Chapter 5 Discussion for further investigation

5.1 Distinction of the eruption cloud

As far as we use image data taken by satellites for the detection of eruption clouds, it is very important to distinguish them in the images, which spread over ground or sea-surface, especially from atmospheric clouds. In the case of GMS, the detector has two kinds of image data of IR and VIS. As described in Chapter 3, most of the eruption clouds out of Alaid volcano clearly showed dark-toned or black domains in VIS images and the clouds could be easily detected in VIS images from ambient and even underlying atmospheric clouds. Many other eruption clouds from several volcanoes including Soputan, Una Una, Galunggung and Sangeang Api volcanoes, also showed relatively low-toned brightness of their domain taken in VIS images.

Albedo in % v. s. surface temperature in °C diagrams between eruption clouds from Alaid, Pagan, Soputan, Galunggung and Una Una volcanoes and atmospheric clouds having the same surface temperature as those of the eruption clouds are shown in Fig. 5-1. Good separation of eruption clouds from ambient atmospheric clouds was recognized for the Alaid eruption clouds. The data used for this diagram were obtained on the images returned during the most active period of the Alaid Eruption on April 28 - 30, 1981. On the contrary, there was no clear difference in the case of the Pagan eruption cloud. There were vague differences between the Galunggung eruption clouds and surrounding atmospheric clouds, but the relation was not so simple as for the Alaid eruption clouds, because the data zones for both clouds crossed each other and reversed the relation at the lower and the higher altitudes as seen in the figure. In the cases of the Soputan and the Una Una eruption clouds, the separation is possible only in the range of high altitudes, because the albedo of the atmospheric cloud is similar to that of the eruption cloud in low altitudes but is higher in high altitudes.

We have to accumulate more data before we can establish a standard method for distinguishing eruption clouds in GMS images. What we have noticed to data is that there is some tendency that the eruption cloud shows a relatively low albedo value compared to that of the atmospheric cloud. This may be due to high concentration of fine ejected materials in eruption clouds. And the intensity of low-toned brightness of the eruption cloud in VIS image may possibly be due to the difference of eruption mechanism controlling the amount of suspended materials in the eruption clouds. Development of better enhancement processing of the eruption cloud based on GMS's digital data using both IR and VIS image data is urgently desired in order to accurately distinguish eruption clouds from ambient atmospheric clouds.

5.2 Estimation of the maximum altitude of eruption clouds

As described in Chapter 3, many results on the highest altitudes of eruption clouds estimated on the basis of their surface temperatures using air-temperature profiles by radio-sounding observation data at nearby stations showed wide differences from the top altitudes determined by visual observations from ground stations. Generally, the altitude estimation from GMS data was greater than the result by ground observations.

There are good visual ground observation data on the duration times and top altitudes of individual eruptions on the 1982 and 1984 Soputan Eruptions and the 1983 Una Una Eruption. In Table 5-1, these data are compiled together with the corresponding values estimated from GMS image data. A comparison of those values has clarified that the duration time by GMS image analysis showed a larger value than that by visual ground observation. The main reason for this is the difficulty of detecting the occurrence time of eruptions in GMS image. In addition to this, there are several cases where the crater is covered by its own eruption clouds which make the recognition of their detachment from the crater difficult, even after the end of eruptions, owing to various wind directions and also various wind speeds at lower and higher altitudes over the volcano.

