Day and Night Detection of Volcanic Clouds and Aerosol by NOAA/AVHRR Data

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Abstract: Volcanic clouds in Kyushu, Japan in NOAA/AVHRR and other satellite images were analyzed during August-November 1989 when the air pollutants concentration measurement was carried out at the Unzen-Nodake(1142m). The results confirm that high concentration events of SO_2 were frequently detected because of the long-range transport of volcanic gas from the Aso and Sakurajima Volcanoes. Detectability of very thin clouds and aerosol from volcanoes are also discussed.

1. Introduction

There are many active volcanoes in south-west Japan belonging to the west-Japanese volcanic belt. Some of them eject ash clouds and aerosol, as observed by earth observation satellites such as LANDSAT. The NOAA satellites are effective in detecting this large scale extension. Thus, the dispersion of volcanic clouds may be regarded as tracer experiments on a gigantic scale which provide information on the atmospheric dynamics of upper and boundary layers.

In this report we discuss the detection of volcanic clouds and aerosol in NOAA/AVHRR data and others during August-November 1989, when the air pollutants concentration measurement was carried out at the Unzen-Nodake(1142m). In this measurement[1], many high concentration events of SO_2 were found, which were probably due to the long-range transport of volcanic gas from the Aso and Sakurajima Volcanoes, as inferred from meteorological conditions. It must be very valuable to study satellite images of volcanic clouds which may well be accompanied by volcanic gas. In a recent work[2], we have analyzed the morning data of NOAA-10/AVHRR processed by Japan Weather Association. Here we extend the analysis to all relevant raw data of NOAA-10 and 11 during this period archived by the Institute for Industrial Science, University of Tokyo[3]. There are four opportunities for observation in a day, taking altogether the descending and ascending paths of two NOAA satellites. We also discuss the satellite detection of very thin clouds and aerosol ejected from volcanoes after a brief introduction concerning their activities.

2. Volcanic activity in Kyushu and Ryukyu Islands

Let us briefly discuss volcanic activity in south-west Japan(see Fig. 1)[4]. Among the volcanoes in Mainland Kyushu, Mt.Sakurajima is the most active on the average, with ash clouds sometimes exceeding 100 km[5]. Since the year of 1972, volcanic plumes have been ejected almost daily from the summit crater(1040 m), mixed with occasional big eruptions. The plumes flow at altitudes around 1000-2000 m, depending on the ejection strength and wind velocity, with a vertical thickness of 200-800 m. The pattern of horizontal dispersion is sensitive to the vertical profile of wind direction and velocity. Typical patterns of dispersion are as follows:

(1) Linear advection with small spread under strong wind, around or over 10 m/s.
(2) Wide angle spread of fan type under weak wind with large vertical shear.
(3) Belt type dispersion under medium wind with indefinite shear.

Some intermediate patterns are also seen, such as the narrow angle or conical type. An extreme limit of case (2) is the flat plate type when the wind is almost nil. In many cases, these features are well reproduced by a vertical shear model with upper level wind data as inputs[6].

Aso Volcano in central Kyushu was very active during June 1989-January 1991. Volcanic clouds observed in the satellite images were with scales comparable to or sometimes exceeding those of Sakurajima Volcano. Especially, in the autumn of 1989, heavy ash-falls from Mt.Aso seriously damaged agriculture and badly affected traffic inside the caldera and its neighboring regions. It is quite plausible that this volcano was an important source of SO_2 observed at the Unzen-Nodake(70 km westward from Mt. Aso).

A big topic recently has been the eruption of Unzen Volcano starting from 17 November 1990, and the pyroclastic flows from the Fugendake lava dome from May 1991 until the beginning of 1995. There are many data of ash clouds of 10-40 km taken by the remote sensing satellites. However, in 1989 when the air pollutants concentration measurement was carried out at the Unzen-Nodake near-by, Fugendake was quite dormant without any effect.

