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Rise and Flow of Volcanic Clouds Observed from the Ground and from Satellites

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***Abstract*:** Typical patterns of volcanic clouds from Mt. Sakurajima are discussed with photographs and satellite images. Volcanic clouds are classified into three types, i.e., eruption cloud, steady flow as a plume, and sequential puffs, according to the variation of the ejection activity with time. While the rise of eruption clouds depends on the strength of the eruption, the vertical shapes of the plumes are sensitive to the velocity of the cross winds around and above the summit of the volcanic mountain. Very strong winds cause blowing down and bouncing up of the plume along the mountain lee wave. Various patterns of horizontal dispersion are observed from the ground and from satellites; typical ones are linear advection, fan- and belt-type spreads, and flat stagnation. These patterns are essentially determined by the wind shear within the vertical thickness of the volcanic cloud.

***Keywords*:** volcanic eruption, plume dispersion, satellite imagery, mountain lee wave.

1. Introduction

The rise, flow and dispersion of volcanic clouds provide important information to understand the properties of the atmosphere as tracer experiments in a gigantic scale. Volcano Sakurajima (31° 35′N, 130° 40′E) in southern Kyushu, Japan, has been ejecting ash and/or vapor clouds almost every time from the summit crater (1040 m) since 1955, and is suited ideally for this purpose, with its simple topographical situation as an isolated mountain surrounded by the sea of Kagoshima Bay (Kinoshita, 1996). Meteorological data of the upper atmosphere can be obtained from radio-sonde measurements by Kagoshima Local Meteorological Observatory. Surface data of SO_2 and suspended particulate matter at the foot of the volcano and the surroundings are available from the continuously monitored air quality data. In this report, we discuss briefly the basic properties of the volcanic clouds at Sakurajima, with the illustrations of typical scenes from the photographs and satellite images. This is based on the ground observation of the volcano since September 1987 by one of the authors (K. K.) mainly from a fixed location 9.8 km WSW from the crater by means of time-lapse video records and manual photographing, supplemented with occasional observations from other points especially at the time of the satellite pass. The methods of the observation and the analysis are described by Kinoshita (1994). Samples of the video movies and photographs can be seen at the homepage on volcanic phenomena ("Volc"), http://www-sci.edu.kagoshima-u.ac.jp/volc/index_e.html. Many satellite scenes of volcanic clouds over Sakurajima and other volcanoes in Kyushu can be seen in the home page of the Satellite Image Network Group in Kagoshima ("SiNG"), http://www-sci.edu.kagoshima-u.ac.jp/sing/index_e.htm.

2. Eruption Clouds and Sequential Puffs

The properties of volcanic clouds are the result of the interaction of volcanic activity and the atmospheric condition, both of which may change with time. The ejection of volcanic plumes with relatively constant strength is the usual activity of Mt. Sakurajima. The eruptions, ejecting volcanic gas, ash and stones explosively, occur up to a few hundred times in a year. For a few big explosions, eruption columns reach a height of about 4000 m above the crater as shown in Figs. 1 and 2, and in most cases the column reaches around 1000 ~ 3000 m as shown in Fig. 3. Development and damping of the turbulence is seen, with the buoyant rise entraining ambient atmosphere. The rise of the column height (m) with time (s) up to the maximum is approximately described by $h(t) = v_0 t - at^2$, with the initial velocity v_0 = 15 ~ 30 m/s and the deceleration factor a = 0.03 ~ 0.07 m/s^2. This is a phenomenological formula obtained from the analysis of thirty eruptions (Kinoshita and Todaka, 1995).

After reaching maximum height in a few minutes, the top of the eruption column lowers gradually, and then flows as an inclined or twisted column, as seen by comparing Figs. 1 - 3. The cross winds for the cases in Figs. 1 and 2 are very weak except at the top altitudes, in contrast to Fig. 3 with strong winds. Satellite images after eruption shown in Fig. 2 are discussed in the home page "SiNG."

(a) (b)

Fig. 1. An eruption cloud on 19 Dec. 1987 at (a) 6:51 and (b) 7:02 in JST.

(a) (b) (c)

Fig. 2. The eruption column at (a) 19:42, (b) 19:46 and (c) 19:50 after an eruption at 19:34 on 29 July 1992.

(a) (b)

Fig. 3. An eruption cloud on 2 Mar. 1993 at (a) 14:46 and (b) its drift at 14:52.

If eruptive activity is maintained over a period of time ejecting sequential puffs, we may see a series of columns downwind above the plume height as shown in Fig. 4.