The highest altitude based on GMS image data sometimes showed higher values, even 5 times higher in one case, than that by ground observation as shown in Chapter 3. This phenomenon may be partly due to the difference of reference temperature by radio-sounding data, which were obtained at places very far from the volcano, from the actual surrounding air temperature, and partly due to the difference of actual surface temperature of an eruption cloud from the ambient air temperature. Basides, there remains the problem of the actual emissivity of the surface of the eruption cloud, because the distribution of surface temperature of an eruption cloud in this study was tentatively obtained under the assumption that the emissivity of 1.0 holds for all portions of the eruption cloud. It is considered, however, that the actual distribution of bulk emissivity on the surface of an eruption cloud should be far from that value since the thickness and shape of an eruption cloud are different from point to point on its surface. Concentration of materials in it will also generate a complicated distribution of emissivity. However, we do not have, at present, accurate data on the distribution of emissivity on the surface of an eruption cloud. At the same time, the inaccuracy of measurements of the top altitude of an eruption cloud by visual ground observations may also be responsible. It might be considered that an actively rising and spreading eruption cloud joins developing and rising air currents and presents an apparently higher altitude. On the other hand, there are several examples of good agreement between the top altitude of an eruption cloud estimated by GMS data and that by visual observation. The highest altitude of the Pagan eruption cloud estimated by GMS data did not exceed the visual ground observation result and the highest altitude of 14 km of the Soputan eruption cloud, estimated by GMS image data on September 18, 1982, well coincided with the altitude of 14 km witnessed by the crew of an aircraft.

On the contrary, there are some cases where the tops of eruption clouds estimated by GMS image data showed lower altitudes than the elevations of erupting craters, as in the cases of Mayon, Asama and Sakurajima eruption clouds described in Chapter 3. This was noticed for low-toned thin eruption clouds. The reason for this should partly be the use of an unrealistic emissivity value, but most probably, the influences of background radiation from down below through eruption clouds. They apparently cause the surface temperature of an eruption cloud to show a value higher than the actual one, resulting in an underestimation of the altitude.

For example, the altitude of the eruption cloud of the April 1982 Asama Eruption was estimated under the elevation of the summit crater of this volcano, but the drifting direction did not agree with the wind direction at the estimated altitude, but with the wind direction at higher altitudes. (see 3.7 in Chapter 3). We have neither emissivity nor transparency data of eruption clouds. The method to get actual and accurate altitudes of thin eruption clouds based on GMS image data should be left for further studies.

It is possible to judge whether top of an eruption cloud penetrated into the tropopause or not by inspections of temperature distribution on the surface of the eruption cloud as described in 1.4 of Chapter 1. An actual example was obtained in the case of the eruption cloud-like domain taken by GMS image during the 1985 Soputan Eruption as shown in 3.14 of Chapter 3. It will not be so simple, however, to judge whether the eruption-cloud penetrated into the tropopause, especially when only slightly. To solve this problem, it is required to develop a method for the accurate determination of the top altitude of an eruption cloud by GMS data and to carry out radio-sounding observation over the respective volcano.

To obtain exact the spreading process of an eruption cloud, it is indispensable to increase the accuracy of measurements of altitude and extent of an eruption cloud by GMS images.

At the same time, we have to know the actual distribution of thickness, brightness and emissivity on the surface of an eruption cloud. This should be attained by more intensive and detailed observation and analysis of GMS image and the related data and by careful comparison with referential data by more direct means. It is strongly required to conduct visual observation of actual spreading processes, physical features such as concentration of ejected materials and of optical features including emissivity distribution on the surface of an eruption cloud.

5.3 Estimation of released thermal energy based on eruption cloud data

Estimations of thermal energy releases associated with eruption clouds have been conducted for Sakurajima and Augustine eruptions (Friedman et al., 1976 and Kienle and Shaw, 1979). In this study, estimations of thermal energy released by eruption clouds detected in GMS images for several volcanoes are conducted based on the method proposed by Briggs (1969) as described in 1.4 of Chapter 1, as one of the methods for the evaluation of intensity or magnitude of volcanic eruptions. The volume of ejected materials, kinetic energy of ejections and thermal energy by juvenile ejecta were also estimated and compared with the estimated thermal energy by eruption clouds.

