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Satellite, Air and Ground Observations of Volcanic Clouds over Islands of the Southwest Pacific

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Abstract

Volcanic ash is dangerous to aircraft. In response to this, a warning system has been created: the International Airways Volcano Watch. Many of the world's active volcanoes are in relatively under-resourced regions of the southwest Pacific and eastern Indian Ocean. We show here examples of recent eruptions in the southwest Pacific and Indonesia, including major eruptions at Rabaul (New Britain, Papua New Guinea), Merapi (Java, Indonesia), and Ruang (Sangihe Islands, Indonesia). We examine the effectiveness of satellite, air, and ground observations. There is a great variation in reported eruption heights between different observations, and we explore some of the reasons for this. There are particular difficulties with the under-reporting of eruption heights from the ground. More funding and development of ground-based observations will improve the overall effectiveness of the warning system.

1. Introduction

The majority of the islands of the western Pacific are part of the 'Ring of Fire', the zones of volcanic and seismic activity near the boundaries of the Pacific and surrounding tectonic plates. The existence, topography and fertility of the islands are substantially influenced by past volcanic activity, and areas with presently active volcanoes are subject to the devastation of large eruptions.

Since the encounter of several commercial passenger aircraft with the eruptions of Galunggung in Indonesia in 1982 (JOHNSON and CASADEVALL, 1994), world awareness of the threat of volcanic ash to aviation has grown. In the most well known of these incidents, a Boeing 747 lost power from all four engines when volcanic ash melted inside them, recovering just in time to avoid ditching in the Indian Ocean. Many incidents, some as serious as this, have since occurred, and in fact it is widely suspected that the number of encounters around the world is greatly under-reported (e.g. SMITHSONIAN INSTITUTION, 2002).

During the past 20 years, an international warning system for aviation has evolved, the International Airways Volcano Watch (ICAO, 2000, 2001). This system, which covers most of the world, consists of a network of meteorological agencies and aviation authorities that exchange information and issue warnings to aviation. The most critical pieces of information received are eruption notifications from volcanological agencies, pilot reports, and remote sensing observations.

The world's nine Volcanic Ash Advisory Centres make forecasts of the dispersion of the volcanic ash from the eruptions, and distribute these forecasts to national meteorological authorities and airlines for warning preparation and further distribution. The southwest Pacific and eastern Indian Ocean area is monitored by the Volcanic Ash Advisory Centres in Darwin (Australia), and Wellington (New Zealand). The Darwin Volcanic Ash Advisory Centre commenced operations in 1993 following a period of warning provision from the National Meteorological Centre in Melbourne (POTTS & WHITBY, 1994).

The complexities of ensuring an efficient warning network are significant and in many cases prohibit efficient operation. The key difficulties are:

- The intricacy of volcanic clouds as they evolve in the atmosphere makes them difficult to observe and describe. In the tropical western Pacific, cloud of non-volcanic origin, often referred to as 'meteorological cloud', frequently obscures volcanic clouds from all but the largest eruptions. Volcanic clouds can also contain or entrain moisture to become difficult to distinguish from meteorological clouds.
- National volcanological agencies are geared and funded towards saving lives on the ground in the proximity of the volcano. They are not necessarily able to provide the instant, accurate information about volcanic clouds required by international aviation.

- The operation of the International Airways Volcano Watch requires a high degree of coordination between organizations of diverse character. Communication and cooperation arrangements are still developing.

Through the process of creating the International Airways Volcano Watch, a formerly proximal hazard has been internationalised, and a new requirement for international communication identified. The International Airways Volcano Watch is thus a good example of the dependence of developed upon developing societies.

In this paper we wish to show examples of eruptions from volcanoes of the region, and to discuss the related issues of volcanic observation. The complexity of most eruptions makes our presentation necessarily brief; we are seeking to indicate points of interest and give an indication of the range of eruptions observed, rather than a comprehensive description. In particular, we wish to illustrate the strengths and limitations of remote sensing observations, and show their relationship to ground observations.

We first introduce some of the methods of observation, and then show many examples of eruptions from the region. We then discuss some of the issues relating to detection of volcanic clouds in the region.

2. Methods of observation

SPARKS *et al* (1997) give a summary of the known characteristics of volcanic plumes. Many aspects of the volcanic eruptions can be deduced from the eruption clouds, but here we are most interested in the aspects of concern to aviation – the height and dispersion of the ash cloud. We consider three broad platforms for making observations; satellite, aircraft, and ground. The *real-time* information available from these platforms determines the aviation warning strategy and content, and therefore the diversion costs, damage, and potential safety hazard to aviation.

2-1. Satellite observations

Meteorological satellites are the primary tool for sensing volcanic clouds. OPPENHEIMER (1998) summarises the established methods of satellite remote sensing. In this region, the satellite platforms used (at time of writing) are the GMS ('Himawari') satellites operated by the Japan Meteorological Agency, and the NOAA series of polar orbiters.