(a) (b)

Fig. 4. Sequential puffs at (a) 6:18 and (b) 6:30 on 14 April 1992.

3. Plumes

The continuous ejection of volcanic clouds of nearly constant strength results in a steady flow of plume clouds. The plume attains an altitude which depends on the ejection strength, atmospheric stability and wind velocity around and above the height of the summit, and then flows horizontally at an equilibrium height with the ambient atmosphere. According to the velocity u of the cross wind, there are three typical patterns of plume rise: (a) an upright rise followed by turn over above the crater to horizontal drift for weak winds ($u < 5$ m/s), (b) slant rise up to an equilibrium height for medium winds ($5 \le u < 10$ m/s), and (c) slight or no rise for strong winds ($u \sim 10$ m/s), such as shown in Fig. 5, respectively. In any case, plumes after the rising phase are characterized by horizontal drift. It should be noted that a straight horizontal flow of a plume in a wide angle photograph looks inclined, when the direction of the camera is not perpendicular to the plume, and a combination of two photographs directed differently results in a bent form (see Figs. 5(a) and (c)).

(a)

(b)

(c)

Fig. 5. Volcanic plumes under different wind speeds in the upper atmosphere on(a) 3 Feb. 1989, (b) 9 Nov. 1991 and (c) 5 Jan. 1993, with $u \sim 3$, 8 and 11 m/s respectively.

4. Mountain Lee Waves

When the cross winds around the summit become very strong such as $u > 10$ m/s, the plume gets blown down along the slope of the mountain, and then bounces up towards the equilibrium height, exhibiting a lee wave as shown in Fig. 6. According to the difference of the wind speed, a variety of lee waves can be seen, including hydronic jumping as shown in Fig. 6(b). The blow down of the plume and the gas by strong wind brings about extremely high concentration of sulfur dioxide and suspended particulate matter at the foot of the mountain (Kinoshita et al., 1994; Kinoshita et al., 1999).

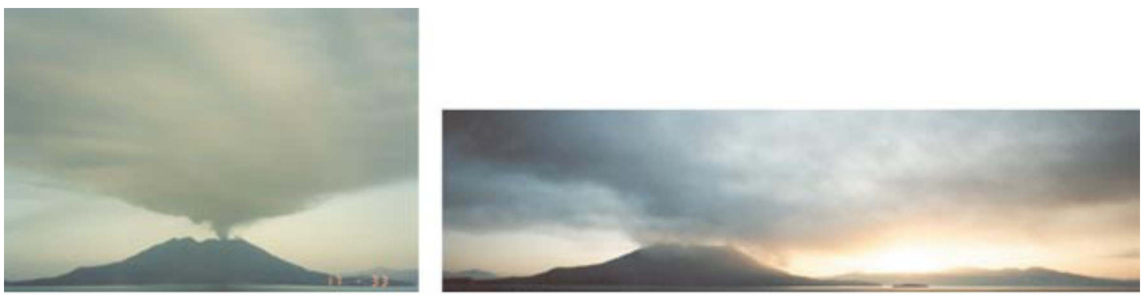
The rear view of Mt. Sakurajima from the north or south direction appears conical in shape with a single top. In fact, its summit part is composed of 1.5 km long sierra from the highest peak (1117 m) at the north to the active crater peak (1040 m) at the south. Strong winds almost perpendicular to the sierra also cause the lee waves such as Fig. 6(c) seen from the downwind direction.

(a) (b) (c)

Fig. 6. Mountain lee waves on (a) 9 Oct. 1992, (b) 21 Jan. 1993 and (c) 10 Oct. 1991, with $u \sim 13$, 11 and 16 m/s, respectively.

5. Horizontal Dispersion of Plumes

After reaching equilibrium heights with the ambient atmosphere, the plumes drift downstream without much vertical diffusion except for the ash fall which depends on grain size. On the other hand, horizontal dispersions exhibit different patterns which are essentially determined by the wind shear within the vertical thickness of the plume cloud. Typical ones are the following: (i) Linear advection with small spread under strong and/or collimated winds, as seen in Fig. 5 from the ground. (ii) Fan-type spread under weak winds with large vertical shear, as shown in Fig. 7(a). (iii) Belt-type spread under mild winds with indefinite shear, or due to shear wind near an edge height of the plume. Some intermediate patterns are also seen. An extreme limit of case (ii) is flat stagnation when winds are almost faded, as shown in Fig. 7(b).



(a) (b)

Fig. 7. Plume spreads under weak or faded winds: (a) Fan-type spread on 17 Feb. 1990; (b) Flat stagnation on 10 Oct. 1992.

