-September.

As volcanic gas tends to move together with the volcanic plume, as found in previous studies of the Sakurajima and Aso plumes (Kinoshita et al., 2000; Kinoshita et al., 2001), advection of the gas could be inferred from the plume images. Horizontal dispersion is seen in satellite images, and vertical plume movement in ground observations.

The Tokyo Metropolitan Government started monitoring volcanic gas concentrations at the foot of Miyakejima volcano from the end of 2000. Here, we focus on periods of high SO_2 concentrations, defined as exceeding 1 ppm/hour, observed in 2001. Analysis of SO_2 data is discussed in conjunction with the upper wind data at Hachijyojima, NOAA/AVHRR satellite imagery, and ground observations of the volcanic plumes from Mikurajima Island. Meteorological conditions when high SO_2 concentrations

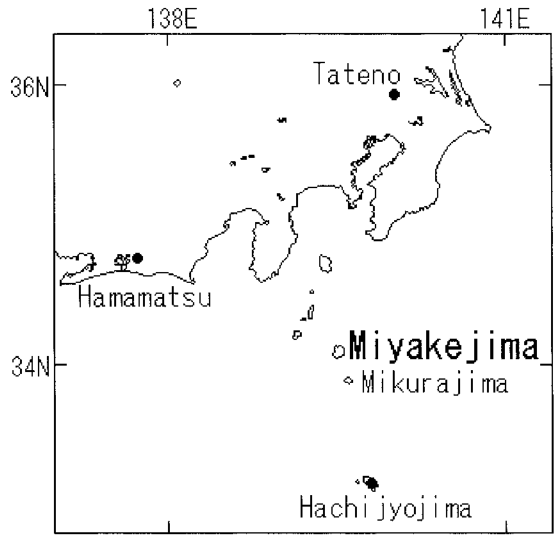

Fig. 1 Locations of Miyakejima, Mikurajima and Hachijyojima islands, and the upper air observatories (closed circles).

KEY WORDS: sulfur dioxide, mountain lee wave, upper wind, NOAA/AVHRR

occurred were assessed. Brief reports in Japanese on this topic are given in Iino et al., 2002 and Koyamada et al., 2003.

2. DATA AND METHODS OF ANALYSIS

2.1. Continuous measurement of sulfur dioxide

The Tokyo Metropolitan Government began continuous monitoring of the SO_2 and H_2S levels at three stations, the Miyake Branch Office, the Airport and Ako, on Miyakejima, in December 2000. Three other locales, Ainohama, Akacooco and Igaya, were added in September 2001. In February 2002, the number of stations was extended to 10 by adding ones distributed around the foot of the volcano. Figure 2 shows the 6 stations in operation in 2001. The SO_2 and H_2S concentrations respectively were measured by the ultraviolet fluorescent and controlled potential electrolysis methods.

The volcanic gas-monitoring stations provided two kinds of temporal data; five-minute and one-hour averaged. Figure 3 shows the variations in SO_2 concentrations observed at the Branch Office on 21-22 August 2001. Although the sharp peaks seen in the five-minute averaged data are smeared in the one-hour averaged data, high SO_2 concentration conditions are well represented by the latter. As the upper wind data used in the comparison with the SO_2 concentration is for six-hour intervals, we consider that the temporal resolution of the one-hour averaged data is sufficient; therefore, only the one-hour values are discussed here.

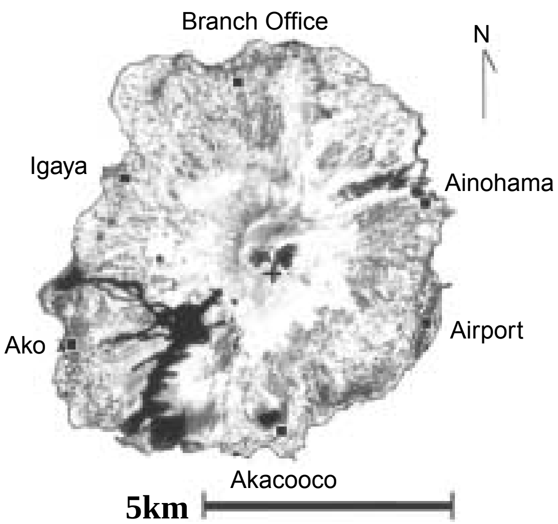

Fig. 2 Locations of volcanic gas-monitoring stations on Miyakejima in 2001(closed squares) and the vent (cross).