In the Ryukyu Islands south of Kyushu, there are many volcanic islands. Among them, a white spot of cloud was often seen above the vent of Satsuma-Iwojima Volcano, indicating that the volcano was continuously ejecting white plumes which were diminished in the dry air. As for Suwanosejima Volcano, such a white spot was rarely seen.
Instead, it occasionally becomes very active ejecting plumes of considerable scale. However, during the term August-November 1989, the level of its activity was not so high, with short plumes in NOAA data[2].

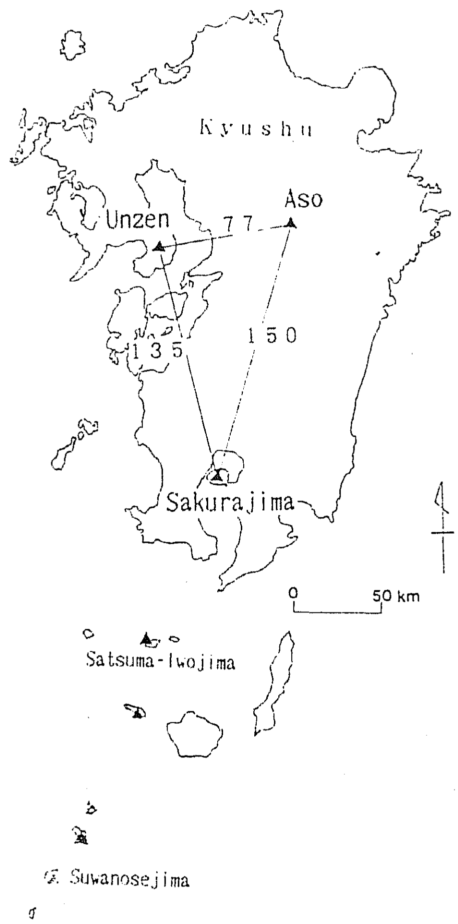

Fig. 1. Prominent active volcanoes in Kyushu and Ryukyu Islands. The distances between the three mountains are indicated in km.

3. Satellite imagery of volcanic clouds

In general, volcanic clouds are composed of volcanic ash, water vapor and other chemical substances such as CO_2, SO_2, HCl and H_2S. During the downstream advection, coarse grained ashes fall off and water vapors evaporate in dry air, but very fine ashes and aerosol of sulfuric acid converted from the oxidation of SO_2 in the air remain. They form very thin tails of volcanic clouds. On the other hand, in the case of wet air, volcanic ejecta may be subject to rain out and wash out. However, in the satellite images with many series of cumulus clouds on the land, volcanic plumes are often recognized with somewhat vague boundaries and extensions over the sea. Thus, the spatial pattern and geographical situation are important in the detection of volcanic clouds and in the distinction from meteorological clouds. Keeping these points in mind, let us discuss the detection problem of volcanic clouds according to the wavelength of the satellite sensors. The home page of SiNG-Kagoshima shows several color images combining different bands[7].

3.1. Visible, NIR and SWIR images

In the daytime satellite images, the volcanic clouds appear as relatively bright objects in visible, near infrared(NIR) and also short-wave infrared(SWIR) images. Thick ash clouds are easily detectable in all of these bands, but thin ash or fumarolic plumes are difficult to see in NIR and SWIR bands. The thin volcanic clouds are somewhat transparent in the NIR band, and relatively insensitive to the SWIR bands. Diffused clouds over the sea, however, are often detectable even in SWIR bands. The sensitivity of semi-transparent clouds according to the wavelength may provide information on grain size distribution. Fig. 2(a) shows a LANDSAT/TM-1 image on 21 Nov. 1989 when a large angle spread of thin volcanic cloud was observed from the ground; the data values of the TM bands are shown along the line AB.

The detection of thin volcanic clouds over land is difficult in the NIR band because of strong reflection from vegetation. On the other hand, the visible band with shorter wave length is more sensitive to thin clouds, since vegetation appears as a dark background as shown in Fig. 2(a).