6. Satellite Images and the Ground-based Photographs

The extension of volcanic clouds from ten to a few hundred kilometers can be studied by using satellite data. Various scenes of volcanic clouds from Mt. Sakurajima have been obtained by LANDSAT, MOS and SPOT series (Kinoshita et al., 1992), and by JERS-1 (Tsutsumi et al., 1995). Furthermore, the NOAA-AVHRR data are useful in detecting ash clouds for many days with wider spatial coverage (Kinoshita et al., 1993; Kinoshita et al., 1998). Here we discuss a few typical scenes taken by LANDSAT and MOS, together with photographs taken at or near the time of the satellite pass at locations as indicated in each image.

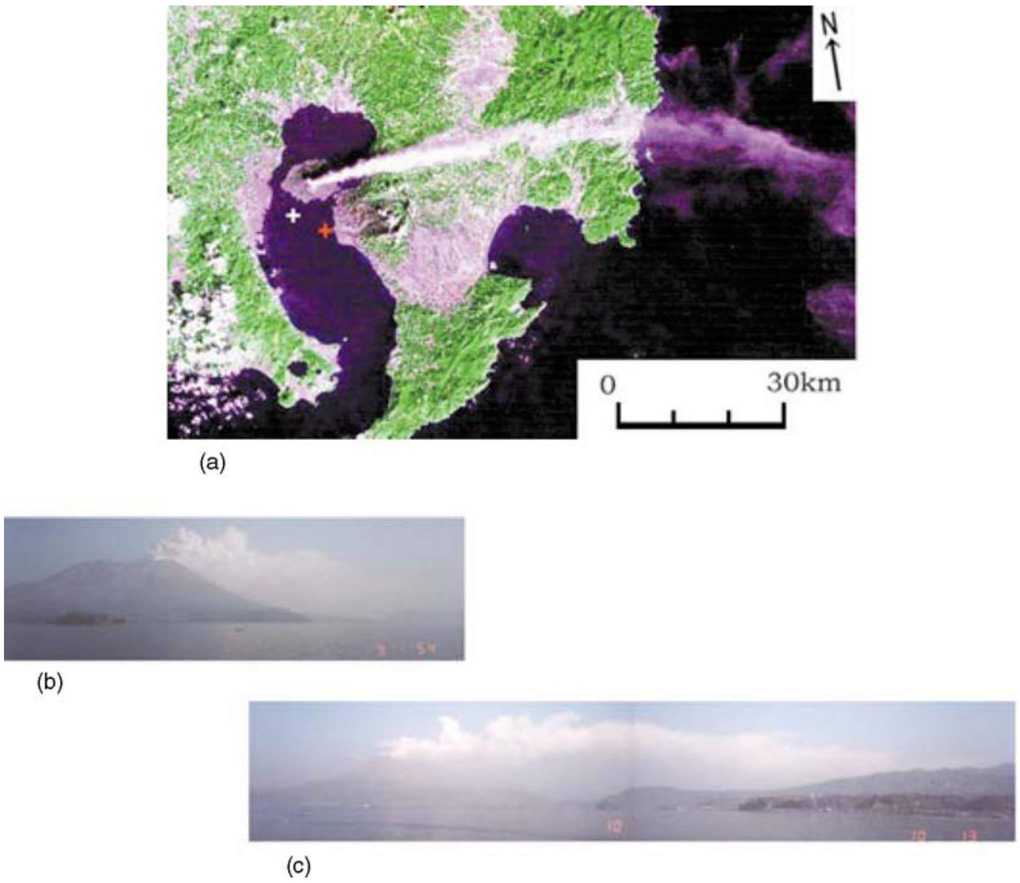


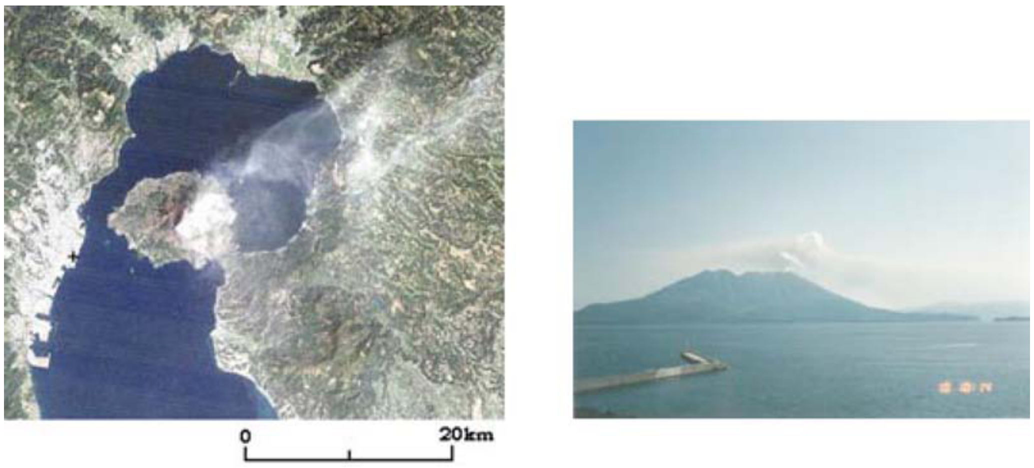
Fig. 8. A natural color image of LANDSAT-5/MSS data at 10:11 on 7 Dec. 1989 (a), and the photographs taken from a ferryboat at 9:54 (b) and 10:13 (c) from the locations indicated by white and red crosses in (a), respectively.

6.1 Linear Advection

As a typical satellite image of linear advection, a natural color image of LANDSAT-5/MSS data on 7 Dec. 1989 is shown in Fig. 8(a), where green color is assigned to near-infrared band. The photographs taken from a ferryboat between Kagoshima and Tarumizu are shown in Figs. 8(b) and (c). The upper winds were collimated toward the east in this case.

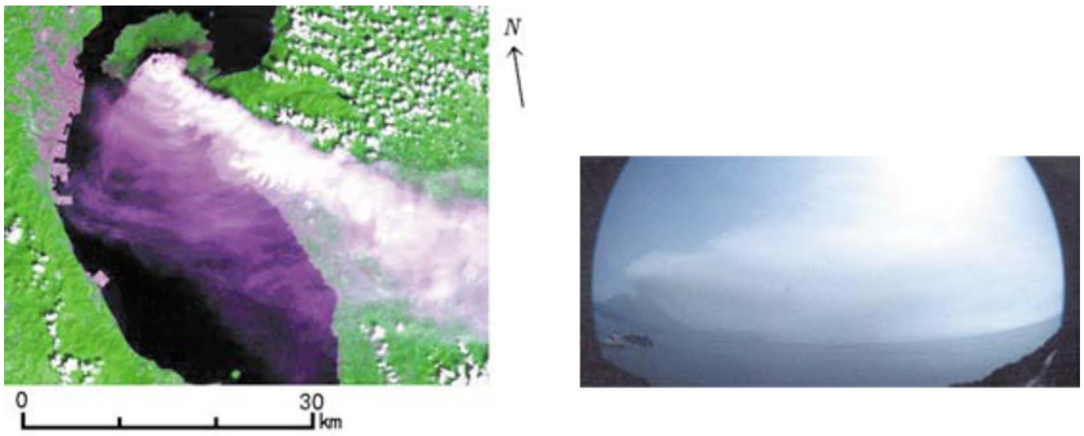
6.2 Fan-type Spread