In Table 5-2, the estimated thermal energy released by eruption clouds was shown in the cases of 5 volcanic eruptions at Alaid, Asama, Pagan, Galunggung and Lopevi. The thermal energy release rate (T. E. R. in this table) was calculated in mega watts for individual eruptions which are divided into strong and small classes (L and S), then their mean (Mean T. E. R.) was obtained in each class. For each one of the 5 volcanic eruptions, the total of thermal energy release by eruption clouds in erg (Total T. E. in the table) was obtained as the summation of the products of Mean T. E. R. and the total duration time in each class (Duration Time in this table), which is assigned with maximum possible values. To present a general idea of the intensity of each activity, the total volume of ejecta in m^3 (Ejecta), its kinetic energy in erg (K. E.) and the total thermal energy by ejecta in erg (T. E.) are also shown in Table 5-2.

According to the results in Table 5-2, the Pagan and the Galunggung Eruptions showed large values in Mean T. E. R., of the order of 10^5 mega watts which are more than 10 times as large as the eruptions at other volcanoes. The Total T. E. was the largest at the Galunggung Eruption showing 7×10^{23} erg and significantly large, of the order of 10^{22} erg, at the Alaid and the Pagan Eruptions. These results well correspond to the individual eruption intensities based on Ejecta, K. E. and T. E. Total T. E. estimated from eruption cloud data here showed as small values as almost around one tenth of T. E. estimated by total volume of ejected materials.

The thermal energy release rate by eruption cloud data for the individual eruptions during the 1982 and the 1984 Soputan Eruptions and the 1983 Una Una Eruption are shown in Table 5-3 (Q in this table). Each of these three eruptions was well separated in GMS images as shown in Chapter 3. The duration time of the individual eruption activity judged in GMS images (GMS Data in this table) and respective height, wind velocity and horizontal distance used for the calculation of Q (h, u and x in this table, respectively) are also shown in Table 5-3. The largest value of Q, 1.9×10^6 mega watt was obtained for the eruption on August 26, 1983, of the 1983 Una Una Eruption. There were many individual eruptions greater than 10^5 mega watts throughout both eruptions. The mean of Q (Mean T. E. R.) is shown in Table 5-4. The Una Una Eruption showed the largest value of Q, the second largest being that of the 1984 Soputan Eruption.

The duration time of each of the individual eruptions has not been well determined in these cases. The total thermal energy values based on eruption cloud data of the three eruptions were calculated assuming the mean duration time of the individual eruptions to be 60 minutes. The results in erg (Total T. E.) are shown in Table 5-4 together with the Mean T. E. R. and total ejecta in m^3 (Ejecta in the table), and the thermal energy by juvenile ejecta in erg (T. E. in the table). According to the results in Table 5-4, Total T. E., 1.9×10^{23} erg, Ejecta and T. E. in Table 5-4 were all the greatest among the three in the case of the 1983 Una Una Eruption. The second was the 1984 Soputan Eruption and the third the 1982 Soputan Eruption. These results indicate that thermal energy estimated from eruption cloud data by GMS image might be one of the methods for evaluation of intensity of volcanic eruption. There was also recognized the tendency of the thermal energy estimated by eruption cloud (Total T. E.) to be smaller, almost one tenth at the maximum, than the thermal energy released by juvenile ejecta (T. E.).

The thermal energy release rate (Q) was determined based on the individual eruption clouds during the 1984 Mayon Eruption and was shown in Table 5-5 together with calculating parameters, height, horizontal distance and wind velocity (h, x and u, respectively). A series of great values of the order of 10^5 mega watts was obtained for eruption clouds taken during the period September 23 - 24 giving the maximum value of 8.7×10^5 mega watts at 00 GMT on September 24. During this period, the eruption clouds presented bright-toned and wide extent in GMS images. Except during this period, eruption clouds showed relatively small Q values of the order of 10^4 mega watts or less and did not show so bright-toned and wide domains. By assuming the duration time of individual eruption to be 60 minutes, the total of thermal energy release by eruption clouds throughout the 1984 September - October Eruption was estimated at 7.9×10^{22} ergs, while the thermal energy estimated by juvenile ejecta is of the order of 10^{24} ergs. The thermal energy by the eruption clouds ejected during the period September 23 - 24 accounted for almost 99.6 % of the total energy.