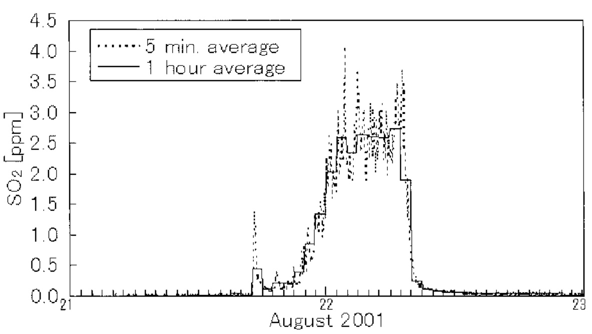

Fig. 3 Comparison of five-minute and one-hour SO_2 concentration values.

The volcanic gas at Miyakejima is the high-temperature type, in which sulfur is mainly oxidized in the reaction $H_2S + 2\,H_2O \rightleftharpoons SO_2 + 3\,H_2$. Equilibrium depends on the ambient temperature and pressure. H_2S is the principal gas at low-temperatures and surface pressures, but not at high-temperatures. Therefore, only the SO_2 concentrations are discussed. The highest SO_2 concentration, 15.2 ppm, was recorded at the Airport station on 20 April 2001, whereas the highest H_2S concentration was 2.9 ppm at the same station on 28 January and 26 March 2001. Environmental standards for the SO_2 concentration set by the Japanese Government as the respective desirable levels for the one-hour and daily averages are below 0.1 and 0.04 ppm. The American Conference of Governmental Industrial Hygienists has designated a 2 ppm concentration of SO_2 as the exposure threshold value for labourer. In this study, we focused on high concentration events, in which the one-hour average value was 1 ppm, in order to clarify the basic features of the phenomena.

2.2. Upper air data

The locations of the upper air observatories around Miyakejima are shown in Fig. 1. Upper wind data were observed 4 times a day, 03, 09, 15, and 21 JST (Japanese Standard Time = UTC + 9 hours), by radiosonde measurement at each station, except Hamamatsu. The temperature and relative humidity at these stations were measured only at 09 and 21 JST. The Hamamatsu wind data were available only for 09 and 21 JST.

The upper wind around the Oyama summit (814 m a.s.l.) of Miyakejima volcano has a dominant effect on the SO_2 concentration at ground level. As shown in Fig. 1, the nearest upper air observatory is at Hachijyojima, which has a similar geographical situation also being an isolated island. The Hachijyojima wind data at 925 hPa, corresponding to an altitude of about 830 m a.s.l., close to the summit height of Miyakejima, was used. To investigate atmospheric stability conditions in detail, vertical profiles of air temperature T [K] up to 3000 m and of the potential temperature θ [K] were plotted as functions of altitude z [m] (e. g., Fig. 10);

$$\theta(z) = T(z)\left(\frac{p_0}{p(z)}\right)^{\frac{R_d}{C_p}},$$

where, p(z), p_0, R_d, and C_p respectively are the air pressure [hPa], standard pressure at 1000 hPa, gas constant for dry air [J / K kg], and specific heat at constant pressure [J / K kg]. In addition, the Froude number Fr [dimensionless] was calculated from the equation

$$Fr = \frac{U}{NH}.$$

Where U is the wind velocity [m/s] around the summit, H the height of Miyakejima volcano, 814 [m], and N the Brunt-Vaisala frequency, [rad /s], represented as

$$N = \sqrt{\frac{g}{T_0}\frac{d\theta}{dz}},$$

Table 1 Total observation times at each monitoring station in 2001 and the number of times that the percentage of high SO_2 concentrations exceeded 1 and 2 ppm. Note that the gas-monitoring stations at Ainohama, Akacooco, and Igaya were installed in September 2001.

