Satellite analysis and mesoscale behaviour of volcanic plumes and gas from Miyakejima, Japan

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ABSTRACT:
Miyakejima plumes of ash-rich and vapour-rich clouds were detected well by the NOAA/AVHRR data, and the height of eruption cloud on 29 August 2000 was estimated reasonably using the brightness temperature at 11 μm of NOAA/AVHRR and the upper air data taking into account the effect of ash emissivity. We found two different mechanisms which bring the high concentration SO_2 to the mainland of Japan. (i) Convective daytime mixing brings gas down to the surface, after advection from Miyakejima in the upper air by winds associated with high pressure system. (ii) The volcanic gas descends to the island surface in strong winds associated with stationary fronts and low pressure systems.

Keywords: NOAA/AVHRR, volcanic ash, eruption clouds, sulphur dioxide

1. Introduction

Miyakejima volcano, about 160 km south of Tokyo (Figure 1), has been ejecting enormous amounts of sulphur dioxide (SO_2) since mid-August 2000. The SO_2 flux monitored by airborne COSPEC (Correlation Spectrometer) was a few ten kt/day in late-2000, and decreased gradually: it is still exceeding 5000 ton/day in March 2003 [1]. The SO_2 flux measurements are described at http://staff.aist.go.jp/kazahaya-k/miyakegas/COSPEC.html. All of the Miyake- jima inhabitants have been evacuated since 1 September 2000.

Miyakejima-Oyama (814 m a. s. l) started eruptive activities on 8 July 2000. Large eruptions were recorded on 10, 18 and 29 August with volcanic cloud altitudes of about 8, 14 and 8 km, respectively. Since 28 August 2000, volcanic clouds and gas caused high concentration episodes of SO_2 at many environmental gas-monitoring stations in Honshu, the main island of Japan, 100-400 km away from Miyakejima. Although large eruptions have not been recorded since September 2000, southerly and southwesterly winds brought the volcanic gas to Honshu, and the smells of sulphuric substances were reported from the end of August to September. From the mid-September 2000, the volcanic clouds became white and vapour-rich with a little ash. The eruption clouds and plumes have been detected by the Kagoshima group by using meteorological satellite data since August 2000, and the resultant satellite images are displayed at: http://arist.edu.kagoshima-u.ac.jp/miyake/index-e.htm.

In this study, we describe the detection techniques of ash-rich and vapour-rich clouds from the volcano, and estimate the height of the 29 August 2000 eruption cloud by using 11 μm brightness temperature from NOAA/AVHRR. We also focus on the SO_2 high concentration episodes observed in Honshu from the end of August to September. To clarify the mesoscale behaviour of the plumes and gas, we investigate these episodes by comparing satellite imagery of plumes, ground level SO_2 concentrations, simulation results of a vertical shear model based on the upper wind data and the mesoscale weather patterns.

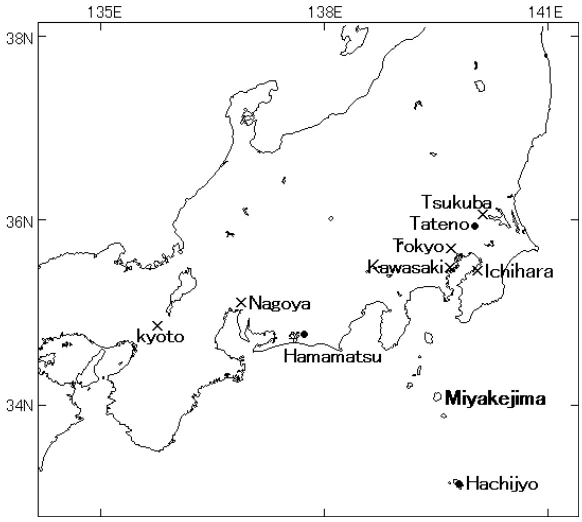


Figure 1 Location map of volcanic island Miyakejima, the upper air observatories, Hachijyo, Hamamatsu and Tateno denoted as circular a symbol, and the National environmental gas monitoring stations, Ichihara, Kawasaki, Kyoto, Nagoya, Tokyo and Tsukuba denoted as a cross symbol

2. Data sets and method of analysis

2.1. The AVHRR instrument of the NOAA meteorological satellites

Figure 2 shows the wavelength bands of NOAA-16/AVHRR and GMS-5/VISSR sensors. The AVHRR/2 sensor on NOAA-12 and -14 has five channels: visible (band 1: 0.58-0.68 μm); near-infrared (band 2: 0.725-1.00 μm); mid-infrared (band 3: 3.55-3.93 μm); thermal-infrared bands of 4 (10.30-11.30 μm) and 5 (11.50-12.50 μm). The NOAA-15, -16 and -17 AVHRR/3 has an additional channel in short-wave infrared (band 3A, 1.58-1.64 μm), and it is time-shared with the mid-infrared channel, designated 3B. NOAA satellites are polar orbiters with spatial resolution of 1.1 km at the nadir, while GMS-5 is a geostationary satellite with the resolution 5 km at the nadir in thermal bands. Spectral resolution of GMS-5 is also shown in Figure 2.