The compiled results in this section indicate that the thermal energy release obtained by eruption cloud data was smaller in many cases than, often as small as almost one tenth of, the thermal energy estimated by juvenile ejected materials. The relation between total thermal energy release based on eruption cloud (T. E. (CLOUD) in ordinate) and juvenile ejecta (T. E. (EJECTA) in abscissa) is shown in Fig. 5-2. Not withstanding the scattering of the points, and gaps of the data in the range of 10^{21-22} ergs of T. E. (EJECTA) or 10^{20-22} ergs of T. E. (CLOUD), there is an approximate linear relation between T. E. (CLOUD) and T. E. (EJECTA). This indicates that the thermal energy release by eruption cloud can evaluate the intensity of volcanic eruption. To obtain a more definite conclusion, further accumulation of data is strongly required.

5.4 Physical characteristics of eruption cloud based on LANDSAT MSS data

Eruption clouds and atmospheric clouds are compared in a temperature - albedo plot in Fig. 5-3 for the Sakurajima erupion on February 24 and July 29, 1985. It must be noted that the eruption cloud shows a lower albedo value (ordinate in %) than the atmospheric cloud at the same surface temperature (abscissa, T_{BB} in °C). This is the same result as obtained in section 5.1. And there is also the same problem that the Sakurajima eruption cloud was thin and was easily affected by background radiation from the sea and ground surface, so it was not easy to clearly distinguish an eruption cloud from an atmospheric one.

To get further information on the optical features of eruption clouds, LANDSAT MSS images were tentatively analyzed through personal computer processing. The data used are of the Sakurajima eruption clouds taken on January 30, October 9, November 14 and December 20, 1979, March 19, 1980, March 23, 1981, and on October 12, 1983. Generally, the eruption cloud taken in LANDSAT MSS image shows clear-toned brightness in bands of Nos. 4 and 5, but is pale in bands of Nos. 6 and 7 (Tanaka et al., 1981). However, in the case of the eruption cloud on November 14, 1979, the images obtained were almost identical in all of the 4 bands after image-enchancement as shown in Fig. 5-4, where intensity of the radiation brightness was assigned to 128 levels. The level of radiation brightness of the Sakurajima eruption cloud showed low values in general, but comparatively high in No. 4 band decreasing towards No. 7 band.

The bands dependency patterns of radiation brightness of eruption cloud, atmospheric cloud, sea surface, city area and forest area are compared in Fig. 5-5 between LANDSAT images taken on October 9, and November 14, 1979. Both of the eruption clouds were rather thin ones spreading over the sea surface which present simple radiation features compared with those over the ground area. The radiation level of eruption clouds is high in No. 4 band and decreases towards No. 7 band. This pattern is in parallel with the patterns of atmospheric clouds and the sea surface, but not with the patterns of forest and city areas. As a whole, the radiation level of the eruption cloud was higher than that of the sea surface, but was in the middle of a wide scattering radiation range of atmospheric cloud (see also Fig. 5-6).

All of the patterns of radiation levels at various points on the surfaces of the Sakurajima eruption clouds taken in LANDSAT MSS images are shown in Fig. 5-7. The portions of individual eruption clouds over the crater or at the central portions of the spreading extent showed a high radiation level, which well coincides with those of atmospheric clouds, but the edges or tips of the spreading extent showed low radiation-level values which nearly correspond with those on the sea surface. The bands dependency of the radiation level in Fig. 5-7 showed a similar pattern as in Fig. 5-6; high at No. 4 band and decreasing towards No. 7 band and approximately parallel with the patterns of the sea surface and atmospheric clouds, despite the presence of several different patterns, especially those with radiation levels higher than about 30 (see Fig. 5-7).