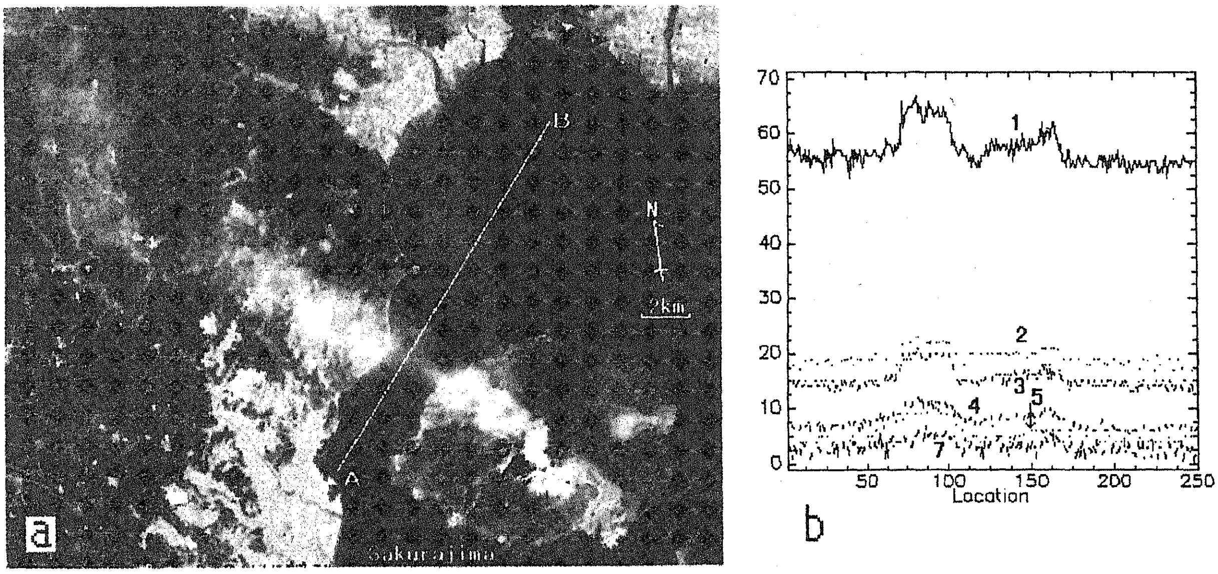

Fig. 2. (a) A LANDSAT/TM-1 image of a Sakurajima plume on 21 Nov. 1989. **(b)** The data values of TM-*n* sensors along the line AB in (a), where the channel number *n* is indicated in the graph.

3.2. Thermal images

Thick volcanic clouds are recognized as cold objects in thermal infrared(TIR) images of NOAA/AVHRR and LANDSAT/TM sensors, as the surface of volcanic cloud becomes in equilibrium with the ambient atmosphere at altitudes of about 1-3 km. Semi-transparent clouds also shield partially the infrared radiation from the surface of the earth. These features are common to day and night time observations, especially for clouds extending over the sea. The AVHRR-3 images in the medium infrared band, 3550-3930 nm, also exhibit similar properties at nighttime, in contrast to the daytime images dominated by solar reflection.

For the NOAA-11 data, the split-window method taking the difference of AVHRR-4 and 5 may be useful for the discrimination of meteorological and volcanic clouds, as confirmed in daytime images under various conditions[8]. This is due to the different spectral properties of the clouds around 11 and 12 μ m, while further distinction between lithic dust and aerosol of sulfuric acid in the volcanic clouds is not possible.

The above methods are useful to study the extension of volcanic clouds over the sea. However, detection over the land is not always easy in the thermal band because of the non-uniformity, the decrease of temperature at night, and the similarity of bare land with ash clouds in the split-window images.

Finally, let us mention the detection of thermal anomalies due to volcanism in TIR images. The LANDSAT-5/TM-6 sensor is useful both in daytime and nighttime with a resolution of 120 m, although it cannot measure very high temperatures above a saturation limit of about 70℃. There are also problems of calibration and absorption correction due to vapors above a vent. The spatial resolution of NOAA/AVHRR sensor with 1.1 km at best is considered to be too poor to detect thermal anomalies. However, we did find several single pixel anomalies due to volcanism(see 4(iii) and Table 1).