	Branch Office	Ainohama	Airport	Akacooco	Ako	Igaya
Obs. Hours	8251	1981	7792	2881	6878	2883
>1 ppm [hours]	36	32	980	41	142	89
>1 ppm [%]	0.4	1.6	12.6	1.4	2.1	3.1
>2ppm [hours]	15	12	695	20	34	40
>2ppm [%]	0.2	0.6	8.9	0.7	0.5	1.4

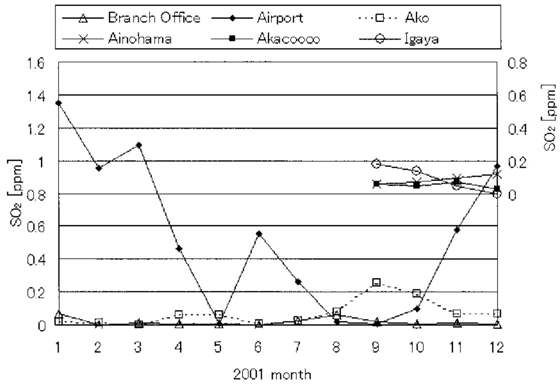

Fig. 4 Monthly average SO_2 concentrations in 2001. Concentrations at the Branch Office, Airport, and Ako are given on the left and those at Ainohama, Akacooco, and Igaya on the right.

where, g is the gravitational acceleration constant [m/s^2], T_0 the lowest layer temperature [K] except for the surface, and $d\theta/dz$ the temperature gradient [K/m] between the lowest layer and summit.

2.3. Satellite data analysis

Since August 2000, eruption clouds and ash-rich/less plumes have been detected at Miyakejima by the Kagoshima group based on meteorological satellite data (Iino et al., 2001; Kinoshita et al., 2003). The resulting satellite images are displayed at http://arist.edu.kagoshima-u.ac.jp/miyake/index-e.htm.

Since mid-September 2000, volcanic plumes were detected by taking the difference between the visible and near infrared channels in the NOAA/AVHRR images. This method enhances the white and vapour-rich plumes because of the size difference between sulfuric acid aerosols and meteorological clouds. Although some types of meteorological clouds appeared very similar to volcanic plumes, we were able to identify the plumes by making color images of the short-infrared channel because that channel is more sensitive to droplet size than the visible one.

2.4. Ground and helicopter observations

The Earthquake Research Institute (ERI) of the University of Tokyo installed a web camera system at Mikurajima, about 20 km SSE of Miyakejima (Fig. 1), and analyzed the motion of volcanic clouds from August 2000 to May 2002 (Terada and Ida, 2003). The system recorded distant and wide view images every 10 seconds, a portion of which has been shown in the website (in Japanese) [*1]. The latter images were analyzed to determine the behaviour and vertical structure of the plumes from the surface to the air.

The Japan Meteorological Agency (JMA) installed high sensitivity cameras at the Airport station in December 2000 and at the Kotekura-pylon station, 1.5 km NE of the Ako gas-monitoring station, in August 2001. These cameras mainly take close-up views of the crater and are able to take photos of plume flows, even at night. During November - December 2001, we checked plume flows by means of video-tapes, in particular when there was a discrepancy between the upper wind data and high SO_2 concentrations.

Helicopter observations of Miyakejima volcano have been made by researchers from the ERI, the Geological Survey of Japan (GSJ) of the National Institute of Advanced Industrial Science and Technology, and other institutions, by arrangement with the JMA. These observations provide precious information; e.g., on change in the crater's structure and the flow of volcanic plumes. Photo images taken from the helicopter and comments of the observers are given in the GSJ website (in Japanese) [*2]. We used these photo images to clarify plume flows in detail because they have a much higher spatial resolution than do satellite images.

[*1] Miyakejima plume observations: http://www.eri.u-tokyo.ac.jp/terada/kansi/.

[*2] GSJ Open File Reports: http://www.gsj.jp/GDB/openfile/ index_j.html (in Japanese).