Ash clouds containing large amount of silicates can be distinguished from meteorological water/ice clouds by the Aerosol Vapour Index (AVI), taking the brightness temperature difference of 11 and 12 μm bands. This technique is based on the split-window method that has developed to estimate water vapour amounts in the air. The lithic aerosols in the 11 and 12 μm bands have opposite extinctive characteristics compared to water vapour. A similar response is expected from sulphuric acid aerosols in the area downstream from the eruption [2]. We identified successfully the plumes from Mt. Sakurajima and Aso, both in Kyushu, Japan, by this technique [3, 4], and also have detected the 2000 eruption clouds of Miyakejima by GMS-5/VISSR, which is able to apply this technique because it has split-window bands in the thermal infrared region, as shown in Figure 2 [5, 6].

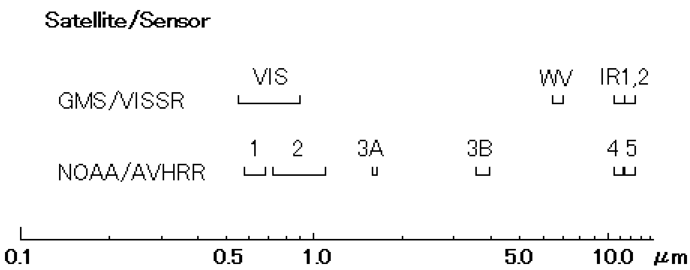


Figure 2 The wavelength bands of NOAA-16/AVHRR and GMS/VISSR sensors

The original NOAA/AVHRR data received at Kagoshima University (K-N) are in 10-bit format, which are converted into 16-bit data where the value n(i) of thermal infrared band i corresponds to the brightness temperature t(i) in centigrade as $t(i) = 0.1n(i) - 50$, for i = 4, 5. The NOAA/AVHRR data provided by Hokkaido University (H-N) is in 8-bit format, thus $t(i) = X\, n(i) - Y$, for i = 4, 5, where X = 0.2 and Y = 10, except for the data on 29 August, where X = 0.3 and Y = 30.

As an expression of the brightness temperature difference, we define the Aerosol Vapour Index (AVI) by the following equations.

$$AVI = n(5) - n(4) + Z, \quad \text{for NOAA/AVHRR with } Z = 200 \text{ (K-N) or } 100 \text{ (H-N)}$$

In the gray-scale AVI images, opaque ash clouds tend to be bright as AVI becomes high, while water vapour predominant areas tend to be relatively dark. The AVI method is particularly important because of its capacity for night-time monitoring of ash clouds.

In order to distinguish semi-opaque plumes from meteorological clouds, colour composite images of R: G: B = bands 1: 2: 4 or AVI are very useful for AVHRR/2 data. The plumes and meteorological clouds are identified as red-pink and yellow, respectively. In this paper we will show the monochrome images, which were converted from these colour composite images such as displayed at:
http://www.mech.kagoshima-u.ac.jp/lab/netu/miyake008/miyake-e.htm.

White and vapour-rich plumes, which were observed since October 2000, are difficult to detect using AVI imagery. The differences of bands 1 and 2 (denoted as b1-2) can enhance the plumes owing to the particle size difference between the sulphuric acid aerosols and meteorological clouds. Colour composite images of R: G: B = bands 1: 2: 3A can distinguish the plumes from meteorological clouds, because the short-wave infrared channel (band 3A) is much more sensitive to droplet size than the visible channel. These images were discussed in detail in our previous study [6]. The colour composite images are shown in our website mentioned in Section 1.

2.2. Upper air data

The location of the upper air observatories, Hachijyo, Hamamatsu, and Tateno, are shown as circular symbols in Figure 1. Upper wind data are obtained four times a day at 0300, 0900, 1500 and 2100 JST (Japanese Standard Time = UTC + 9 hours) at Hachijyo and Tateno stations by sounding balloon measurement, while at Hamamatsu they are obtained only at 0900 and 2100 JST. We use the wind data at standard pressure levels, 925, 900, 850 hPa and so on up to the height of the volcanic clouds to simulate the plume morphology shown in satellite images by a vertical shear model. The temperature and relative humidity at these stations are obtained only at 0900 and 2100 JST, and these data are used to estimate the height of eruption clouds.