4. High SO_2 concentration events and NOAA images

When the air pollutants concentration measurement was carried out at the Unzen-Nodake during Aug.-Nov. 1989[1], the concentration of sulfur dioxide revealed the strongest time variation exceeding the background level, compared with other components such as SO_4^{--} and Ca^{++}. The latter two exhibited positive correlation with SO_2, in accord with volcanic origin. The SO_2 concentration has been measured also at Aso Volcano Museum(1150 m). The high concentration events detected there were attributed not only to Aso Volcano with the crater at 3 km east but also to Sakurajima Volcano at 150 km SSW[9]. Since volcanic plumes tend to keep their altitudes during the advection without much vertical dispersion as observed from the ground[5] and aircraft[10], mountain site measurements are good for detecting their long-range transport. In the following, we discuss the SO_2 concentrations at these stations together with

Table 1. Volcanic clouds at Aso and Sakurajima, with the direction Dir, length L and the type denoted as Lin., Long, Belt, Con., Fan and Stag. for linear or long advections, belt type dispersion, small angle dispersion of conical type, fan type spread and stagnation, respectively. The marks - and X denote cases without signal, and unobservable cases due to cloud coverage, respectively. The mark * denotes thermal anomaly at the vent in ch. 3.

		Sakurajima			Aso		
Date	JST	Dir	L	Type	Dir	L	Type
9/10	8:15	NW	125	Long		-	
	19:34	W	84	Lin.		X	
9/11	2:45	NW	82	Lin.		X	
	7:53	NW-NNW	129	Long		X	
	14:10	N	82	Lin.		-	
	19:11	NW	62	Fan		X	
10/27	7:23	W-SW	46	Fan	WSW-SSW	51	Fan
10/29	8:18	SSW-SW	86	Lin.	SW	44	Con.
	14:10	SW-SE	227	Belt	SW	50	Con.
	19:30	W	125	Long		-	
10/30	2:35		-*			-*	
	7:55	E-NW	65	Lin.	NE-E	53	Lin.
	14:00	NNW	23	Fan	NE-E	93	Long
	19:13	NW	77	Fan		-*	
11/03	1:52		-*			-	
	8:06	W-SSW	27	Stag	NE	46	Lin.
	13:16	NW	20	Fan		X	
11/04	1:42		-*			-*	
	7:43	N	39	Lin.	NNE	103	Lin.
	13:06	NNW	187	Long	NNE	213	Long
	19:01	NNW	60*	Lin.		-	
11/05	7:21	N	18	Lin.	NE	102	Lin.

satellite images.

In August, there were several high concentration events of SO_2 with one hour values exceeding 30 ppb at two stations. However, corresponding image data by satellites were not obtained because of the cloud coverage and the lack of good timing, though there were Sakurajima plumes extending more than 100 km on other days.

During September-November 1989, there were 18 morning data of NOAA-10, LANDSAT-5, MOS-1 and SPOT, which were relevant to the high concentration events at two stations[2]. In addition, we found altogether 26 candidates of NOAA-10 in the evening plus NOAA-11 in the midday and midnight. Here we discuss three prominent groups of them as listed in Table 1 with 19 candidates and other images.

(i) September 10-11 scenes

In these days, Kyushu area was at the north-west boundary of the Pacific high pressure system with typhoons No.19 in SW and No.20 in SE seas, as seen from the geopotential height and wind field at 850 hPa shown in Fig. 3(a). The meso-scale weather conditions were relatively stable, and isentropic forward trajectories starting from Mt.Sakurajima at 1500 m at 9, 21 JST on 10 Sept. and 5 JST on 11 Sept. exhibited similar behavior, with the starting direction at WNW and NNW, and then curved slowly towards NE as in Fig. 3(b). There are six NOAA images, all with volcanic plumes from Sakurajima, as summarized in Table 1. Their directions and the curved shapes are consistent with the computed trajectories, and the detected scales of about 40-130 km are enough to suggest their effects on high SO_2 concentration on 11 Sept. shown in Fig, 4 in two stations. Fig. 5 illustrates NOAA/AVHRR images at 7:53 and 14:10 on 11 September. We can see that Sakurajima plumes in these images are in accord with the trajectories in Fig. 3(b). On the other hand, plumes from Aso Volcano were not observed in NOAA images, partly because of the cloud coverage. The high SO_2 concentration on 10 Sept. observed only at Aso Volcanic Museum may be attributed to Aso Volcano as inferred from the westward direction of Sakurajima plume.