In general, polar orbiting satellites have higher resolution and better discrimination of features than geostationary satellites, but geostationary satellites have a much higher observation frequency (generally every hour or half-hour, as opposed to twice a day for a polar orbiter). Geostationary satellites are therefore much better suited for observing ash cloud, supplemented by higher resolution data from polar orbiters when available.

Satellite observations can either use single sensor channels, such as visible or infared channels, or use a combination of channels to discriminate ash from meteorological cloud. The most common remote sensing technique for ash discrimination is widely known as the split-window method (PRATA, 1989a,b), and has been used successfully on many occasions, although it suffers to some extent from difficulties caused by the presence of water vapour in the atmosphere or water in the volcanic cloud (ROSE *et al*, 1995, SIMPSON *et al*, 2000, PRATA *et al*, 2001), and from false alarms (POTTS and EBERT, 1996).

The TOMS instrument is an alternative method of volcanic cloud detection with a long and successful record of detecting ash and sulphur dioxide from major eruptions. TOMS is somewhat limited by having only one pass per day and a relatively low resolution, but is often able to detect volcanic ash where no other instrument is able. An online archive of TOMS volcanic cloud images is at http://skye.gsfc.nasa.gov/archives.html

A comprehensive survey of eruptions visible on satellite imagery in the Western Pacific was undertaken by SAWADA (1987). Later studies in the region have focused on particular eruptions, such as the eruptions of Pinatubo in the Philippines (e.g. KOYAGUCHI and TOKUNO, 1993) and Ruapehu in New Zealand (e.g. PRATA and GRANT, 2001, POTTS and TOKUNO, 1998). Many volcanic clouds in the northwest Pacific are well documented (e.g. KINOSHITA, 1996), but little has been published about volcanic clouds in Indonesia or Papua New Guinea since the work of SAWADA (1987). TUPPER *et al*

(2003) show examples of eruptions from Raung, Ruang, and Rabaul in a short discussion of operational satellite methodology.

Satellite remote sensing is continuing to develop rapidly and is becoming more widely available (CARN and OPPENHEIMER, 2000). The recent introduction of the MODIS sensors on the NASA EOS satellites has provided enhanced opportunities for post-analysis of eruption events. However, MODIS data is not yet used in real-time by Volcanic Ash Advisory Centres.

Satellite times given in this study are approximate overpass times. All times are in UTC.

2-2. Aircraft Observations

Because of their viewing perspective, established aviation communication networks and the awareness of volcanic ash as a potential hazard, pilots are the first to report eruptions on many occasions.

Although on many occasions pilot observations have been shown to be skilful, night observations of volcanic clouds from the air are almost impossible, and there are many times (especially following a major eruption) where visibility is too poor to make a good observation. There have also been events where pilot reports are confusing or contradictory (eg SIMPSON *et al*, 2002). Pilot observations are examined further in our discussion.

It is the experience of the Darwin Volcanic Ash Advisory Centre that the receipt of pilot reports has largely depended on the strength of the relationship between the airline or aviation authority involved and the Volcanic Ash Advisory Centre.

2-3. Ground –based observations

Instruments used by volcanologists to measure volcanic activity include seismometers and infrasonic microphones. These instruments cannot observe volcanic clouds directly but provide evidence of eruption magnitudes. Volcanic clouds can be observed directly from the ground by eyewitnesses, by weather radar, by lidar, and by using remote cameras.

Table 1 summarises the different primary operational methods of observation of volcanic clouds, and the effect on each of various factors.

	Observation	*Strengths*	*Weaknesses*
Satellite	Visible Imagery	Detects albedo differences, usually high resolution	Meteorological cloud or poor visibility will obscure volcanic cloud. Daytime only. Ash often difficult to see if very low albedo
	Infrared imagery	Temperature sensitive, unaffected by night	Meteorological cloud or poor visibility will obscure volcanic cloud, won't see albedo differences, temperature can be misleading
	Split-window infrared	Discriminates ash from cloud	Meteorological cloud or poor visibility will obscure volcanic cloud, false alarms from desert areas or stratospheric cloud, water vapour mixed with ash will 'hide' ash.
Radar	Ground Based Weather Radar	Can measure height and position of larger particles in ash cloud.	Expensive ground stations and limited range. May not detect smaller particles. Obscured by heavy rain. Requires local infrastructure, communications and must be well staffed.
Camera	Web/video camera	Remote access to direct observations	Meteorological cloud or poor visibility will obscure volcanic cloud. Requires locally developed infrastructure and reliable communications, prone to vandalism or theft. Daytime only
	Thermal infrared	Heat / night-time measurement	Meteorological cloud or poor visibility will obscure volcanic cloud. Expensive, requires locally developed infrastructure and reliable communications, prone to vandalism or theft.
Aircraft	Pilot reports	Airborne perspective, great viewing distance	Meteorological cloud or poor visibility will obscure volcanic cloud. Requires some local infrastructure and reliable communications. Daytime only. Pilot weather radar is not sensitive to volcanic ash.
Direct observation	Human observation	Low technology, power of local interpretation	Meteorological cloud or poor visibility will obscure volcanic cloud. Daytime only.