<u>2.2.1. Height of eruption cloud</u>

The height of eruption cloud is one of the most important pieces of information for estimating volcanic activity and for aviation safety. We can estimate the height of opaque clouds using the brightness temperature obtained from band 4 data (see Section 2.1.), if the surface temperature of the volcanic cloud is balanced with the surrounding air. To derive it from the brightness temperature, the most important thing is the assumption that the cloud is opaque, and it is necessary to correct the effect of the emissivity of ash.

In addition, since the water vapour absorbs the radiation, we also examine the water vapour amount above the cloud.

The precipitable water amount, W, in a column is able to estimated using the significant level upper air data, i. e., pressure, temperature, and relative humidity, by calculating the following equations.

$$W = \int_0^\infty \rho_w(z)dz \tag{1}$$

$$\rho_w = \frac{P_w}{R_w T} \tag{2}$$

$$P_w = e_s \frac{RH}{100} \tag{3}$$

$$e_s = 611 * 10^{\frac{at}{b+t}} \tag{4}$$

where W = precipitable water [kg/m^2], z = altitude [m], $\rho_w(z)$ = density of water vapour [g/m^3], T = air temperature [K], t = air temperature [Celsius], $R_w = R/M_w = 0.4615$ [$J\ g^{-1}\ K^{-1}$], R = gas constant [$J\ g^{-1}\ K^{-1}$], M_w = molecular weight of water, P_w = water vapour pressure [Pa], RH = relative humidity [percent], e_s = saturation vapour pressure [Pa], a and b = constant, a = 7.5 , b = 237.3 for water, and a = 9.5 , b = 265.3 for ice.

Since the upper air data are provided as a function of pressure, we may rewrite Equation 1 by using

$$dp = -g \frac{pM_{air}}{RT} dz, \tag{5}$$

to obtain

$$W = \frac{6.11 M_w}{M_{air} g} \int_0^{p_h} RH(p) 10^{\frac{at}{b+t}} \frac{dp}{p} \tag{6}$$

where M_{air} = molecular weight of dry air, g = gravitational acceleration [ms^{-2}], P_h = pressure at the surface [Pa].

2.2.2. Vertical shear model

To understand the mesoscale transport of volcanic plumes and gas, we simulate the morphology of plumes shown in satellite images by a vertical shear model (VSM) which utilizes the upper wind data as an input. The wind data sets in height and time at intervals of 10 hPa and of one-hour are preprocessed by the linear interpolation for wind velocities and directions. For large changes of wind direction, we choose the direction change according to the weather patterns. The trajectories of dimensionless and weightless particles, which are released into the atmosphere at specified pressure-altitudes above the volcano, are calculated by using the two observatory data sets. The spatial interpolation of wind data at a particle location is performed with the weight reciprocal to the square of the distance between the particle location and each observatory. The emission rate of the model's ideal particles is assumed to be constant, one particle per one hour interval at a pressure level, and the particles remain at the initial pressure-altitudes at which they are released. Finally, their positions at a certain time are displayed that correspond to the satellite images of volcanic plumes. In our previous studies, various morphologies of Sakurajima volcanic plumes shown in satellite images are reproduced well by VSM [7].

2.3. Continuous monitoring of SO_2 in the mainland

National environmental gas-monitoring stations are indicated by cross symbols in Figure 1. We plotted the one-hour value of SO_2 concentrations from the end of August to September 2000. We discuss the same kind of data observed by the Tokyo Metropolitan Government for investigating the high concentration episodes which occurred on 9 September 2000. In this study, we assume that volcanic gas behaves together with volcanic clouds, based on the previous study of Sakurajima and Aso plumes [4].

3. Results and discussions

3.1. Height of eruption cloud on 29 August 2000

Miyakejima volcano erupted at 0435 JST on 29 August 2000 (1935 UTC on 28th), and the maximum height of the plume was reported to be 8000 m at 0628 JST. A NOAA-12/AVHRR AVI imagery at 0528 JST on 29 August 2000 detect the eruption cloud (Figure 3). According to the Tokyo VAAC (Volcanic Ash Advisory Center) internal report, the top of ash plume reached over an altitude of 5800 m at 0538 JST (personal communication).

As the eruption cloud observed by NOAA-12/AVHRR was a puff not yet diffused, we assume it to be opaque. The lowest brightness temperature at the ash cloud indicates 261.8 K by NOAA/AVHRR band 4 data. From the profile of altitude-temperature at 0900 JST at Hachijyo, shown in Figure 4, we see the temperature lapse rate is almost constant. Thus we may obtain a raw value of the cloud height, 6576 m, from the following approximate equation of the altitude versus air temperature:
$z = 51156 - 170.28\,T$.