Table 2 Direction of the crater from each station and the average values and standard deviations of wind direction and velocity for each station when high SO_2 concentration events occurred in 2001.

	direction to the crater [deg]	wind direction [deg]		wind velocity [m/s]	
		average	standard deviation	average	standard deviation
Branch Office	170	178	16	18.6	6.0
Ainohama	245	235	23	14.0	5.4
Airport	288	280	25	13.7	4.1
Akacooco	357	338	59	14.0	7.5
Ako	71	68	43	11.3	6.1
Igaya	123	118	34	9.0	4.4

3. HIGH CONCENTRATION EVENTS IN 2001

3.1. Annual tendency

Table 1 shows that the SO_2 concentration rate exceeding 1 ppm at the Airport station in 2001 was 12.6 %. In addition, the rate exceeding 2 ppm, the exposure threshold value designated by the American Conference of Governmental Industrial Hygienists, was 8.9 %. The rates exceeding these levels at the other stations were a few percent or less. The monthly average SO_2 concentration value at each station (Fig. 4) indicates that high concentration events frequently occurred in winter at the Airport station located southeast of the volcano owing to prevailing north-westerly winds.

Table 2 shows the direction of the crater from each station, and the average values and standard deviation in wind direction and velocity for each station when high SO_2 concentration events occurred. According to the idiomatic expression for meteorology, the wind direction representations of 0, 90, 180 and 270 degrees respectively are northerly, easterly, southerly, and westerly winds. As stated previously, we used the 925 hPa wind data observed every 6 hours at Hachijyojima station. To utilize hourly SO_2 concentration data, we interpolated the nearest time wind data for the intermediate time SO_2 data. In calculating the average wind direction at Akacooco station, 360 degrees was added to the raw data if less than 180 degrees to eliminate the numerical jump at 0 degree. The results given in Table 2 are also shown as sectors in Fig. 5. The radius and angle of each sector respectively show the average wind velocity values and the wind directions range. Fig. 6 is a scatter diagram of wind velocity and SO_2 concentration for each station at the wind observation time for a leeward direction of within 10 degrees. It shows that high concentration events were recorded at leeward stations in fresh wind exceeding approximately 7 m/s, which value might be a criterion for predicting high concentration events.

It should be noted that high concentrations were occasionally observed at Igaya and Ako stations when the wind velocity was lower than 7 m/s and that the standard wind direction deviation for Akacooco station is notably large. This may be because of local wind variation at Hachijyojima is not representative of Miyakejima, as understood from the meso-scale meteorological patterns. Synoptic charts for days when high SO_2 concentrations were recorded at these stations, show the local weather to be strongly affected by typhoons, low/high pressure systems, or a nearby cold fronts. In those situations, spatial and temporal differences in the wind field between Hachijyojima and Miyakejima may become large. In such cases, the upper air observations at six-hour intervals at Hachijyojima are not sufficient to follow changes in the wind field around the summit of Miyakejima.

To examine those cases in which wind direction alone could not explain high concentrations, Iino et al. (2003) studied the events for each station in which the concentration exceeded 0.5 ppm when the leeward direction was not within 90 degrees. Most events could be understood by examining the weather patterns, but a few could not be, even though the volcanic plumes were seen to be directed to the stations in ground observation videos recorded at Miyakejima by the JMA. These events may have been caused by local winds and have been affected by topography. In related research, Sasaki et al. (2002) made numerical simulations for four typical cases, taking into account detailed topographical and meteorological conditions, in order to understand the high surface SO_2 concentrations recorded at Miyakejima. They concluded that advection is dominant over other factors and that a slight change in wind direction causes a marked variation in the SO_2 concentration.

3.2. Seasonal characteristics

(1) Winter and summer

In winter, as discussed in Sec. 3.1, steady north-westerly winds brought high SO_2 concentrations lasting many hours to the monitoring station located southeast of the volcano. These persisted for 15-20 hours at the Airport station; markedly longer than at the other stations. In summer, winds are relatively calm due to the dominant Pacific high-pressure system, and the volcanic plumes tend to rise. The SO_2 concentrations on the island therefore are low, except when typhoons pass near the island. We found, however, that downwind of the volcano, 100-400 km away on the mainland, volcanic gases affected areas due to daytime convection (Nagai et al., 2001; Furuno et al., 2002; Kinoshita et al., 2003; Iino et al., 2004).