Table 1. Strengths and weaknesses of operational methods of volcanic cloud observation

It is evident from Table 1 there is no perfect operational method of observing a volcanic cloud. In particular, overlying cloud, rain or haze prohibit any direct observation of volcanic clouds. Since these are almost constants in the western tropical Pacific and over Indonesia, it follows that many eruptions are not well observed, and if the volcano is not instrumented, may not be detected at all. This is somewhat magnified by the poor weather and visibility that usually accompanies volcanic eruptions.

It also follows that, since eruptions that have occurred in good visibility are more readily studied, the scientific record of observed volcanic clouds is to some extent biased towards eruptions that have occurred during the day in sunny, dry conditions.

3. Selected Eruptions

The eruptions shown here are a selection of the known eruptions in the region since the commencement of operations of the Darwin Volcanic Ash Advisory Centre in 1993. Fig. 1 shows the volcanoes discussed in this paper, and Table 2 gives relevant background information.

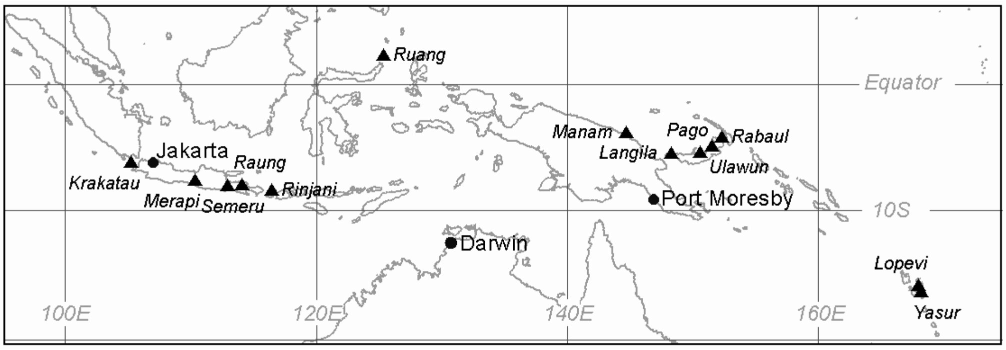


Figure 1– Locations of volcanoes discussed in this paper.

Volcano	*Number*	*Country*	*Elevation*	*Period shown in imagery*
Rabaul	0502-14	Papua New Guinea	688 m	18-21 September 1994
Ulawun	0502-12	Papua New Guinea	2334 m	29 April 2001
Manam	0501-02	Papua New Guinea	1807 m	8 February 1997, 5 October 1998, 20-21 May, 2002
Pago	0502-08	Papua New Guinea	742 m	5,7 August 2002
Yasur	0507-10	Vanuatu	361 m	25 January 2002
Lopevi	0507-05	Vanuatu	1413 m	8 June 2001
Langila	0502-01	Papua New Guinea	1330 m	12 February 1997
Semeru	0603-30	Indonesia	3676 m	18 July 2000
Krakatau	0602-00	Indonesia	813 m	27 June 1999
Raung	0603-34	Indonesia	3332 m	6 June 2002
Ruang	0607-01	Indonesia	725 m	25 September 2002
Merapi	0603-25	Indonesia	2947 m	22 November 1994
Rinjani	0604-03	Indonesia	3726	2,5 July 1994, 5 September 1994

Table 2. Eruptions shown in this paper. Volcano details are taken from the Smithsonian Institution's Global Volcanism Program, http://rathbun.si.edu/gvp

The climate of Indonesia and Papua New Guinea is maritime tropical and is warm throughout the year. Broadly speaking, the wettest months are October to April, and May to September is relatively dry, although in many locations rain is possible through the year. Atmospheric circulations and ocean currents ensure very warm seas and heavy shower and thunderstorm activity in the region, so cloud is particularly widespread and satellite observations are often difficult.

Two eruptions from Vanuatu are mentioned briefly in this paper. Vanuatu comes under the influence of drier south-easterly winds during the winter (June – August) and can be cooler, but is still often affected by cloud. In the International Airways Volcano Watch, Vanuatu is in the area of responsibility of the Wellington Volcanic Ash Advisory Centre. All other eruptions shown are in the area of responsibility of the Darwin Volcanic Ash Advisory Centre.

The volcanoes of these islands are generally 1000-3000 metres above sea-level. Moist flow will generally cause cloud on the windward side and often covering the mountain, making visual observations problematic. On some occasions, cloud near the mountain base will obscure the volcano from the ground but leave it observable by air or satellite.

3-1. Rabaul, September 1994

The devastating Rabaul eruption is summarised from a ground perspective in BLONG and MCKEE (1995), and also in the Bulletin of the Smithsonian Institution Global Volcanism Program (SMITHSONIAN INSTITUTION, 1994). ROSE *et al* (1995) used reduced (4 km) resolution AVHRR data to discuss ice in the cloud. The 1 km resolution data received at the Darwin Volcanic Ash Advisory Centre shows many interesting features of the cloud, and the hourly GMS-4 data also aids our understanding of this eruption. Some aspects of the eruption are highlighted in Figs. 2, 3 and 4.