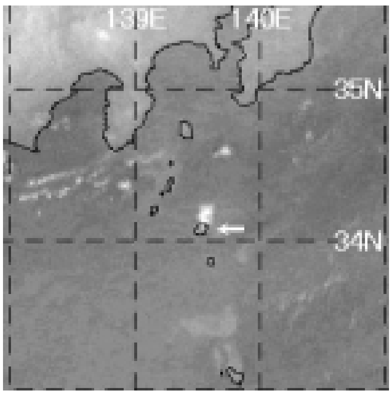


Figure 3 NOAA-12 AVI image at 0528 JST (2028 UTC on 28th) on 29 August 2000. The location of Miyakejima is denoted by an arrow

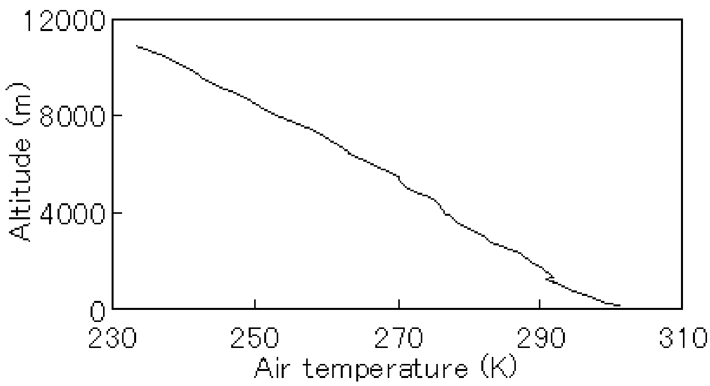


Figure 4 The profile of the altitude- temperature at 0900 JST on 29 August 2000 at Hachijyo

In general, the brightness temperature at the surface of an object is observed from the satellite to be lower than the real temperature, because water vapour absorbs the radiation, and the emissivity is less than black body radiation. To check the necessity of the correction for the first effect, we calculated the precipitable water amount above 6500 m, using the upper air data at Hachijyo at 0900 JST. The amount, $W = 0.65$ kg/m^2, was calculated using Equation 6 which is negligible in the height estimate.

Since the eruption cloud contains large amount of ash, we may put the emissivity at 0.9 - 0.95. Then the corrected temperatures become higher than the original brightness temperature, and the cloud height is estimated as 5920 - 6250 m. This is quite comparable to the reported height of 5800 m.

3.2. Mesoscale behaviour of volcanic plumes and SO_2

3.2.1. The first episode of Miyakejima gas in the Kanto area

Figure 5 indicates the SO_2 concentrations in Kanto area during 28-29 August 2000. The environmental standards for SO_2 concentration in Japan are 100 and 40 ppb, respectively for one-hour and daily averages. In this study, we define the level of a high concentration episode caused by Miyakejima gas as one-hour average 40 ppb, which is remarkably higher than background values. On both days, the SO_2 concentrations exceeded this level, and inhabitants reported the smells of sulphuric substances at various places in the Kanto area. The maximum concentration at each station was 87 ppb at 1200 JST in Tsukuba on 28th, while on 29th, it was 167 ppb at 1000 JST in Tokyo, 56 ppb at 1000 JST in Kawasaki, and 56 ppb at 1400 JST in Tsukuba. All of the maximum concentrations recorded during the daytime.

Figure 6a shows a monochrome converted colour composite image of NOAA-12 at 1646 JST on 29 August, and Figure 6b illustrates a corresponding VSM simulation. In Figure 6a, 'C' indicates the clouds region, below 10 [Celsius], and it is masked by using band 4 data, and 'S' shows the shadow region of the clouds on the volcanic plume. The plume crossing over the Kanto area are reproduced by the VSM simulation about 1000 m, and it helps to understand of the SO_2 high concentration episodes shown in Figure 5, though the plume flowing southern part of Boso peninsula can not be reproduced. We discussed the correspondence of satellite data and VSM simulations for 28th episode in [5]. Satellite images and the VSM simulations give clues to understanding the SO_2 high concentration episodes.

The mechanism of the 28th episode was studied by the Japan Atomic Energy Research Institute group using SPEEDI (System for Prediction of Environmental Emergency Dose Information), and they clarified that the convective daytime mixing pulled down the gas in the upper air, which was brought from Miyakejima by winds along the edge of the high pressure system, to the ground surface [8].

