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Ground and Satellite-based Observations of Mayon Volcano, Philippines

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Abstract

Automatic interval recording of volcanic clouds at Mt. Mayon, Philippines started in June 2003 as joint work of PHIVOLCS and the Kagoshima University group, and evolved into a real time monitoring system accessible from Quezon and Kagoshima in April 2004. In this system, a conventional visible camera is used in tandem with a near-infrared camera, which is less sensitive to atmospheric haze and able to detect hot anomalies. It is intended to eventually provide live access to imagery of the volcanic cloud on the World Wide Web. The necessity of the ground-based system in conjunction with satellite-based volcanic cloud monitoring is discussed for worldwide aviation safety, exhibiting some satellite imagery of clouds from the Mayon eruptions of 29 February 2000. The performance of the system until November 2006 is reported including the summer 2006 eruptions with lava flows from the summit crater.
Keywords: eruption cloud, interval recording, lava flow, near-infrared

Introduction

Mayon Volcano, near Legazpi in southeast Luzon, Philippines shown in Fig. 1, is the most active volcano in the Philippines with 48 eruptions in recorded history. Mt. Mayon is an andesitic stratovolcano, with a height of 2,462 m above mean sea level, and has a world-renowned near-perfect symmetry. Following a major eruption in 1993 which resulted in 77 fatalities, the volcano has recently become active again with

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significant eruptions in 1999, 2000, and 2001 (CATANE *et al*. 2003, 2005). A lava dome inside the summit crater grew and its glow after dark was often observed from June to November 2005. In the summer 2006, a considerable amount of lava was emitted from the summit crater, resulting in lava flows down to the foot of the volcano and the evacuation of about 40,000 people around the volcano (PHIVOLCS-DOST 2006).

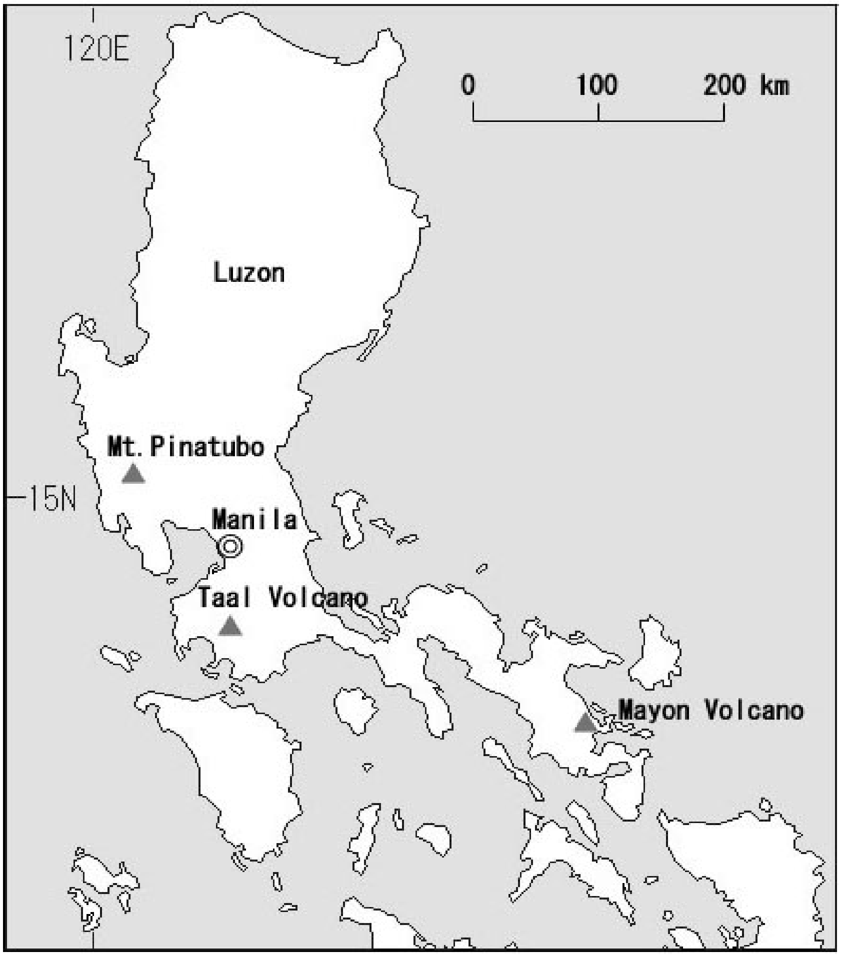

Fig.1. Location of Mayon volcano.