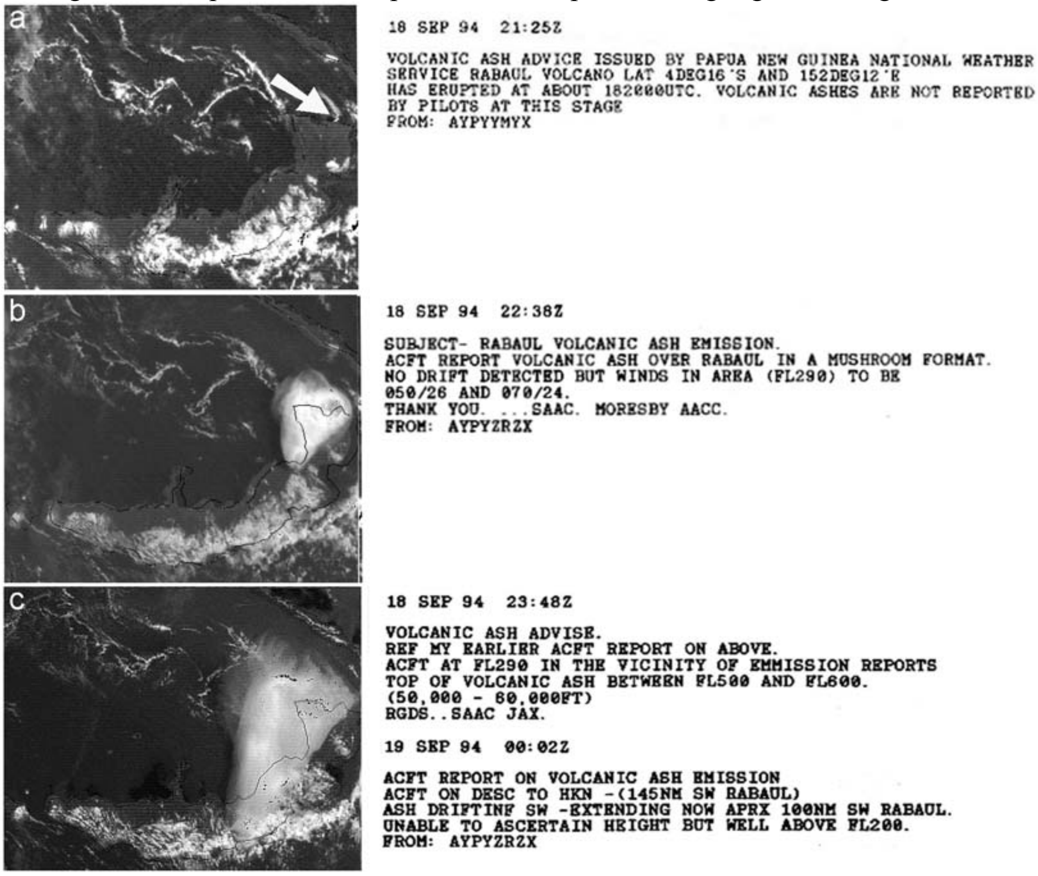


Figure 2 a – c) GMS-4 visible images during the beginning of the Rabaul eruption, showing the first, low level plume, then the explosive eruption, at 2145, 2245 and 2345 UTC on 18 September 1994. Figure 2 d –g) warnings and reports received at Darwin Volcanic Ash Advisory Centre during the same period.

For our purposes, the seasonal and diurnal timing of this eruption was fortunate. The eruption occurred in the dry season shortly after dawn, when visibility is usually the best. At that time, local air traffic in the Papua New Guinea region is relatively heavy. The pilots of the region are well educated about volcanic activity and are usually prompt to report eruptions. The proximity and effectiveness of the Rabaul Volcano Observatory ensured a high awareness of the situation. Thus, the eruption was well observed by satellite and from the air. It was even seen by a crew of NASA's Space Shuttle, who took some spectacular photographs of the plume on the first afternoon of the eruption.

The three GMS-4 visible images shown in Fig. 2, and the messages received in Darwin from Port Morseby show how well the eruption beginning was observed. The initial, low level plume from the Tavurvur vent can be seen on the first image extending northwards from Rabaul. On the next image, the plinian eruption from the Vulcan vent is obscuring the region.

This plume is composed of two parts, the top part directly above the volcano that punched through the tropopause into the stratosphere and is spreading radially, and a more extensive tropospheric region advecting south-westwards with the mid-tropospheric winds.

The warnings received during the first few hours of the eruption are shown as received at Darwin Volcanic Ash Advisory Centre, with the time shown the time of receipt in UTC. The fast reactions of the aviation community are evident.