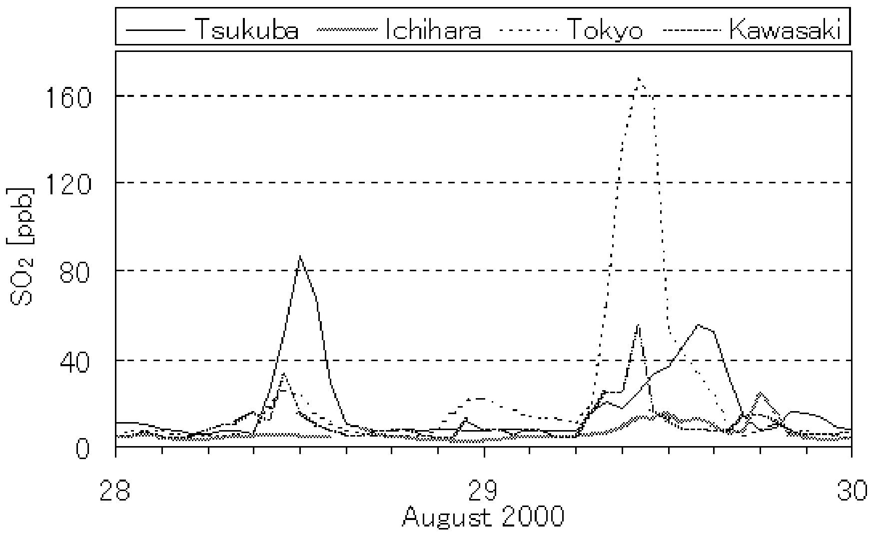


Figure 5 The temporal variations of the one-hour SO_2 concentration in Kanto area during 28-29 August 2000.

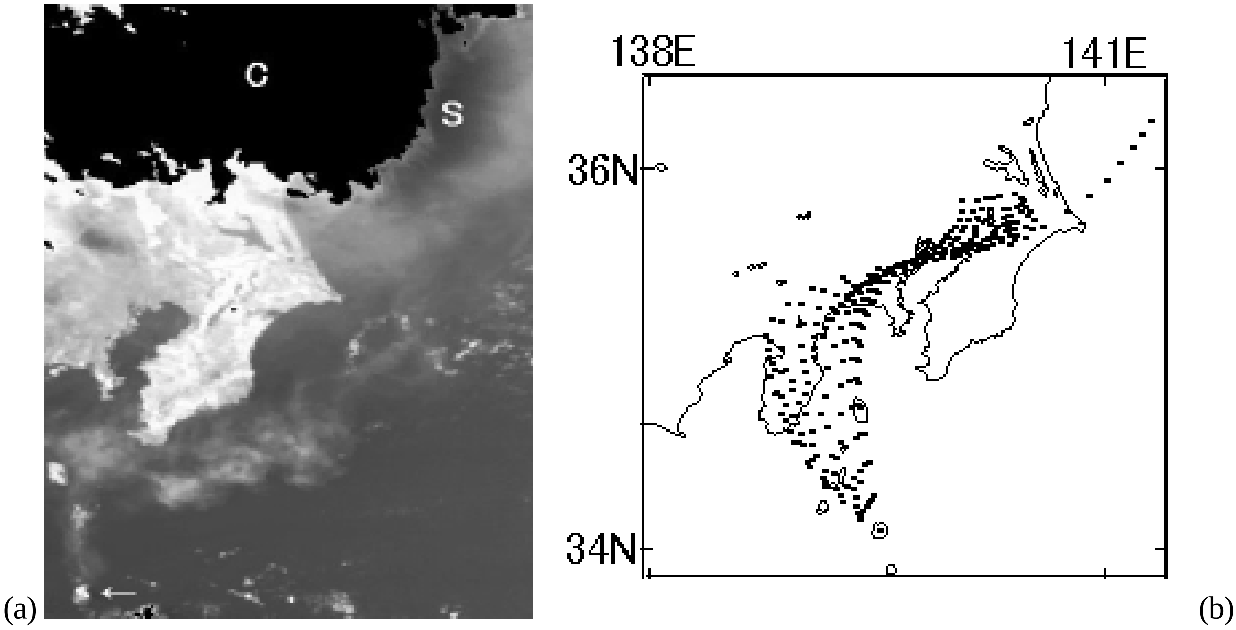


Figure 6. (a) A monochrome converted colour composite image of NOAA-12 at 1646 JST on 29 August 2000. R: G: B = bands 1: 2: 3. (b) The simulation result at 800 - 3000 m, for the ejection during 2100 JST on 28 August - 1700 JST on 29 August 2000.

3.2.2. Gas episodes in windy days

Figure 7 shows the temporal variation of SO_2 concentrations in the Kanto area from 6 to 12 September 2000. During this period, a high pressure system was located over the northwest Pacific Ocean, and stationary fronts extending from Hokkaido to Kyushu were located north of the Kanto area. Weather conditions in the Kanto area were cloudy or rainy except for on 9 September. As shown in Figure 8, in an AVI image at 1523 JST on 9 September, the plume width is narrow because of little directional shear with height, and SO_2 high concentration episodes were recorded only in Kawasaki and in eastern of Tokyo (Figure 9). The plume and gas were brought to the Kanto area by southerly winds blowing towards the front. It should be noted that the mechanism that caused these episodes is different from the mechanism described in Section 3.2.1. High concentrations of SO_2 will come to the Kanto area not only in daytime but at any time, e. g., 110 ppb at 0600 JST in Kawasaki on 11 September, in this weather pattern.