(2) Spring and autumn

Travelling high/low pressure systems that move eastward are characteristic of spring and autumn weather. High SO_2 concentrations caused by strong changeable winds were recorded at various stations as low-pressure systems that accompanied cold fronts passed near the island.

Typical temporal variations in SO_2 concentrations in autumn for one-hour SO_2 concentration values at six stations and 925 hPa wind directions at Hachijyojima from 4 to 6 November 2001 are shown in Fig. 7. The SO_2 concentration peaks observed in turn at Akacooco, Ako, Igaya, and the Branch Office and Airport stations (clockwise) clearly correspond to changes in wind direction. The peak occurrence is consistent with change in wind direction. The weather patterns on 4 to 5 November were a mobile high-pressure system that extended and followed behind a low which moved from southwest to northeast near the southern coastline of the Japanese archipelago. After this mobile high, another low accompanied by a cold front passed over the Miyakejima volcano on 6 November. Again, peaks were observed at stations leeward of the volcano. SO_2 concentrations increased at stations downwind, and decreased as the wind direction again changed. Throughout this

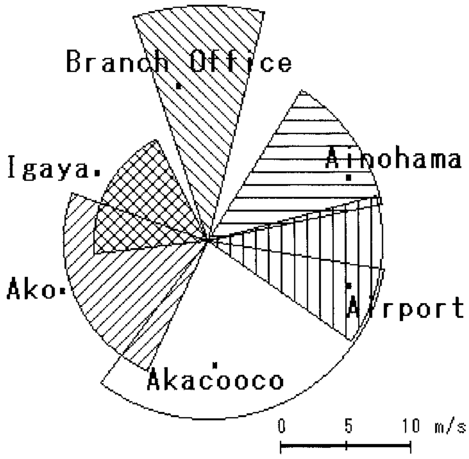

Fig. 5 Graph of Table 2. The radius and angle of each sector respectively show the average wind velocity and wind direction range values obtained from the average value +/- the standard deviation. The center represents the crater of the volcano. The relative location of each station from the crater is shown by a closed square.

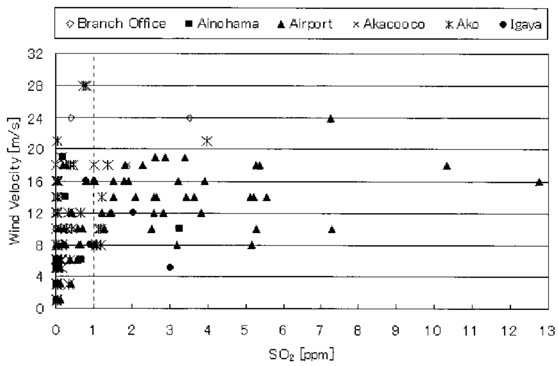

Fig. 6 Scatter diagram of the wind velocity and SO_2 concentration at each station at wind observation time for a leeward direction within 10 degrees.

period, wind velocities were about 10 m/s, except at 03 and 09 JST on 6 November. The respective velocities at those times on that day were 24 and 28 m/s, and high concentrations at Ainohama station were expected from the wind directions, but the concentrations there remained at 0.1 to 0.2 ppm. This may be attributed to very strong, collimated wind that produced volcanic gas and plume flow in a very narrow band. Under that condition, a slight deviation would produce a large difference in SO_2 concentrations. Similar events are plotted in Fig. 6. In section 4, some similar situations are discussed based on photo and satellite images.

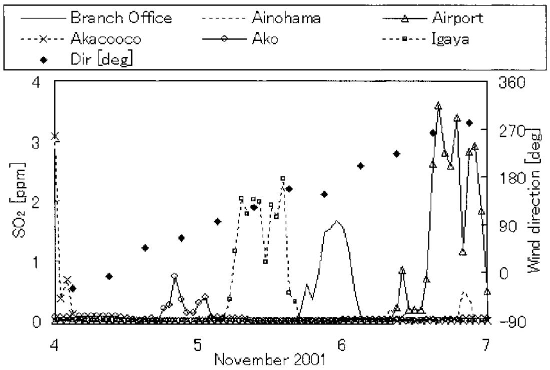

Fig. 7 Temporal variations in the one-hour SO_2 concentration values at six stations (left) and 925 hPa wind directions at Hachijyojima (right) from 4 to 6 November 2001. The first two pairs of wind directions are the values for -360 degrees subtracted from the raw data to maintain varying wind direction continuity.