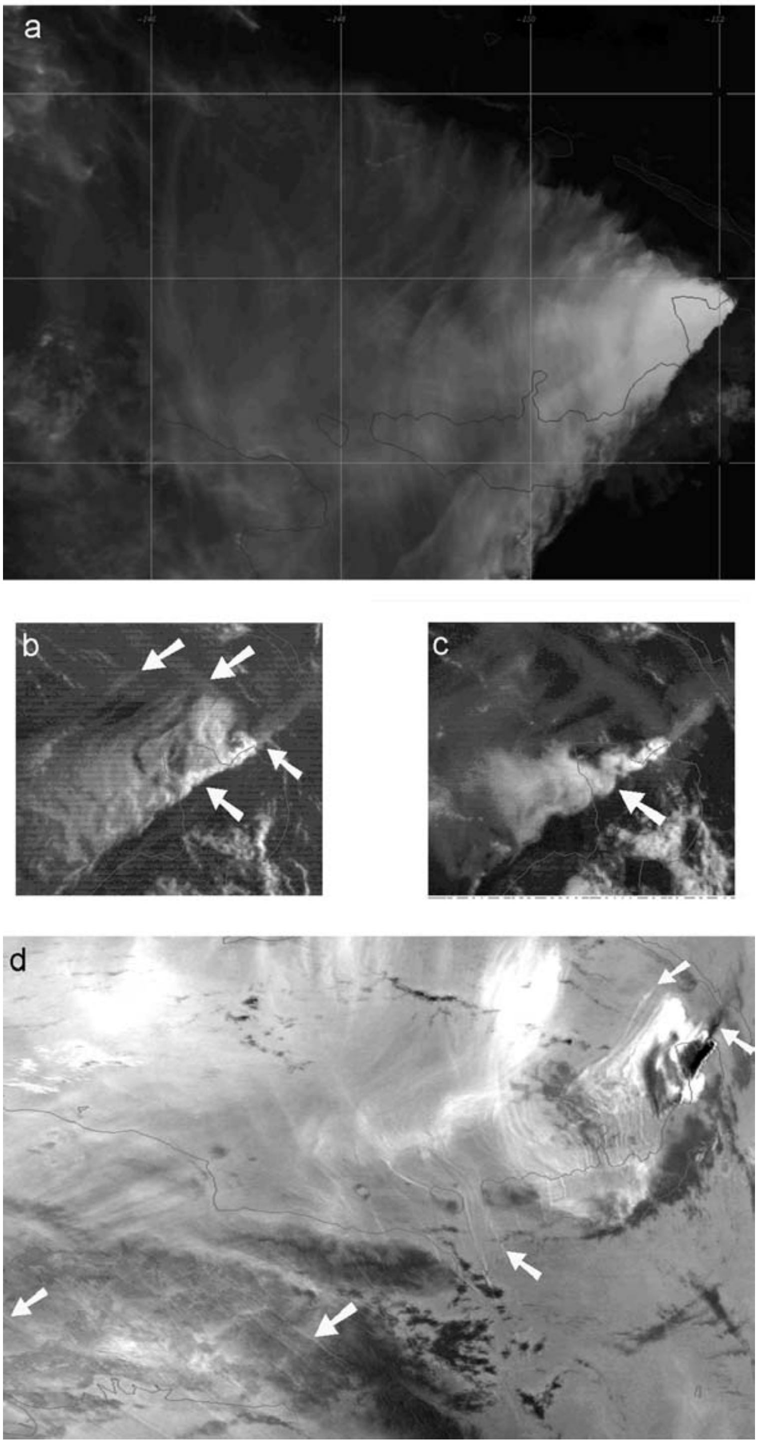


Figure 3 a) NOAA-12 AVHRR image, 19 September 0904 UTC, 1 km, channel 5. b, c) GMS-4 visible images, 19 September 1994 at 2045 and 2240 UTC d) Contrast stretched 'split-window' image, NOAA-12 AVHRR, 19 September 2146 UTC.