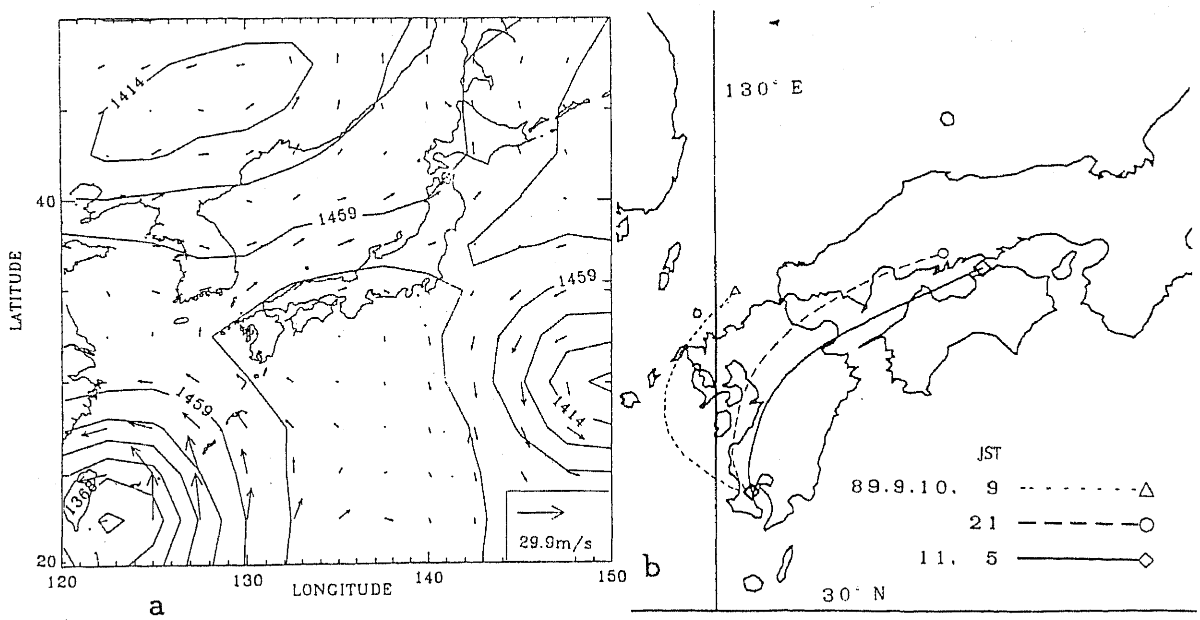

Fig. 3. (a) Geopotential height and wind field at 850 hPa at 9 JST on 11 Sept. 1989.
(b) Forward trajectories from Sakurajima at height 1500 m and starting times indicated in the graph for 24 hours.

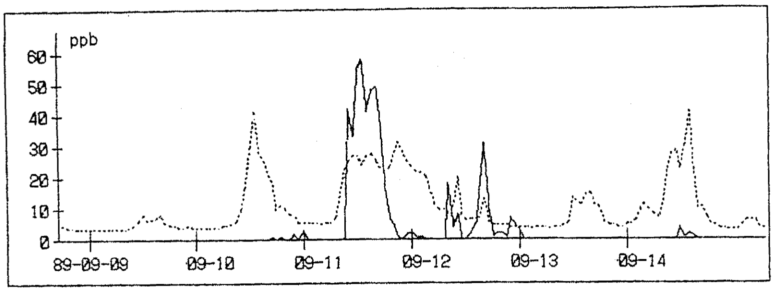

Fig. 4. One hour values of the SO_2 concentration at Unzen-Nodake(solid line) and Aso Volcano Museum(dotted line) for 9-14 Sept. 1989.