Approximately 900,000 people live around the volcano, and the location also coincides with major Asia/Pacific air routes. Therefore, its eruptions pose a hazard for both local populations and international aircraft. Volcanic monitoring and warning in the Philippines is the responsibility of the Philippine Institute of Volcanology and Seismology (PHIVOLCS). PHIVOLCS maintains a well-staffed observatory at Lignon Hill, 11 km SSE of the crater, with observation network of seismicity- and tilt-meters around the volcanic mountain. The remote sensing of the SO_2 emission by a correlation spectrometer (COSPEC) is done every week.

The worldwide volcanic warning service for aviation is known as the International Airways Volcano Watch (IAVW), and is composed of aviation, meteorological, and volcanological agencies (INTERNATIONAL CIVIL AVIATION ORGANIZATION 2000). Regional warnings for aviation are the responsibility of the Philippine Atmospheric, Geophysical & Astronomical Services Administration (PAGASA), based in Quezon City. Volcanic ash dispersion forecasts are provided to PAGASA by two Volcanic Ash Advisory Centres (VAACs) in Tokyo (operated by the Japan Meteorological Agency) and Darwin (operated by the Australian Bureau of Meteorology). The two VAACs use satellite techniques to monitor the Philippines north and south of 10° S for ash clouds, and dispersion models such as HYSPLIT (DRAXLER and HESS 1998) to forecast the ash dispersion. Mayon volcano, at 13.3°N 123.7°E, lies in the Tokyo VAAC area, but ash from the eruptions can drift into the Darwin VAAC area. Therefore, information about the state of the volcano is shared by all agencies.

The recent development of the IAVW has expanded the area that a volcanic eruption is perceived to affect, and focussed attention on the need for international co-operation in volcanic hazard mitigation in the Asia/Pacific region (TUPPER and KINOSHITA 2003, TUPPER *et al*. 2003b), as well as closer ties between volcanological and meteorological agencies. One of the limitations of satellite-based monitoring of Mayon is that, being in the moist tropics, it is often obscured by cloud. While there have been some successes in satellite-based volcanic cloud monitoring (SAWADA 1987) and with satellite detection of hot spots (WRIGHT *et al*. 2002), many eruptions have been completely obscured.

A critical piece of data for volcanic cloud monitoring is the height of an eruption. The greater part of ascent of volcanic clouds is driven by convection (WOODS 1998), and the amount of water entrained into, or already present in an eruption plume, substantially influences the height of ascent of small-to-medium sized eruptions (GRAF *et al*. 1999, WOODS 1993). However the dynamics of volcanic clouds are still imperfectly understood, with relatively few reliable observations taken of volcanic cloud ascent (SPARKS *et al*. 1997). The location and activity of Mayon Volcano make it an ideal subject for study of eruption clouds. The PHIVOLCS observatory at Lignon Hill provides a well staffed, secure observational site. In addition, a PAGASA upper-air station (WMO 98444) is located in Legazpi.

In this paper, we show some satellite imagery of clouds from the eruptions of 29 February, 2000. Then we explain the ground observation system, and discuss the preliminary results until November 2006.

The 29 February 2000 Eruption

Summary of eruption:

The 29 February 2000 eruption was a Vulcanian phase during a sequence of mostly Strombolian activity that began in May 1999 (CATANE *et al*. 2003, SMITHONIAN

INSTITUTION 2007). PHIVOLCS had recommended evacuation of the population by 23 February 2000; on that night lava emission commenced, and ash and gas explosions occurred from 24 February to 1 March. Of these, only the eruptions beginning on 29 February and continuing to early 1 March were clearly visible on satellite imagery. In addition to the local effects, the eruptions caused major disruption to aviation, in part because of various difficulties in obtaining and receiving aviation warnings. Fortunately, no aircraft encounters with the ash clouds were reported. The total volume of pyroclastic deposits from the eruption was estimated at 13,907,810 m^3 (CATANE *et al*., 2003, 2005).