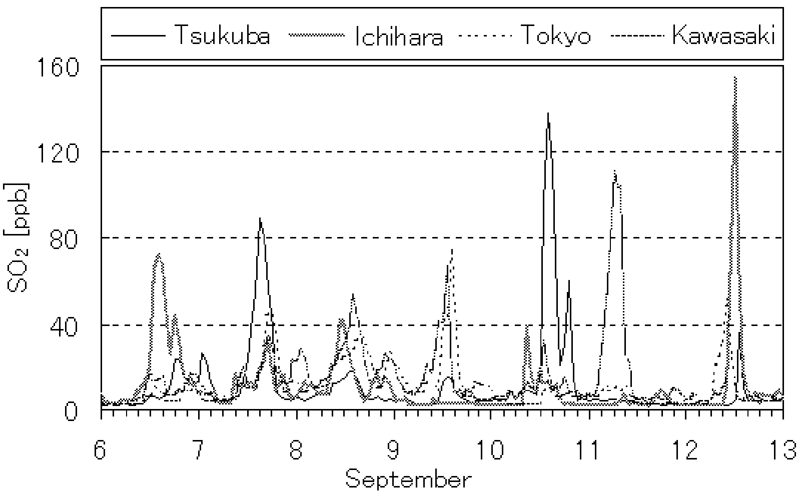


Figure 7. The SO_2 concentrations during 6 - 12 September 2000 in the Kanto area.

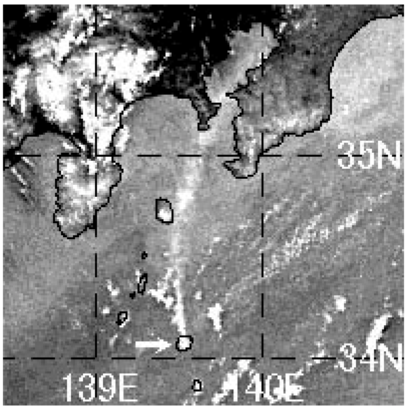


Figure 8 NOAA-14 AVI image at 1523 JST on 9 September 2000.

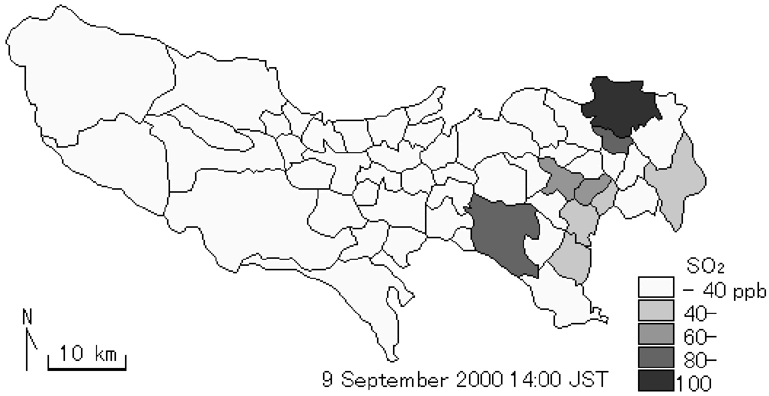


Figure 9 The distribution of SO_2 concentration in Tokyo at 1400 JST on 9 September 2000.

3.2.3. Gas episodes at long distances with a typhoon in the area

During 13-15 September 2000, high concentrations of SO_2 were recorded in Nagoya and Kyoto (Figure 10), and at many stations in the Chubu district [9]. The weather pattern in these days was as follows: Typhoon, No. 14, located southeast of Kyushu, was moving very slowly northwards, and a stationary front was located over the Japan Sea. Thus, the upper wind field at an altitude of about 1000 m from the Kanto area to the Chubu district was west-northwesterly. A 'fan-shaped' Miyakejima plume, which reached to the Japan Sea, was shown in a monochrome converted colour composite image of NOAA-14 at 1553 JST on 15 September 2000 (Figure 11a) and in the corresponding VSM simulation (Figure 11b). The maximum SO_2 concentration of 336 ppb at 1000 JST on 15 September in Nagoya, shown in Figure 10, was suggested by the VSM simulation at 925 - 880 hPa, i. e. about 800 - 1200 m for the ejection during 0100 - 1000 JST.