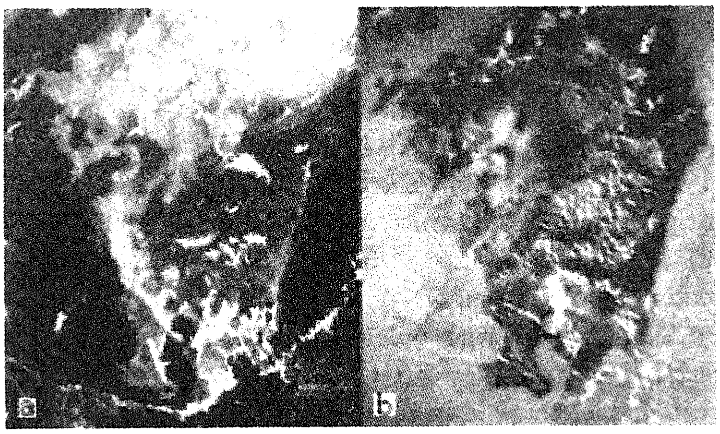

Fig. 5. NOAA/AVHRR images on 11 Sept. 1989. **(a)** ch. 1 at 7:53. **(b)** The difference of raw data values of ch. 4 and 5 at 14:10.

(ii) October 27-30 scenes

Very high concentrations of SO_2 at both stations on 27 October, shown in Fig. 6, are evidently attributed to Aso Volcano, because of the east wind due to the typhoon No.28 approaching Kyushu from the south. The NOAA-10 data in this morning exhibited westward diffusion of plumes about 50 km both from Aso and Sakurajima Volcanoes. As the wind direction turned from E to NE with the ascent of the typhoon to the east of Kyushu and the

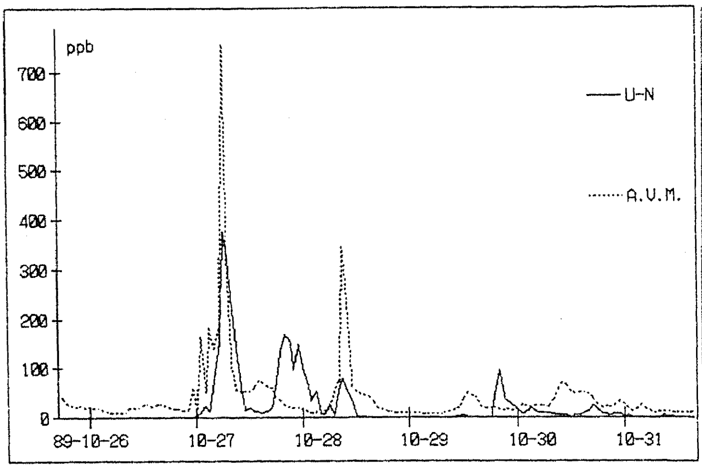

Fig. 6. As in Fig. 4 in the end of October 1989.

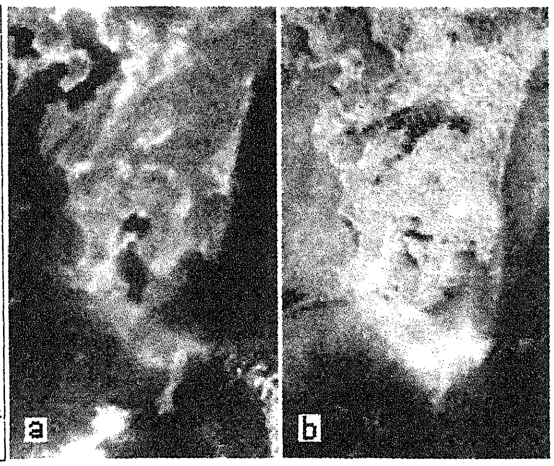

Fig. 7. The NOAA-11 images at 14:00 on 29 Oct. 1989. **(a)** AVHRR-1. **(b)**The difference as in Fig. 5(b).

approaching of a high pressure system from the west, the SO_2 concentrations of both stations once decreased to the background levels. Then, as the high pressure system moved to the east, the wind direction turned south to bring volcanic gas from Mt.Sakurajima, resulting again in high SO_2 concentrations at both stations. The NOAA data on these days are in accord with the above inspection as listed in Table 1. Fig. 7 illustrates a comparison of visible band image(a) and the split window method applied to the raw data(b). We see that the volcanic clouds from Mt.Sakurajima are very much enhanced in Fig. 7(b), while a thick cloud from Aso Volcano is not, suggesting the water rich properties. The enhancement of ash-rich cloud is also seen in Fig. 5(b) in contrast to meteorological clouds.