Satellite Imagery of Eruption Clouds

The major operational algorithm for volcanic clouds detection in the region is the

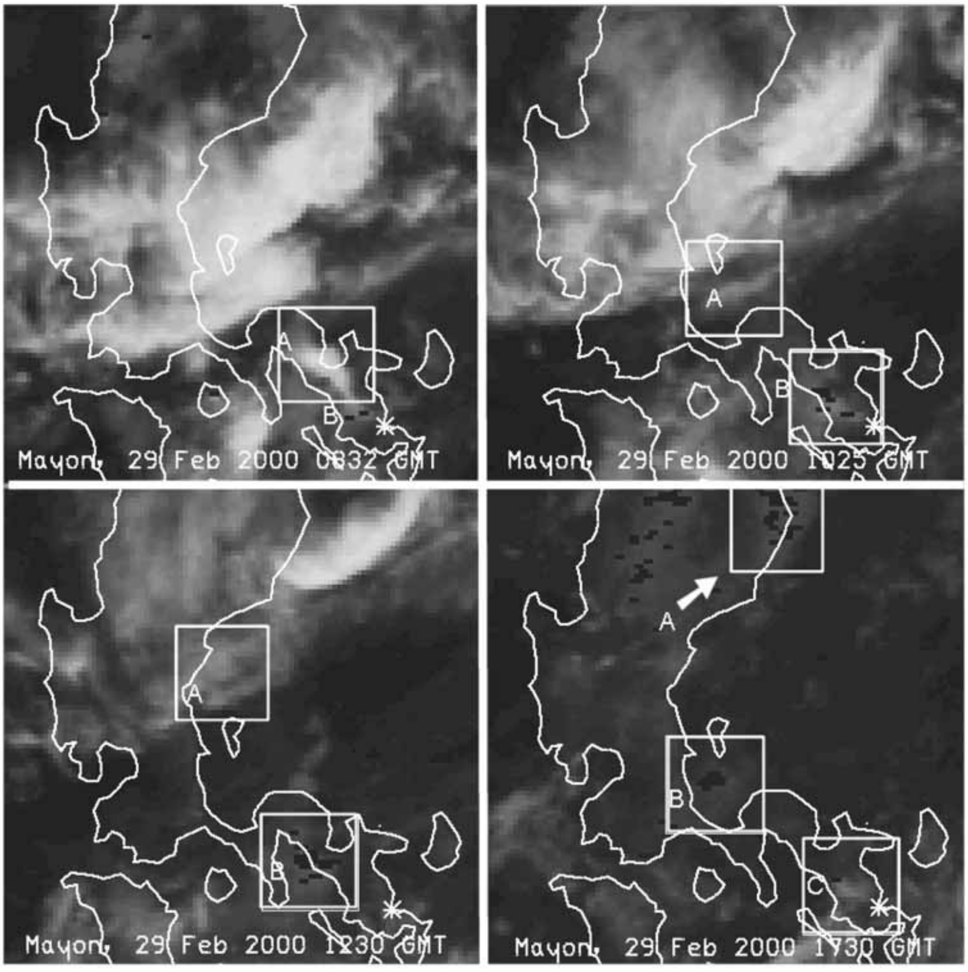

Fig.2. Infrared GMS-5 imagery of eruption clouds from the 29 February 2000 eruption, labelled A, B, and C. Images times are nominally 0832, 1025, 1230, and 1730 UTC - satellite scanning time over Mayon is approximately 10 minutes later.

'reverse' absorption algorithm (also known as the 'split-window', 'brightness temperature difference(BTD)', or 'aerosol vapour index' technique) (PRATA,1989a, b), and is used in combination with visible and infrared imagery (TUPPER *et al*. 2004).

Fig. 2 shows four infrared images during the dispersion of three of the ash clouds observed during this period. In this image, pixels with negative BTD (suggesting ash) are overlaid in dark grey. Clouds A and B appear to derive from the same explosion, at 0701 UTC, but dispersing at different rates. A notable point is that cloud A shows no negative BTD pixels. Examination of scatter diagrams of BTD vs. brightness temperature for the eruption (PRATA *et al*. 2001) further suggests that there is no detectable ash signal in cloud A, but strong ash signatures in clouds B and C. It appears that either glaciation of water onto the ash aerosols within the high level cloud obscured the ash signal, or that the cloud contained insufficient ash to detect. Fig. 3 shows trajectory forecasts from NOAA (DRAXLER and ROLPH 2003) and Bureau of Meteorology (DRAXLER and HESS 1998) implementations of HYSPLIT, with FNL and LAPS data respectively, where FNL is the final meteorological data of global meteorological model by NOAA, and LAPS is Limited Area Prediction System (PURI *et al*. 1998). The data were consistent at high levels (not shown for the HYSPLIT/LAPS run); however variations in the lower level wind fields have produced slight differences in the lower levels.