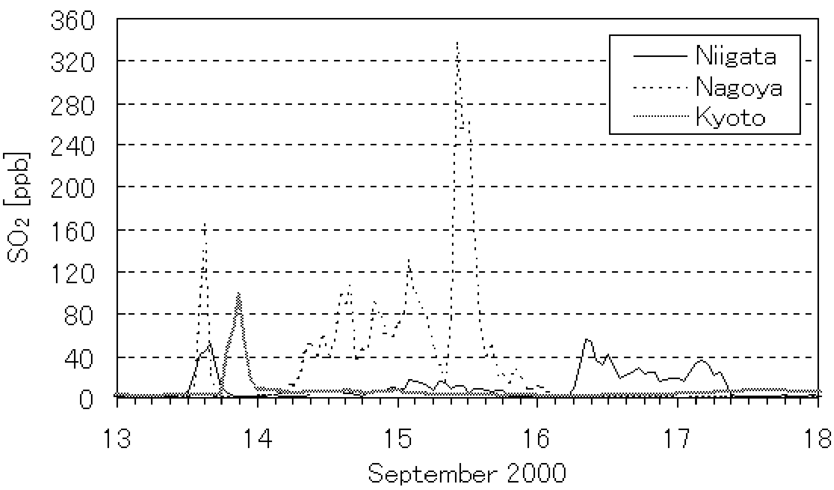
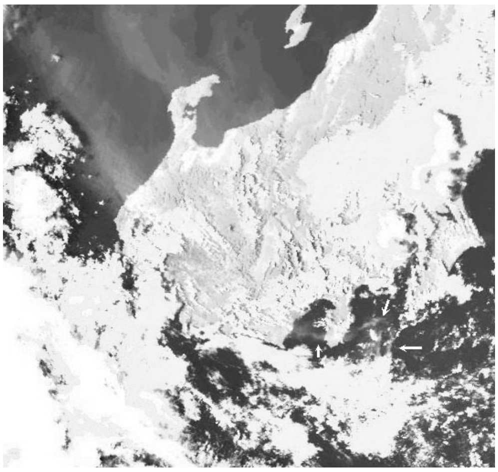
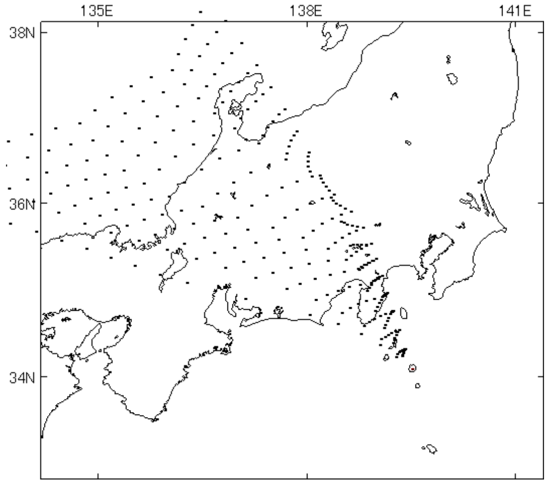


Figure 10 The temporal variations of the SO_2 concentration in Kyoto and Nagoya during 13 - 15 September 2000.

(a)  

(b)

Figure 11 (a) Same as in Figure 6a, but NOAA-14 at 1553 JST on 15 September 2000. (b) The simulation result at 800 - 2500 m for the ejection during 2200 JST on 14 - 1600 JST on 15 September 2000. The upstream of plume from Miyakejima is denoted by arrows

3.2.4. Gas episodes with low pressure systems

Figure 12 shows the temporal variation of SO_2 concentrations in Nagoya and Kyoto during 22 - 23 September 2000. Low and high pressure systems were located west and northeast, respectively, of the Chubu district. SPOT-2 imagery shows that the plume was flowing towards west at 1020 JST on 22 September. The VSM simulations suggest that the maximum SO_2 concentrations of 63 ppb in Kyoto and of 58 ppb in Nagoya may have been caused by the gas ejecta at 1000 JST and at 1300 JST at around 1000 m altitude.

For the SO_2 high concentration episodes observed in the Chubu district from October to early December, the distributions of SO_2 concentration were simulated by SPEEDI, and it was also shown that the high concentration episodes occurred with similar weather patterns, which we described in Sections 3.2.3 and 3.2.4 [10].

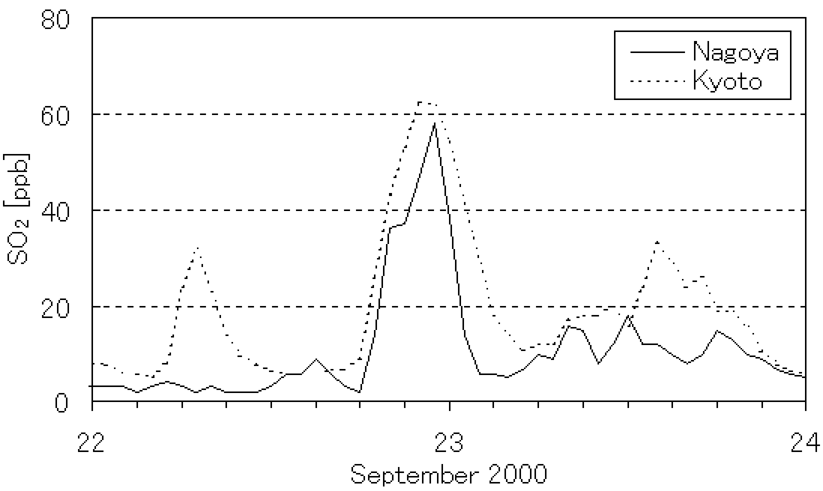


Figure 12 The SO_2 concentrations in Kyoto and Nagoya during 22 - 23 September 2000