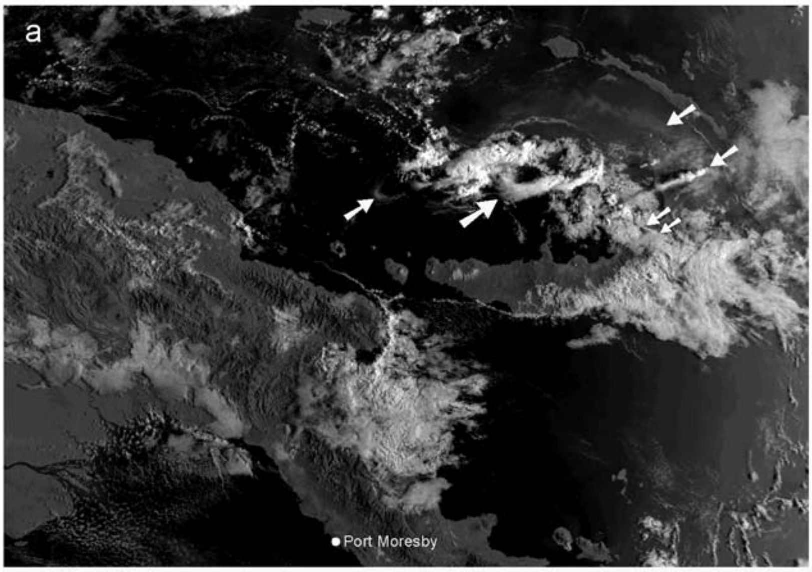
It must be remembered that in crises many mistakes are usually made. One problem arose from the second message shown. The warning at 2236 UTC signals a major eruption with the phrase 'Mushroom Format' used; however the height given is not the height of the eruption but of the aircraft at the time of the report. This resulted in some confusion, but was clarified over an hour later at 2348 UTC when the eruption was described as being at 50,000 to 60,000 feet (15 - 18 km). The 2245 UTC image showing the explosive eruption would have been received at Darwin at 2255 UTC, and available for inspection by meteorologists at about 2305 UTC.

Fig. 3 a) shows the evening NOAA-12 image of the plume. At this stage the cloud extended over most of Papua New Guinea and was moving toward the Coral Sea. The plume contained a great deal of moisture from sea-water entering the eruption cloud, as discussed by ROSE *et al* (1995). The changes in opacity of the plume are clear as it fans outwards at different levels in the atmosphere; as it approaches mainland Papua New Guinea it is relatively transparent.

Fig. 3 b) and c) are magnified GMS-4 visible images covering northeastern New Britain the next morning, as the eruption continued. The first image shows many wave features (arrowed). The second is also interesting as it shows the plume appearing to snake from side to side in a pattern resembling a Karman vortex trail. On both images, the low level plume continuing to the northeast can be seen. Two cones of the volcano at Rabaul were in eruption; while the majority of this probably derives from the lower level eruption from the Tavurvur cone, ash shearing from the higher eruption column from the Vulcan cone would certainly be mixed in.

The NOAA image shown in 3 d) was taken at approximately the same time. The wave structure (arrowed) is very clear on this split-window image, and can be seen to extend to the south of the Papua New Guinea mainland. Although it is possible that these are 'lee waves' generated by a stable flow of the upper atmosphere over the eruption column, they could be also be generated by an oscillating column in the manner seen with deep cumulus convection (LANE *et al* 2001) and occasionally eruptions, such as Pinatubo (HOLASEK *et al*, 1996).

Another feature of the same image, and other high-resolution split-window images of the eruption, is that the plume to the north shows as being ash-rich (arrowed, dark in this image) in contrast to the high level plume that ROSE *et al* (1995) discussed. The cloud immediately to the southwest of the volcano also shows dark not because of its high ash content, but because of its high opacity and cold cloud tops (PRATA *et al*, 2001)). Possibly the Tavurvur plume had less water in it, or the glaciation of the high level plume obscures the ash far more than the non-glaciated low level plume.



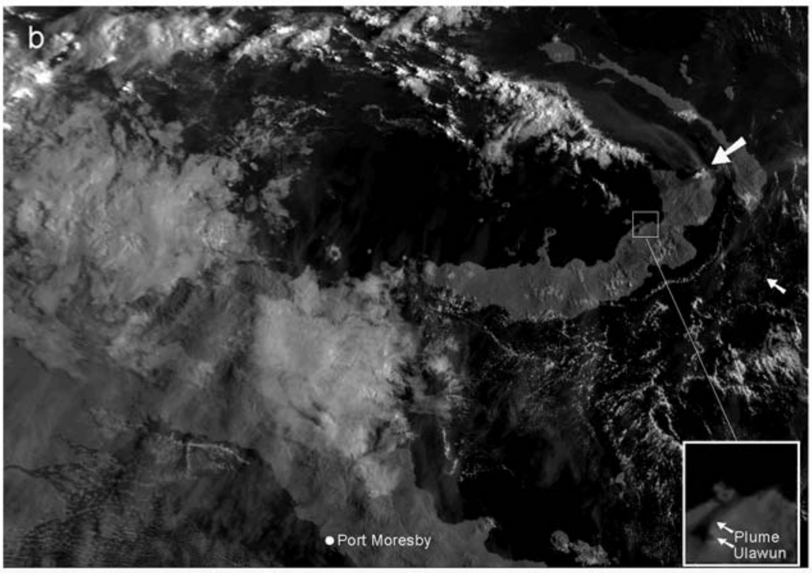


Figure 4 a) NOAA-12 AVHRR, band 2, 20 September 2126 UTC, b) NOAA-12 AVHRR, band 2 21 September 2105 UTC

The eruptions were clearly subsiding by the next morning (Fig. 4 a), two days after the main eruption. The emissions produced clouds reflecting discrete pulses (arrowed), but the clouds were still high level and clearly glaciated, with a feathered shape to the eruption clouds.