Figure 9(a) exhibits a LANDSAT-TM image of the fan-type spread of the cloud on 10 Mar. 1989. This is a true color image with blue, green and red band, while other satellite images in this paper are natural color composite as Fig. 8(a). In the photograph of Fig. 9(b), the vertical shear of upper winds can be observed.



(a) (b)

Fig. 9. Fan-type spread of the cloud on 10 Mar. 1989: (a) LANDSAT-5/MSS image taken at 10:17; (b) A photograph taken at 10:14 from the fixed location 9.8 km WSW from the crater indicated by a cross in Fig. 9(a).



(a) (b)

Fig. 10. Belt-type diffusion on 2 Oct. 1991: (a) MOS-1/MESSR image taken at 10:58; (b) A semi-fish eye photograph taken at the same point as Fig. 9(b) at 11:00.

6.3 Belt-type Diffusion

Figure 10(a) is a MOS-1/MESSR image of the belt-type diffusion on 2 Oct. 1991. Early in the morning on the same day, a thick plume of linear advection type had been observed. Around the time of the satellite pass, shear winds at the lower side of the plume extended the horizontal width of the plume. Figure 10(b) is a photograph with a semi-fish eye lens from the same observation point as Fig. 9(b).

6.4 Flat Stagnation

On 18 Oct. 1989, upper winds at the altitudes of 1 - 2 km almost faded, resulting in flat stagnation of the volcanic clouds as seen in the MOS/MESSR image, Fig. 11(a), and the photographs from three points around Kagoshima bay, Figs. 11(b), (c) and (d).