4. RELATION BETWEEN HIGH CONCENTRATION EVENTS AND PLUME IMAGES

The relation between visible plumes shown in ground and satellite observations and high SO_2 concentration events at the ground surface was investigated based on the vertical structure of the plumes seen in photo images taken by the Mikura-camera and those from helicopters [*2]. The NOAA images show the advection and dispersion of plumes over a wide area. Although cloudy weather obstructed both types of observation, the NOAA difference images of the visible and near infrared bands discriminate the plumes containing sulfuric aerosols from the meteorological clouds. In the gray scale difference image, the plume is shown as a bright object, as in Fig. 8, whereas meteorological clouds appear dark. Some 176 scenes of plumes having various shapes were detected in 2001, all of which are displayed on the website mentioned in 2.3.

The plume behaviour in these images, SO_2 concentration, and 925 hPa upper wind data at Hachijyojima are given in Table 3. In the plume column, 'no rise' means an almost horizontal plume flow near the summit with no rising. 'Lee wave but miss' indi-

Table 3 Summary of plume behaviour, SO_2 concentration, and 925 hPa upper wind data in 2001 at Hachijyojima for the days NOAA satellite images were available.

mon.	day	ground observation			upper wind			SO_2 [Obs. Time]
		time	source	plume	dir[deg]	v[m/s]	time	
1	29	9:56	helicopter	mountain lee wave	294	14	9h	Airport: 2.7 ppm [9h]
	31	15:45	Mikura Camera	rising	296	7	15h	
2	9	13:22		rising	292	6	15h	
	10	8:05		mountain lee wave	270	8	9h	Airport: 3.0 ppm [9h]
	22	8:03		rising	304	8	9h	
	27	10:45		rising	152	3	9h	
4	13	10:00	helicopter	mountain lee wave	267	12	9h	Airport: 2.1 ppm [9h]
	16	10:00		rising	293	11	9h	
	23	7:50	Mikura Camera	rising	47	2	9h	
5	13	14:48		rising	230	2	15h	
	18	7:49		rising	235	3	9h	
6	1	10:00	helicopter	mountain lee wave	276	12	9h	Airport: 8.7 ppm [9h]
7	1	9:29	Mikura Camera	mountain lee wave	281	16	9h	Airport: 1.02 ppm [9h]
	3	12:48		rising	224	6	15h	
	4	12:00	helicopter	lee wave but miss	254	13	15h	
	6	14:00		lee wave but miss	259	17	15h	
	10	8:49	Mikura Camera	rising	33	2	9h	
	11	5:49		rising	233	6	9h	
	15	7:49		rising	182	3	9h	
	21	16:42		rising	145	2	15h	
8	13	15:54		rising	138	2	15h	
	14	8:54		rising	93	5	9h	
	23	9:54		no rise	246	11	9h	
9	25	5:54		mountain lee wave	3	9	9h	Akacooco: 1.08 ppm [6h]
10	12	14:54		no rise	261	8	15h	
	31	7:54		rising	331	5	9h	
11	4	13:54		mountain lee wave	47	8	15h	
	23	15:54		rising	113	2	15h	
	24	15:54		rising	144	2	15h	
	25	13:54		mountain lee wave	74	1	15h	Airport: 1.23 ppm [14h]
	26	9:54		mountain lee wave	280	16	9h	Airport: 2.56 ppm [10h]
	28	14:54		no rise	269	9	15h	
12	1	14:54		mountain lee wave	292	8	15h	Airport: 5.16 ppm [15h]
	2	13:54		mountain lee wave	258	11	15h	Airport: 2.31 ppm [14h]
	8	14:54		rising	295	8	15h	
	12	13:54		rising	239	3	15h	
	23	14:54		mountain lee wave	297	11	15h	Airport: 1.39 ppm [14h]

cates that the photo image shows a mountain lee wave but that the plume does not cover the area around a gas-monitoring station. High SO_2 concentrations were often recorded when a mountain lee wave formed in fresh wind exceeding 7 m/s and was blown to a gas-monitoring station, whereas high SO_2 levels were not recorded when a plume missed a station.