The patterns over crater or at the center of the Sakurajima eruption clouds showed as high radiation levels as those of thick atmospheric clouds. On simple consideration, these results may indicate the possibility that the eruption cloud is composed of ice or water droplets or a mixture of both particles like the atmospheric cloud. So materials ejected and then borne inside an eruption cloud might be in the form of droplets coated with ice, water or both at least near the surface, and therefore, reflects the characteristics of water or ice surfaces, and shows bands dependency patterns of radiation levels of the sea surface or of atmospheric clouds. The level differnce might be explained by their thickness or concentrations. It has been known that the density or thickness of an atmospheric cloud is due to the concentrations of droplets and their size-distributions. When a large quantity of ejected materials are borne inside eruption clouds as in cases of strong ash-clouds ejections, the eruption clouds will manifest a dark tone. This may be due to the decrease of optical contribution of the ice or water coating with the increase of concentrations of ejected materials. However, in many cases of ordinary eruption clouds which do not contain a large quantity of ejected materials inside, it might be assumed that the concentration or size-distribution of droplets which compose an eruption cloud is almost similar to that of the atmospheric cloud. Therefore, it will be possible to estimate the total volume of ejected materials borne within a spreading eruption cloud using or substituting the experimental or observed results on various kinds of atmospheric clouds concerning concentrations or size-distributions of droplets borne within them.

5.5 Consideration on satellite monitoring of volcanic eruptions

For the establishment of more effective GMS image-monitoring of volcanic eruptions, there are several problems to be solved in the author's opinion as follows:

(1) Image-taking intervals

It is important to observe the complete sequence of behavior of eruption clouds for monitoring volcanic eruptions, but generally, eruption cloud ejected to high altitudes quickly spread and disperse within a short time. Besides, it is also necessary to detect eruption clouds at low altitudes when they are still small, immediately after the occurrence of volcanic explosions to determine the accurate occurrence time of the volcanic eruption. For these purposes, a shorter image-taking interval is fundamentally demanded.

(2) Ground resolution of GMS image

The detection limit of the dimensions of an eruption cloud in GMS image reached experimentally about 10 km under the best weather conditions, but it is usually 20 - 30 km in its horizontal extent at an altitude of several km. The detection limit of GMS image is sufficiently fine for the detection and monitoring of large eruption clouds generated by big volcanic eruptions. However, for the monitoring of volcanic eruptions in more detail and of eruption clouds with small size, ground resolution of at least 1 km of IR image is needed.

(3) Distinguishing eruption clouds

Careful inspections of GMS images by observers will make the detection of volcanic eruption clouds possible, as far as the feature of eruption clouds is peculiar compared with that of the atmospheric cloud. However, since eruption clouds are mostly composed of vapours or droplets of water including ejecta-particles coated with water, ice or their mixtures that have optical features apparently similar to those of atmospheric clouds, it is difficult to well separate eruption clouds from atmospheric clouds based on only two kinds of IR and VIS image data. Besides, it is almost impossible to detect eruption clouds spreading under atmospheric clouds.

To solve the above-mentioned problems, additional detectors having diffrent wavelengths like LANDSAT's MSS or TM and using microwave-sensors will be effective for distinguishing and detecting images of eruption clouds not only in the daytime but also at night time. The detector such as TOMS (Total Ozone Mapping Spectrometer) borne on Nimbus satellite which could detect eruption clouds as highly concentrated SO_2 clouds (Krueger, 1983) is also one of the effective sensors to distinguish eruption clouds.

(4) Easy operating image-processing method

When we apply GMS image-monitoring for the purpose of observations of volcanic eruptions or movement of volcanic eruption clouds in the field of volcanic hazard-reduction, many of the image data of eruption clouds have to be quickly processed. And also, processing of many image data have to be conducted for analyses of time variations of spreading eruption clouds to investigate into the dynamics of spreading eruption clouds or volcanic eruptions. For these purposes, the development of a convenient and easy-operation system for image analyses is required.