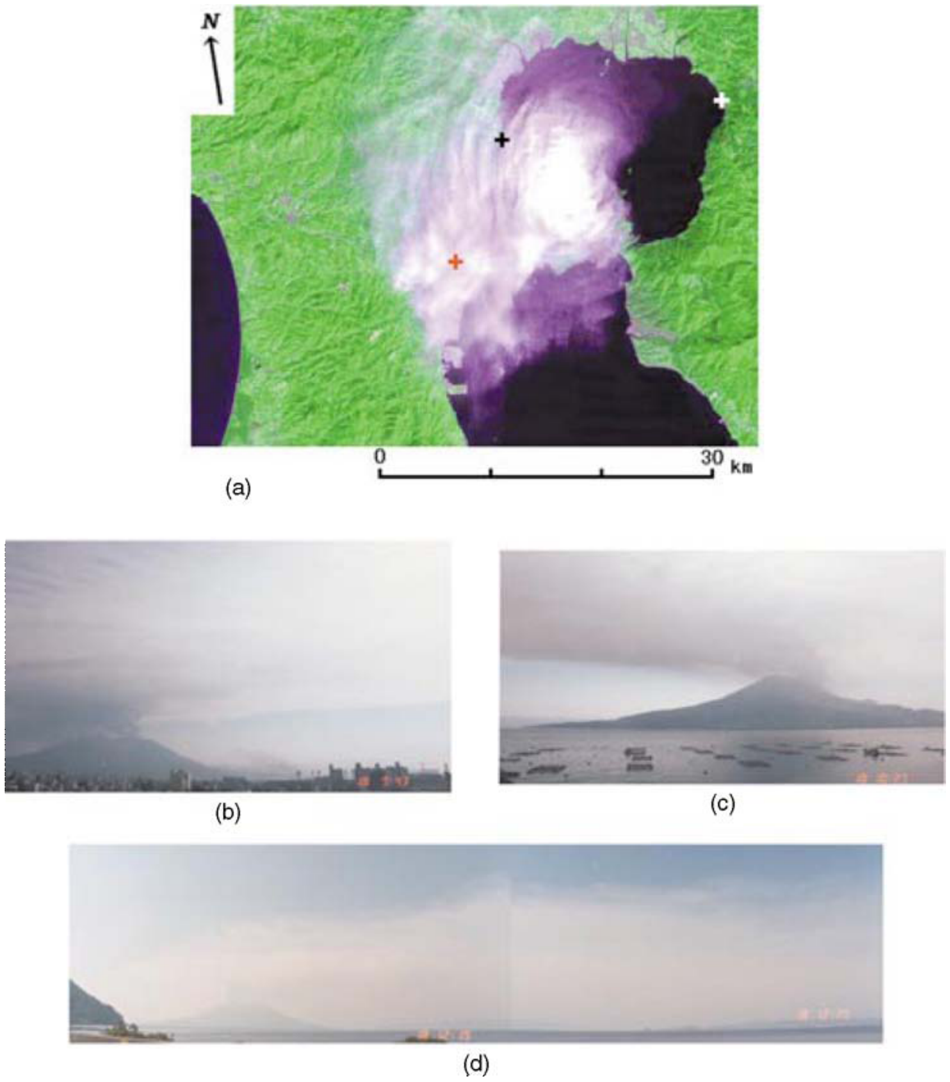


Fig. 11. Flat stagnation of the volcanic cloud above Mt. Sakurajima and the surroundings on 18 Oct. 1989. (a) MOS-1/MESSR image taken at 10:57. The photographs (b), (c) and (d) are taken at 9:43, 10:27 and 12:19 at three locations indicated in (a) by red, black and white crosses, respectively.

7. Discussion

Typical scenes of volcanic clouds at Mt. Sakurajima observed from the ground and from satellites are discussed here. As for the photographs and video images, stereo-graphic analyses have been done with a mesh frame along the wind direction for the eruption columns (Kinoshita and Todaka, 1995), and with an envelope formula for stationary plumes (Kinoshita and Yoshida, 1991; Kinoshita and Hosoyamada, 1992). The gross features of the satellite images are understood by a simple model taking into account the vertical shear of winds to simulate the horizontal dispersion (Iino and Kinoshita, 1996).

There are many important problems to be studied: the dynamics of the rise of the plume and the eruption cloud, the estimation of ejection energy and cloud components, the large-scale dynamics of ash fall, and so on. An immediate task is to construct a database by fusing visual information from the ground observation, the satellite images and related data on volcanic gas and clouds. Efforts in this direction have started in the home pages mentioned in the introduction, and also in the form of CD-R.

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