In the HYSPLIT/FNL trajectories (Fig. 3), the right-most line shows the forecast path of a cloud at a height of 14 km, which is consistent with the observed movement of cloud A and the coldest observed temperature in that cloud. The middle trajectory, at 6000 metres altitude, is consistent with the much slower movement of clouds B and C. The explosion leading to the release of cloud C does not appear to have been specifically reported (SMITHONIAN INSTITUTION 2007), which is unsurprising given the darkness, and heavy ash-fall from earlier activity. Heavy ash fall at the ground was reported to the west and southwest of the volcano(SMITHONIAN INSTITUTION 2007) con-

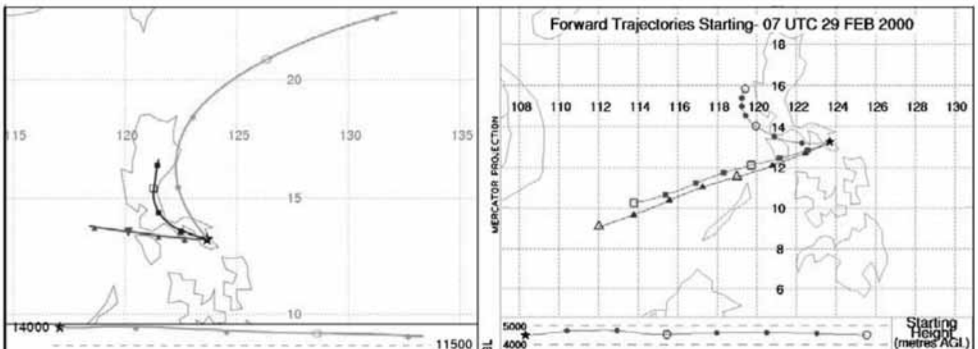

Fig.3. Forecast trajectories for clouds from the 0701 UTC eruption. Left panel: NOAA/HYSPLIT display using FNL data, trajectories starting at 3000, 6000, and 14000 metres. Right panel: Bureau of Meteorology HYSPLIT using LAPS data, trajectories starting at 2462 (mountain top), 3000, and 4500 metres.

sistent with the lower level trajectories in both sets of the model output.

This reflects a common difficulty with ground-based volcanic cloud reporting; the higher level clouds tend to have finer ash particles and little noticeable fallout away from the eruption source, and tend to be less well observed.

NOAA/AVHRR data will generally offer a clearer picture of volcanic ash clouds due to data and spatial resolution, and a better separation between the 11 and 12 μm channels (TOKUNO 2000). Fig. 4 is a reverse absorption image shortly after the release of cloud C. The 12-11 μm signal for clouds B and C is clear, but the AVHRR results are consistent with the GMS imagery in having no substantial reverse absorption image for cloud A

The meteorological satellite data of the 29 February 2000 eruption was also analysed with similar results by Tokyo-VAAC (2003).