(5) Physical and optical characteristics of eruption cloud-surface

Temperature distribution on the surface of an eruption cloud is very important to estimate the altitude of an eruption cloud and the thermal energy it releases. However, we do not have enough data on the actual physical and optical characteristics of the surfaces of rising, spreading and dispersing eruption clouds in the atmosphere, including the actual distribution of emissivities of eruption clouds. The physical or optical nature of eruption cloud such as the distribution of thickness, transparent features or emissivity on the surface are strongly needed to accurately estimate the altitude and extent of an eruption cloud, to monitor the time variations of altitude and extent, and to estimate thermal energy release or mass of ejected materials borne inside the eruption cloud. Observations, measurements and theoretial studies should be conducted more intensively by applying every available method to get the physical or optical properties of eruption clouds.

(6) Theoretical and experimental investigations on the dynamics of spreading eruption cloud and the eruption mechanism

Detection of widely spread eruption clouds in the atmosphere and stratosphere could be well conducted using satellite images. For example, many image data on spreading sequences of eruption clouds in the atmosphere were shown in this paper, and the regional spreading sequences of the eruption cloud by the big eruptions of El Chichōn volcano ejected to the stratosphere could be well traced using satellite images (Matson, 1984). Investigations for dynamics of rising, spreading and dispersing eruption clouds will be supported by these satellite image data. The theoretical and experimental results of dynamics of eruption clouds are very important for an accurate estimation of thermal energy release as one of the evaluation methods of intensity and strength of volcanic eruptions. Their results will provide effective and fundamental data for further studies concerning the eruption mechanism and atmosphere sciences.

(7) Precise observation of volcanic eruptions

Satellite-monitoring technique for volcanic eruptions is a useful tool for volcanological study and volcanological surveillance work, and can provide effective and fundamental materials for them. To make the technique more effective, precise ground observation data such as the begining and end or decay times of a volcanic eruption, mass of ejected materials, and time variations of the top-altitude of eruption clouds are important information for the investigations, forming the so-called ground-truth data. Visual observations from the ground, radar measurements or aerial observations and orbital satellite image data on the sequences of volcanic eruption clouds are also strongly demanded for the further development of investigation of satellite image analyses.

(8) Establishment of a quick communication system

In the field of volcanic hazard reduction work including security of transport, especially for aircraft in their flight, various data and information are demanded. For forecasts of ejecta-fall areas, estimation of ejecta-mass and monitoring of movement of eruption clouds over wide regions will be possible through analyses of eruption cloud image data taken by

GMS. For these purposes, accurate radio-sounding data around and over respective volcanoes and quick image-data processing systems are needed, and besides, quick communication systems for the issuance of warnings based on analyzed results of image data on the occurrence of volcanic eruption are strongly demanded. The early establishment of an international data-exchange system for volcanic events should be promoted.

(9) For prediction of volcanic eruption

Monitoring eruption clouds by GMS images can not directly contribute to the prediction of volcanic eruptions. Seismological observation, detection of ground deformations or monitoring of thermal state at active sites of volcanoes are useful means for the purpose of predicting volcanic eruptions, but those kinds of measurements should be conducted on the ground or by aerial observations. Analyses of orbital satellite images which have higher ground resolutions of IFOV than those of GMS images may be used for monitoring the thermal activities of active sites of volcanoes. The GMS should be effective as a data-collecting platform (DCP) for such radio-telemetered data as seismological events, ground deformations, ground or fume temperatures, chemical compositions of volcanic gases etc. from volcano sites that have no fully-equipped volcano observatories.

(10) Observation of non-explosive volcanic activity

There are also volcanic activities not accompanied by active ejections of eruption clouds, but show only gentle pourings of lava flows or growth of lava domes, and discolorations of sea-water by submarine activities. To monitor these activities by GMS images is very difficult owing to its limit of IFOV. These activities should be monitored by ground or aerial observations and sometimes orbital satellite image analyses. Of course, the GMS can be a useful DCP system for monitoring those activities.