By the following day (Fig. 4 b), the Rabaul plume had taken on a continuous, diffuse appearance suggesting constant emissions of water vapour and presumably other gases. Of interest in this image is a small but distinct northeast plume from the active volcano, Ulawun, to the southwest of Rabaul (arrowed, and inset box). The shadow of Ulawun itself is far more clearly defined than that of the plume. In fact, reinspection of Fig. 4 a) from the previous day also shows what appears to be a plume from Ulawun (arrowed), extending to the southeast. This reflects the fact that, during relatively cloudy periods such as that shown in Fig. 4 a), detection of small volcanic plumes can depend largely on prior knowledge of volcanic activity.

3-2. Ulawun

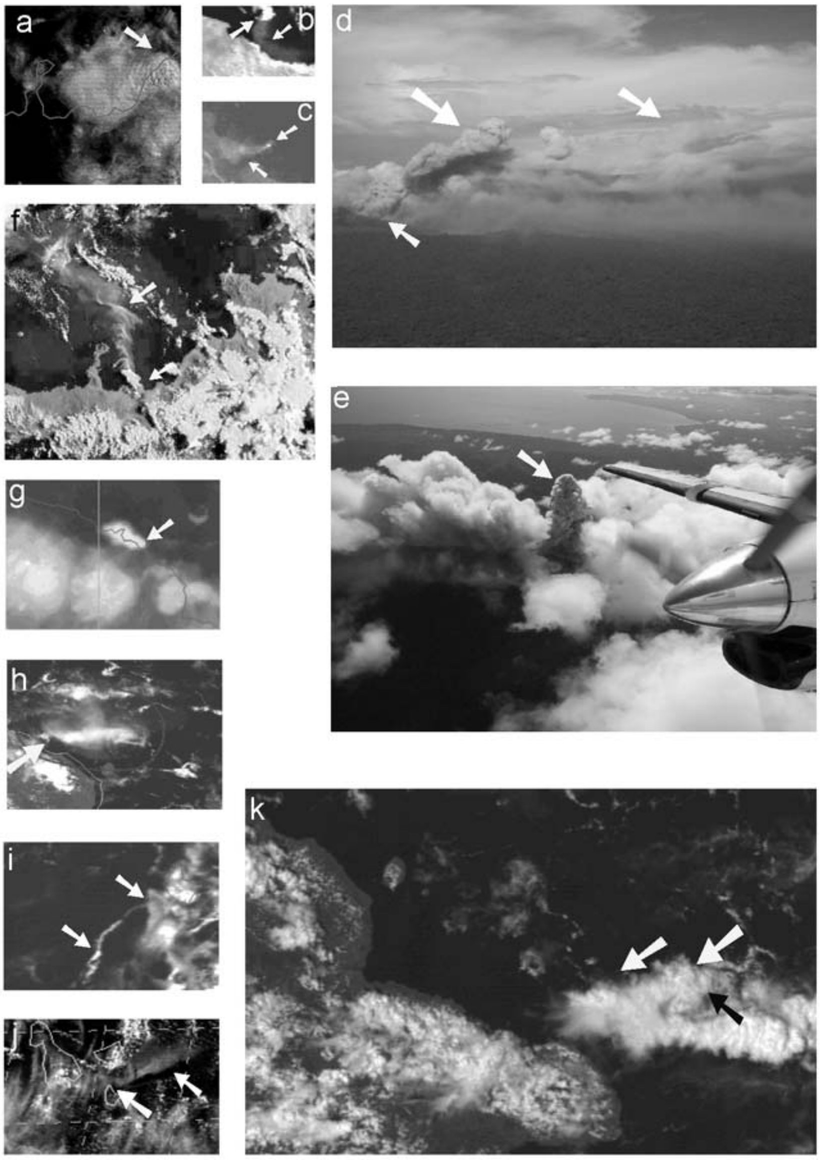


Figure 5 a) High level eruption of Ulawun, 29 April 2001, 2145 UTC. GMS-5 visible image. b,c) Low level plumes from Manam, 21 May, 2124 UTC, and 20 May 2002, 0645 UTC. NOAA & GMS-5 visible images. d,e) Aerial photos of Pago in eruption, 5 August 2002, at approximately 00 UTC These photographs were taken by Capt. Phil Marshall (flying777@bigfoot.com) and are used with his kind permission. f) Plume from Pago, 7 August 2002. Multi-band NOAA image. g) Eruption from Manam, 8 February 1997. GMS-5 infrared image 1230 UTC. h) Eruption from Manam, 5 October 1998. GMS-5 visible image, 0230 UTC. i) Thin plume from Yasur, 25 January 2002. GMS-5 visible image, 0250 UTC. j) Eruption from Lopevi, 8 June 2001. GMS-5 visible image, 0550 UTC. k) Suspected plume from Langila, 0545 UTC, 12 February 1997.