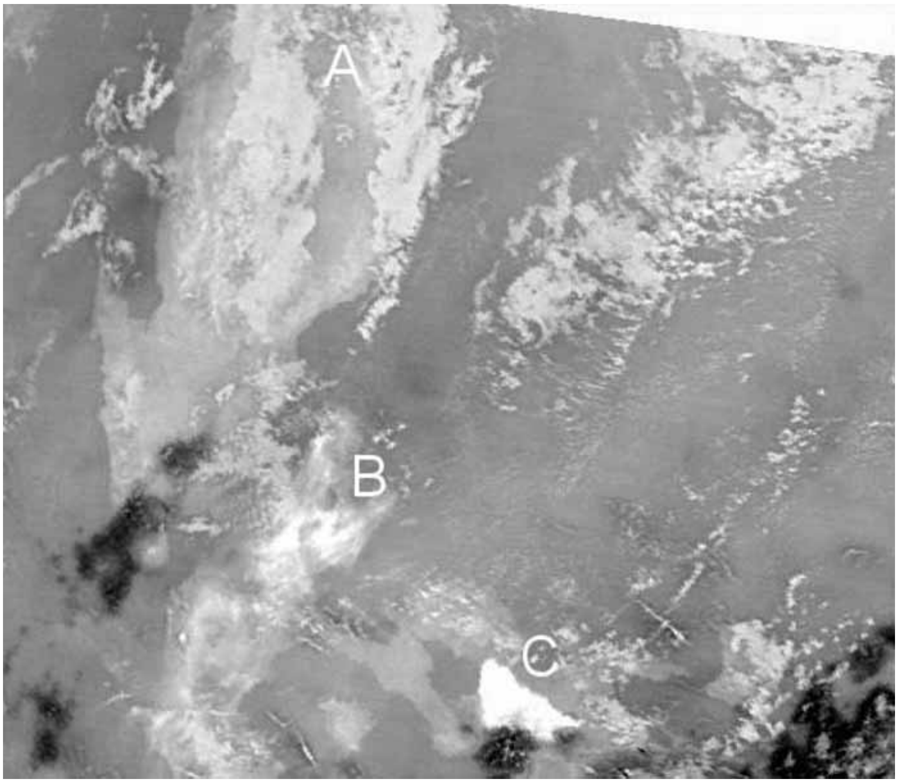

Fig.4. Contrast-stretched 1730 UTC NOAA-14/AVHRR image of 12-11 μm brightness temperature differences, corresponding to the last image in Fig. 1. Negative differences are shown in white. Data courtesy NOAA.

Interval Recordings with Visible-spectrum Cameras

Video monitoring at Mayon Volcano Observatory in Lignon Hill commenced on

22 June, 2003, with the installation of a digital camera to take one photo an hour, and a video camera recording for 0.5 seconds every ten minutes. This time interval has been found to be suitable for monitoring the evolution of volcanic clouds in experiments at Japanese volcanoes (KINOSHITA *et al*. 2003). The digital camera Sharp MD-PS1 operated for 58 days until 19 August, recording images with the pixel size 640x480 and a horizontal angle of 24°, which is the telephoto option of the camera. Part of the records, at 700, 1200 and 1700 hours in Philippine standard time (= 8+UTC) every day during June 24 - Aug. 19, 2003, are shown at http://arist.edu.kagoshima-u.ac.jp/volc/mayon/2003mayon/photo.html .

During this period, the volcano has been ejecting plumes from the summit crater almost continuously in the visible scenes, though the activity remained relatively quiet without strong eruptions. The height and direction of the plumes are analysed by comparing with wire frame images and scales, with the following results (HAMADA *et al*. 2004): (1) Cloud-free scenes are rather limited to morning and evening, as the clouds develop to cover the summit in the daytimes in sunny days. (2) The average height of the rising plume is about 560 m from the summit for the analysable scenes during 24 June and 16 August 2003 (blow down cases and plume directions where it is difficult to estimate the height are excluded). (3) There is a seasonal variation even in the short term.

As the English manual of the digital camera was not supplied and the indications in its display screen are only in Japanese, the restart of the camera was not successful with hand-made quick notes only.

The SONY video camera DCR-TRV22, with the 1/4 inch CCD composed of 680000 pixels, has been set for the interval recording, by adjusting the field of view mostly to the wide-angle side in the zooming range of the horizontal angle 4-40°. The video camera is equipped with the display and a manual both in English. The restarts have been successful in dealing with unavoidable power shortages beyond the capacity of the uninterrupted power supply, such as typhoon, thunder-squall, troubles in the power plant and supply lines, and renovations in the observatory for new systems. Dur-

Fig.5. Mayon volcano and the observatory at Lignon Hill, viewed from Legazpi Airport.