(iii) November 3-5 scenes

A traveling high pressure system approached Kyushu from west on 3 November, resulting in flat plate type stagnation of volcanic clouds over Mt.Sakurajima in the morning, and slowly passed east on the next day. Then southern winds dominated and continued further, bringing volcanic gas from Mt.Sakurajima and resulting in SO_2 concentrations shown in Fig. 8. There are NOAA images with Sakurajima plumes such as shown in Fig. 9. However, there are clear scenes of volcanoes without plumes as listed in Table 1. We should bear in mind that transparent gas with high SO_2 concentration might be ejected in such cases. In such clear scenes at nighttime, hot spots are seen at the vents of volcanoes in ch. 3 as indicated by the mark* in Table 1. Fig. 9 shows an Aso plume exceeding that of Sakurajima, but directed to NE without affecting the high SO_2 concentrations in two stations.

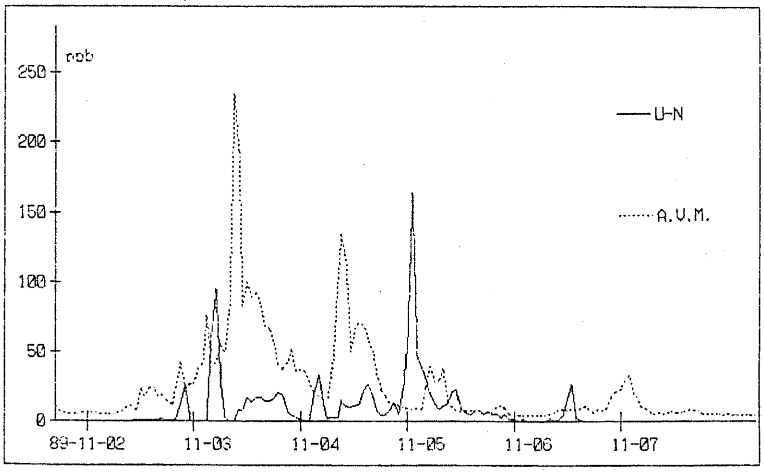

Fig. 8. As in Fig. 4 in early November.

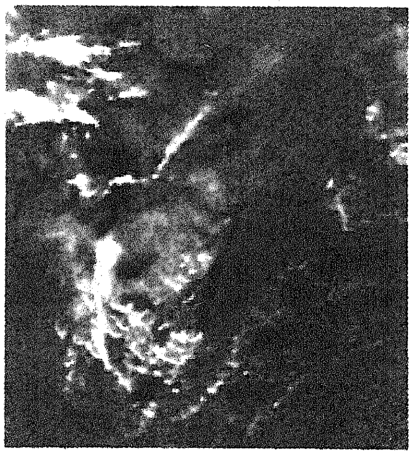

Fig. 9. The NOAA-11/AVHRR-4 image at 13:06 on 4 Nov. 1989.

6. Concluding remarks

We have found that the directions of the plumes from Aso and Sakurajima Volcanoes found in NOAA images are well understood by the wind field and the geopotential height at 850 hPa, which are closely related with the weather chart on the ground. As for Sakurajima plumes, this is also in accord with the ground observations[5].

Mountain site measurements of the SO_2 concentrations in Kyushu can be considered as very good measures for the long-range transport of volcanic gas in this area. The NOAA data, with a high frequency of observation interval, may be good information to study this problem.

As for the dispersion pattern of the volcanic plumes, the vertical shear model[6] was found to describe gross features in most cases studied here. It is very interesting to apply the Lagrangian particle model[11] to describe quantitative aspects of plume dispersion. We can also understand the emission rate of SO_2 and its time variation by means of the correlation spectrometer measurements from the ground[12].

It also remains to estimate quantitatively the particle sizes and densities of volcanic clouds and aerosol from satellite data.

Acknowledgments

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