4. Concluding remarks

We found that the volcanic ash clouds from Miyakejima were detected by the AVI imagery, taking the brightness temperature difference between 11 and 12 μm, and that the colour composite imagery assigning bands 1, 2 and 4 or AVI to blue, green and red is useful to distinguish volcanic plumes from meteorological clouds. The vapour-rich clouds are identified well by making colour images of R: G: B = bands 1: 2: 3A.

The height of the eruption cloud on 29 August 2000 was estimated reasonably well using the brightness temperature at 11 μm of NOAA/AVHRR and the upper air data taking into account the effect of ash emissivity. It should be noted that this estimation is applicable to opaque clouds, and the correction of water vapour may become considerable for the clouds flowing at lower altitude. The satellite estimation of the cloud height, using the brightness temperature, is very important because of the capacity of night-time monitoring of eruption clouds.

We found two different mechanisms, which bring the high concentrations of SO_2 to Honshu.

1. The convective daytime mixing brought the gas, which is brought from Miyakejima in the upper air by light winds along the edge of the high pressure system, to the ground surface.
2. The volcanic gas descends to the island surface by strong winds associated with stationary fronts and low pressure systems.

Acknowledgements

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References

[1] K. Kazahaya, J. Hirabayashi, H. Mori, M. Odai, Y. Nakahori, K. Nogami, H. Shinohara and K. Uto, "Volcanic gas study of the 2000 Miyakejima volcanic activity: Degassing environment deduced from adhered gas component on ash and SO_2 emission rate", Journal of Geography, **110**, pp.271-279, 2001. (Japanese with English abstract)

[2] A. J. Prata, "Observations of volcanic ash clouds in the 10-12 μm window using AVHRR/2 data", International Journal of Remote Sensing, **10**, pp.751-761, 1989.

[3] K. Kinoshita, S. Hosoyamada, A.Goto and S. Saitoh, "NOAA-AVHRR imagery of volcanic clouds in Kyushu, Japan", Proc. 1993 Interenational Geoscience and Remote Sensing Symposium, pp.1824-1826, 1993.

[4] K. Kinoshita, N. Iino, I. Uno, A.Mori, S. Ikebe and J. Kohno, "Satellite analysis of volcanic clouds and transport of acidic substances from Mt. Aso and Mt. Sakurajima", Water, Air & Soil Pollution, **130**, pp.385-390, 2001.

[5] N. Iino, K. Kinoshita, M. Koyamada, S. Saitoh, K. Maeno and C. Kanagaki, "Satellite imagery of ash clouds of the 2000 eruption of Miyakejima volcano", Proc. CEReS International Symposium on Remote Sensing of the Atmosphere and Validation of Satellite Data, pp.13-18, 2001.

[6] K. Kinoshita, C. Kanagaki, N. Iino, M. Koyamada, A. Terada and A. Tupper, "Volcanic plumes at Miyakejima observed from satellite and the ground", Proc. SPIE Vol. 4891, Optical Remote Sensing of

the Atmosphere and Clouds III, pp.227-236, 2003.
[7] N. Iino, K. Kinoshita, T. Yano and S. Torii, “Detection and morphology of volcanic ash clouds from Mt. Sakurajima in satellite images”, Proc. 3rd Pacific Symposium on Flow Visualization and Image Processing, F3023, pp.1-8, 2001.
[8] H. Nagai, H. Terada and M. Chino, “Relation between nasty smell at Kanto area on 28 August 2000 and Eruption at Miyakejima Island: Examination by numerical simulation”, Tenki, **48**, pp.227-230, 2001. (Japanese with English abstract)
[9] M. Koyamada, K. Kinoshita, N. Iino and C. Kanagaki, “Flow of volcanic clouds and gas from Miyake-jima and satellite image analysis”, Proc. 29th Japanese Conference of Remote Sensing, pp. 37-40, 2000. (Japanese with English abstract)
[10] A. Furuno, H. Nagai, N. Umeyama and M. Chino, “Real-time simulation and analysis on long-range atmospheric dispersion of volcanic gases discharged from the Miyake island”, Journal of Japan Society for Atmospheric Environment, **37**, pp.23-34, 2002. (Japanese with English abstract)