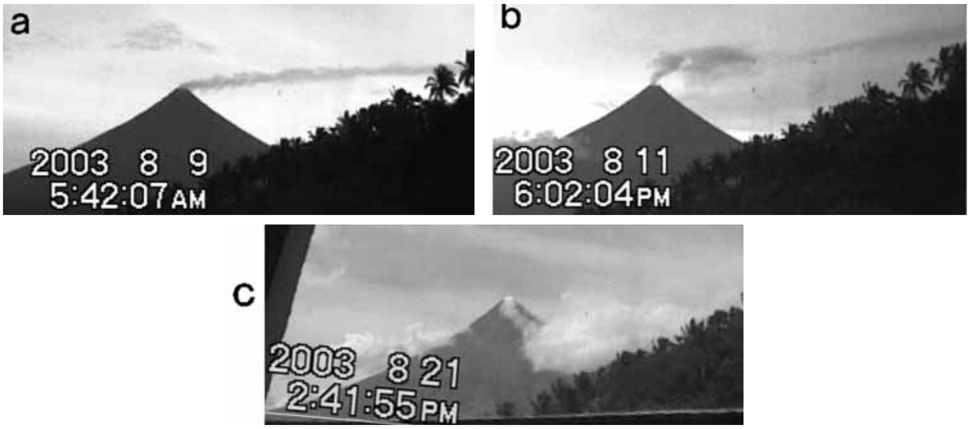

Fig.6. Typical scenes of the plumes at Mayon volcano.
(a) Horizontal flow, (b) Rize and flow, (c) Lee wave pattern.

ing 22 June 2003 and 24 February 2004, records for 167 days were obtained, while the data for 77 days are lacking. All the data with the summit scenes have been converted into mpeg movies. It should be noted that more than half of the days recorded are cloudy without a view of the volcano, and good views are rather limited to the morning and evening because of the tropical weather and the orographic effect of the high mountain. Some of the highlighted scenes until 21 September 2003 are displayed at http://arist.edu.kagoshimau.ac.jp/volc/mayon/2003mayon/VIDEO/VIDEO.HTM

Fig. 6 shows typical patterns of the plume flow according to the wind around the summit height: For fresh wind, the plume flows almost horizontally without rising as shown in (a), as the buoyancy is lost by quick mixing with the ambient air, in contrast to the rise up to the balanced height under mild wind as shown in (b). If the wind is so strong to form a mountain lee wave, the plume is blown down along the flank of the mountain and then rises as shown in (c). Such features are in common with the plumes at Sakurajima, Japan, and other volcanoes well observed with the height around 1km. A different feature is that the 'blow-down' seems to be confined to the middle of the flank, without descending to the ground level, indicating that the Froude number is lower than previous cases, because the crater height is more than twice that of Sakurajima.

Video imagery also shows a remarkable scope of interactions between the volcano and the moist atmosphere (Fig. 7). In particular, we have been able to see the frequency with which plumes from Mayon interact with convection forming on the mountain, enabling the transport of trace amounts of volcanic materials to high altitudes even in the absence of explosive eruptions (TUPPER *et al*. 2003a).

Fig.7. Three sequences of still shots from video recording of Mayon during 2003, showing, top to bottom: orographic cloud formation on 23 June 2003, shallow convection in the plume from the volcano, gradually evolving into deep convection on 11 August 2003, and rapid formation of deep convection about the plume on 15 August 2003.

Network Camera System to Take Visible and Near Infrared Images

On 24 February 2004, we installed a network camera system that has a visible and near-infrared camera in parallel, as shown in Fig. 8. The near-infrared camera 'AXIS2420-IR sensitive' with a filter Fuji film IR84 to shield visible light is used for

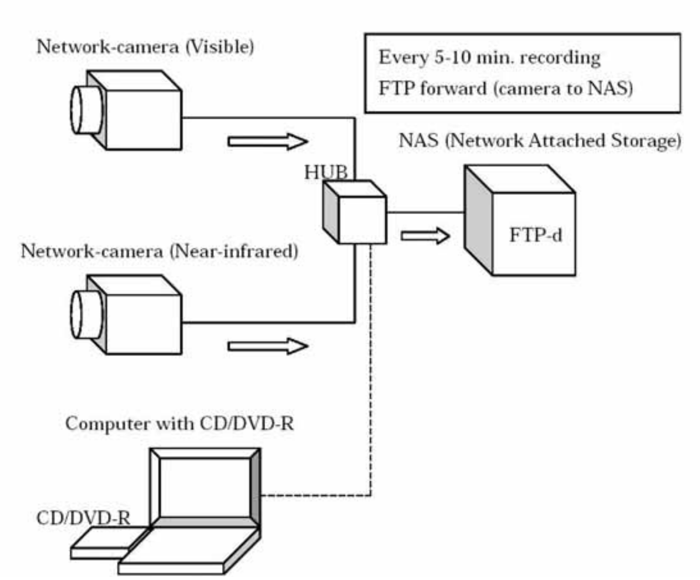

Fig.8. System design for visible and near-infrared network camera system.

clearer discernment of ash cloud (Kinoshita *et al*. 2004), and also the detection of high-temperature anomalies, as in the case of 2001 eruptions. Although the sensitivity of the camera is not so high as that of high-sensitivity cameras during nighttime, it is relatively inexpensive, and ideal for exploratory investigations. Visible network camera is AXIS2120, and the network-attached storage is Logitec LHD-NAS120 with a capacity of 120 GB (large enough to store the JPEG images of both cameras with the pixel size 704x480). The system is modular in design, easily maintained, expandable and suitable for both research and real-time applications.