Typical respective cases of fresh and light winds are shown in Figs. 8a and b as seen on NOAA satellite images at 13:38 JST on 1 December and at 13:28 JST on 23 November. Corresponding photo images from the Mikura-camera are shown in Figs. 9a and b.

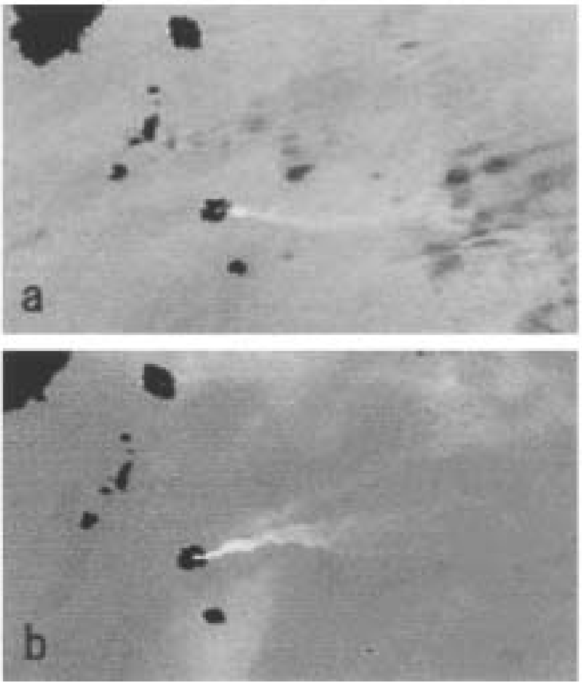

Fig. 8 NOAA images. (a) 1 December 2001 at 13:38 JST. (b) 23 November 2001at 13:28 JST.

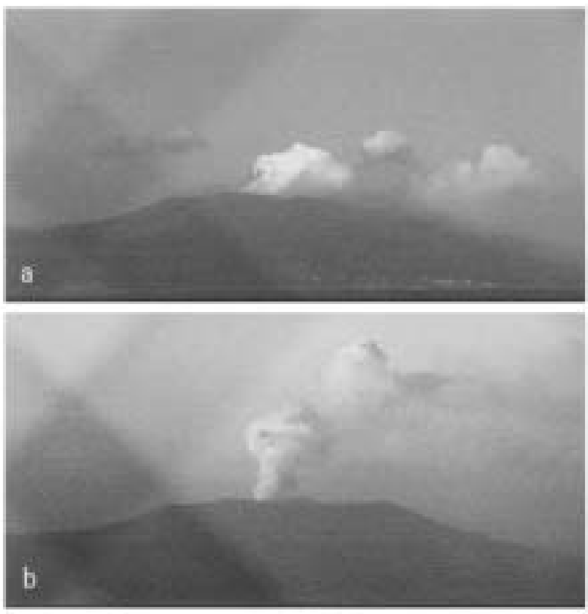

Fig. 9 Mikura-camera images. (a) 1 December 2001at 10:36 JST. (b) 23 November 2001at 15:37 JST.

The 925 hPa wind velocities at Hachijyojima were 16, 9, 8, and 8 m/s at 03, 09, 15, and 21 JST on 1 December. The atmosphere at 09 JST on 1 December was neutrally stratified to 1000 m and at which height there was a 0.6 K temperature inversion (Fig. 10a). The Froude number between z = 196- 800 m was 1.9. A mountain lee wave was formed (Fig. 9a) and high SO_2 concentrations were maintained at the Airport station for the whole day, but concentrations were not so high at Ainohama station slightly north of the former station (Fig. 11). This suggests that only the narrow regions downstream of the volcano are strongly affected by volcanic gases, little being dispersed during steady, fresh winds.

In the case of the mild winds on 23 November 2001, the respective velocities were 3, 2, and 3 m/s at 03, 15, and 21 JST (09 JST data was missing), the atmosphere was stable with a 0.3 K temperature inversion around 1500 m (Fig. 10b). The Froude number between 192-800 m, based on 15 JST wind data, was 0.5. Figure 9b shows plume rise with no lee wave formation. SO_2 concentrations from 01 to 17 JST were less than 0.1 ppm at all the stations on the volcanic island.