The system started to operate as a local network, able to store visible images every ten minutes during 5:30 and 18:30, and near-infrared images every one-hour continuously. The numbers of the image files were thus limited, not because of the capacity of the network-attached storage, but for the problem of easy data transfer. Zoom lenses, with focusing lengths 2.8-11 mm and 3.5-8 mm, are attached to the 1/3 inch

Fig.9. Scope of the view for the network cameras.
(a) Visible camera (Left), (b) Near-infrared camera (Right).

Fig.10. Three cameras at Mayon Volcano Observatory. From the left to the right, near-infrared and visible network cameras connected to the hub, and a video camera standalone. The power is provided through uninterrupted power supply.

CCD cameras AXIS2420-IR sensitive and AXIS2120, respectively. A wide field of view is adopted for the visible camera (Fig. 9a) to see the flow of volcanic cloud, while the near-infrared camera is set closer to see the hot anomaly at the summit crater (Fig. 9b). The interval recording by the video camera continues as a backup of the system. The set-up of three cameras is shown in Fig. 10.

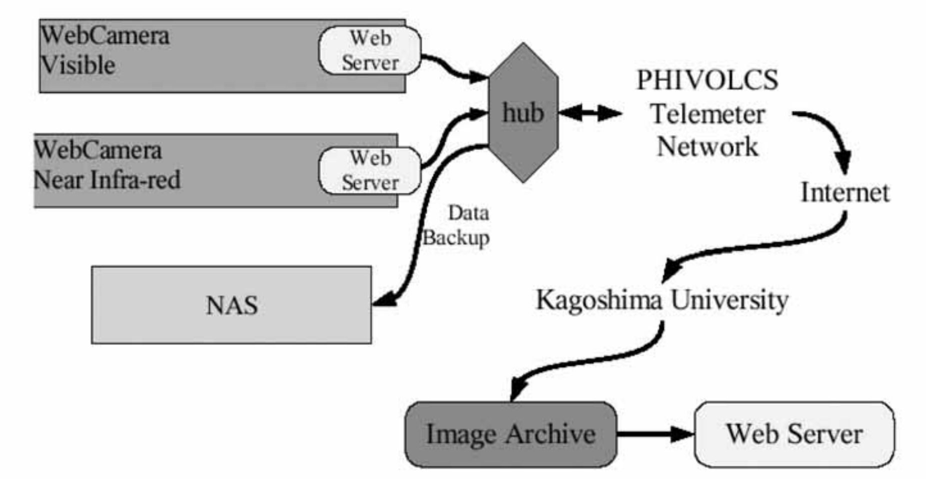

Fig.11. Network camera system connected with Internet.

Since April 2004, the network camera system has been connected to the Internet, and real time access is occasionally possible from Quezon and Kagoshima. We have tried to construct a semi-real time homepage for the worldwide web, with the flow of the information shown in a schematic diagram (Fig. 11). A conservative policy is adopted to protect the system against destruction by hackers. However, the Internet link with the servers at the nearby stations was not strong enough in the tropical conditions, and often disconnected. Therefore, the local storage of the data is very important for the research studies. Fortunately, the Internet connection was revived in the summer 2006, enabling the access to the network cameras from Japan for many days.

The Summer 2006 Eruptions

A lava dome inside the summit crater grew and its glow after dark was often observed from May to November 2005. In July 2006, considerable amount of lava was emitted from the summit crater, resulting lava flows down to the 450 m elevation of the volcano in the southeast direction. Several volcanic earthquakes were also detected, generated from the ascent of magma inside the volcano. In addition, the emission rate of sulphur dioxide (SO_2) increased with the rate several kilo tons per day, also indicating fresh magma inside shallow levels of the volcano. Lava extrusion from the summit crater appeared more vigorous during August, and PHIVOLCS announced on August 7 the raise of the Alert Level 3 since July 14 to the Level 4, indicating the possibility of hazardous explosive eruptions. The Extended Danger Zone (EDZ), where people should be off-limits at all times, was defined as the southeast sector of the volcano within 8 km from the summit crater and the other areas within 7 km. About 40,000 people were evacuated from within and near EDZ until the decrease of the Alert Level on September 11. The Alert Level 2 was announced on 3 October with the decrease of the volcanic activity (PHIVOLCS-DOST 2006).

The Lignon Hill Observatory is very suited to observe the development of the lava flow from the summit crater, as well as the volcanic plume and pyroclastic cloud from rock fall breaking off the lava flow. Although the summit crater area was often cloud covered or obscured, many records were obtained by three cameras as shown in the following URL for the selected scenes: http://arist.edu.kagoshima-u.ac.jp/volc/mayon/mayon067-b/mayon067-b.htm .

In particular, the glows of the lava dome and lava flows in the nighttimes were observed not only by the near-infrared camera but also by the video camera using night-shot mode (the extended sensitivity to the near infrared light in addition to the visible light). In this mode, the cut-off filter of near-infrared light is removed (Kinoshita *et al*. 2004). The visible network camera and the video camera using daylight mode also occasionally recorded red glows of them in the dark, when the glows were particularly bright. In the summer 2006, the video camera was sometimes operated manually with night-shot mode at night, and recorded beautiful shows of lavas snaking its way down slope. It was also used for the recording from the air. Some of such scenes can be seen in the above URL as MPEG movies.

In August 2006, the Internet link between Legazpi and Japan was rather good, and real time monitoring and automatic image data download was often possible. The results were reported in domestic conferences (Kanagaki *et al*. 2006, Iino *et al*. 2006), and shown in the URL, "the Eruptions of Mayon Volcano in Summer 2006", which was originally at
http://ese.mech.kagoshima-u.ac.jp/Mayon/mayon2006/mayon2006.htm and has moved to http://arist.edu.kagoshima-u.ac.jp/volc/mayon/mayon2006/mayon2006.htm .

Fig.12 shows a sample set of network camera results in the daytime and after dark on August 4.

Fig.12 Network camera images on 4 Aug. 2006.
(a) Visible , (b) NIR in the morning, and (c) NIR after dark.

Conclusions and Discussions

The February 29, 2000 eruption was one of a few recent events where volcanic ash from Mayon volcano could be detected from space. While the lower level eruption clouds showed ash using the reverse absorption technique, the higher cloud did not.

Following the success of our initial installation of time-lapse video and still camera recording system at Mayon, we installed a network camera system with near-infrared and visible images, which is now connected with the Internet. It may contribute to real time monitoring of the eruption with the improvement of the Internet link, and to the investigation of volcanic clouds in the tropical atmosphere. Tentative results are displayed in the homepage "Volcanic Clouds at Mt. Mayon since June 2003", http://arist.edu.kagoshima-u.ac.jp/volc/mayon/mayontop.htm .

The tropical weather and the orographic effect of the high mountain are problematic for ground monitoring. Good views are generally limited to the morning and evening because of the diurnal development of convection. As for the satellite imagery, the chance to observe volcanic clouds at Mt. Mayon is even more limited. We could not yet detect them in the NOAA/AVHRR data received at Kagoshima University even during the Summer 2006 eruptions because of cloud cover.

Glows of the lava dome at the summit crater and lava flows were detected by the near-infrared camera and the video camera with the night-shot mode in the summer 2006 eruptions. Visible cameras were also able to detect red glows when they are particularly bright. Selected results are displayed in the URLs indicated in the previous section. If we had enough budgets to introduce a thermal camera, the coverage could also extend to the detection of moderately hot anomalies during the nighttimes.

In order to study the detailed structure of volcanic clouds, coincidental observations from different viewpoints are very helpful. However, the observatory on Lignon Hill is the only staffed one around the volcano. This paper is intended to understand basic features of them from single point observations.

On 30 November 2006, Super-typhoon Reming (Durian) brought extremely heavy rain around Mayon volcano, and generated destructive lahars and river floods, resulting in 1200 casualties. The Lignon Hill Observatory was also heavily damaged, and our camera system had to suffer long term suspension. Further continuation of the camera observation is important for the understanding of the volcanic activities and its disaster mitigation.

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