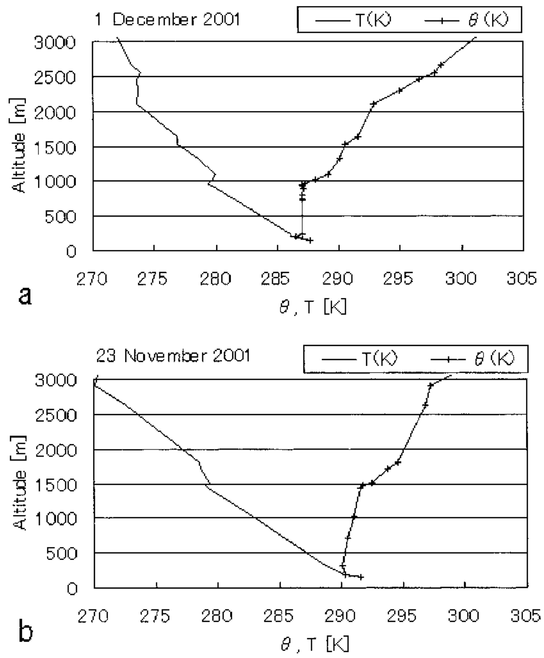

Fig. 10 Atmospheric conditions at 09 JST on 1 December and 23 November 2001.

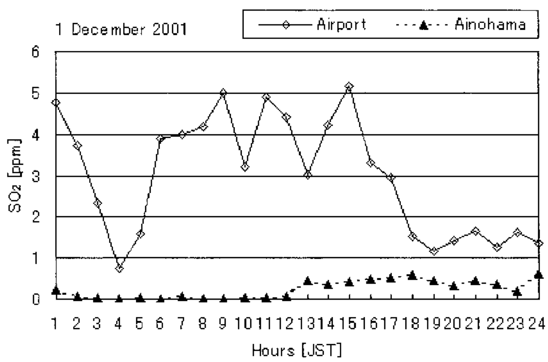

Fig. 11 Temporal variations in SO_2 concentration observed at the Airport and Ainohama stations on 1 December 2001.

These findings suggest that high SO_2 concentrations caused by fresh winds occur in narrow regions downwind and that slight deviation produces a large concentration change. For instance, on 4 and 6 July (Table 3) wind velocities respectively were 13 and 17 m/s, and wind direction seems to have brought high concentrations to the Airport station. Helicopter observations, which have much finer spatial resolution than NOAA images, well explain the low SO_2 concentrations at the Airport station (less than 0.1 ppm), because the plumes flowed only in a narrow north-side area and missed the station. In contrast, light winds allowed the plume to rise without producing high concentrations at ground level. The behaviour of volcanic gas resulting in high SO_2 concentrations therefore is confirmed from the flow of the visible plume.

5. CONCLUDING REMARKS

Miyakejima volcano has been ejecting a tremendous amount of volcanic gas since mid-August 2000. Continuous measurement data on SO_2 levels at the foot of the volcano in 2001 in conjunction with upper wind data, satellite imagery of NOAA/AVHRR, and ground observations of plumes from Mikurajima Island were investigated with the following results:

(i) High SO_2 concentrations in the volcano were caused by fresh upper winds around the summit height, and a narrow area downwind of the plume was in danger of experiencing excessively high SO_2 concentrations. In particular, for many hours in winter, steady north-westerly winds brought high SO_2 concentrations to monitoring stations located southeast of the volcano.

(ii) When there was a calm wind, as in summer covered with the Pacific high-pressure system, SO_2 concentrations on the island were low.

(iii) During changeable weather patterns caused by a mobile high-pressure system or a low-pressure system accompanied by a cold front, high SO_2 concentrations were recorded at various stations downwind of the plume due to change in the wind direction.

(iv) We confirmed that the behaviour of volcanic gas emitted from the crater at Miyakejima, which is of the high-temperature type, can be inferred from the behaviour of the visible volcanic plume.

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