Fig. 5 a) shows a much higher level eruption from Ulawun in 2001, when widespread cloud made satellite detection difficult. This eruption also appeared to be water rich, either from water in the eruption cloud or entrainment of water into the eruption column, and was impossible to detect using the 'split-window' technique and available AVHRR and GMS-5 data. The distinctive 'ripples' in the eruption cloud are likely to be gravity waves caused by the eruption column, as in the Rabaul case. The wavelength of these waves is about 5 km, and is only identifiable for a few hours on the 1 km resolution imagery.

3-3. Manam

Eruptions from Manam are shown in Fig. 5 b, c, g, and h). The first two images show an eruption with a maximum height of about 8 km in May 2002. This eruption occurred in good visibility and was well observed from the air, satellite and the ground, although no monitoring instruments were installed at that stage. As for the Rabaul 1994 eruption, the eruption was reported early in the morning; the first air report was made at about 0530 local time.

The higher level eruptions of Fig. 5 g) and h) highlight some problems of volcanic cloud observation. The 8 February 1997 eruption of Manam (Fig. 5 g) occurred at night during a period of intense convective activity, and during a time when the Langila and Rabaul volcanoes of New Britain were also erupting. For this eruption, ground based observers reported dark, ash laden clouds to 7 km, blown to the south (Rabaul Volcano Observatory, eruption bulletin). However brightness temperature analysis of the satellite imagery again shows that this eruption reached at least 15 km. The eruption was blown to the west at levels close to the tropopause. Because it happened at night, 7 km could be regarded as being a reasonable observation from the ground even though it is less than half the actual height. As it occurred during a very busy period and there were no real-time reports transmitted from Papua New Guinea, the eruption was also missed in real-time by meteorologists in Darwin and no Volcanic Ash Advisories were issued for the event.

The 1998 eruption (Fig. 5 h) was reported by ground observers as attaining a height of 5-6 kilometres above sea-level, but analysis of GMS brightness temperatures showed that it formed a high level cloud (15 – 16 km) and then quickly dissipated. The TOMS satellite detected SO_2 from the eruption, but no ash was detected with TOMS or the split-window technique. The high eruption height may be in part due to the typically moist and unstable atmosphere experienced in Papua New Guinea for most of the year.

3-4. Pago

The eruption of Pago in August 2002 produced some rare aerial photographs (Fig. 5 d,e), taken by Capt. Phil Marshall who is a pilot in the region. The cloud reached an altitude of approximately 2 km and extended approximately 80 km to the north over the Talasea Peninsula.

A multi-band AVHRR image of a Pago plume is shown in Fig. 5 f). The plume stretches well to the north. The lack of convective development for most of the length of the plume suggests a low energy plume close to the ground, with a more strongly convective cloud near the volcano suggesting a stronger eruption. The plume structure is interesting with wave-like features apparent. Analysis of this eruption is continuing.

3-5. Langila

Fig. 5 k) shows a suspected plume from Langila, Papua New Guinea, during February 1997. As for the concurrent Manam eruption (Fig. 5 h), this was a very active time for weather and satellite observation was difficult. Good observations for this event came from pilots, who reported the eruption to 8 km, and ground based volcanological observations, who reported the eruption to 10 km. However, that night an aircraft encountered a volcanic ash cloud south of Papua New Guinea at an altitude of 11 km, so the ash extended to at least that level. The aircraft crew smelt fumes and experienced radio interference, which indicates both ash and volcanic gas in the cloud. There is a slight possibility that the source of the eruption cloud could have been Manam, but dispersion modelling strongly suggests that the source was Langila. Heavy convective activity, interruptions to the GMS-5 observation programme, and the saturated atmosphere made the suspected plume shown here impossible to track across Papua New Guinea.

3-6. Yasur

Vanuatu (which is within the area of responsibility of the Wellington Volcanic Ash Advisory Centre) has several active volcanoes. Fig. 5 i) shows a thin and low level plume apparently coming from Yasur. However, the feature was only evident for a short time.

3-7. Lopevi

A more substantial eruption is shown in 5 j), from Lopevi in June 2001. This eruption showed particularly well on GMS-5 split window imagery. The image shown is actually a visible image where the grey colour of the middle level ash cloud is evident.

3-8. Semeru

Semeru, Indonesia (Fig. 6 a) has been in eruption since 1967. Activity is frequently reported from aircraft and from the ground, but the small eruption cloud size and frequency of meteorological cloud makes satellite observations difficult. This is one of the very few cases where the eruption clouds have been seen in meteorological satellite imagery, although plumes can sometimes be detected on high resolution SPOT imagery. This NOAA-AVHRR image has captured two discrete ‘puffs’ from

Semeru – clouds of ash drifting down to the southwest that were close to invisible on casual inspection, but show well using the split-window technique. For Semeru, as with many other volcanoes, there are generally only a few hours each day where clear observation of the summit and surrounding areas is possible by satellite.

One persistent aspect of Semeru's activity has been that, while ground based observations generally place the level of activity as a few hundred metres above the summit (3676 m), reports from high flying aircraft often report the plume much higher. We will discuss this issue later.

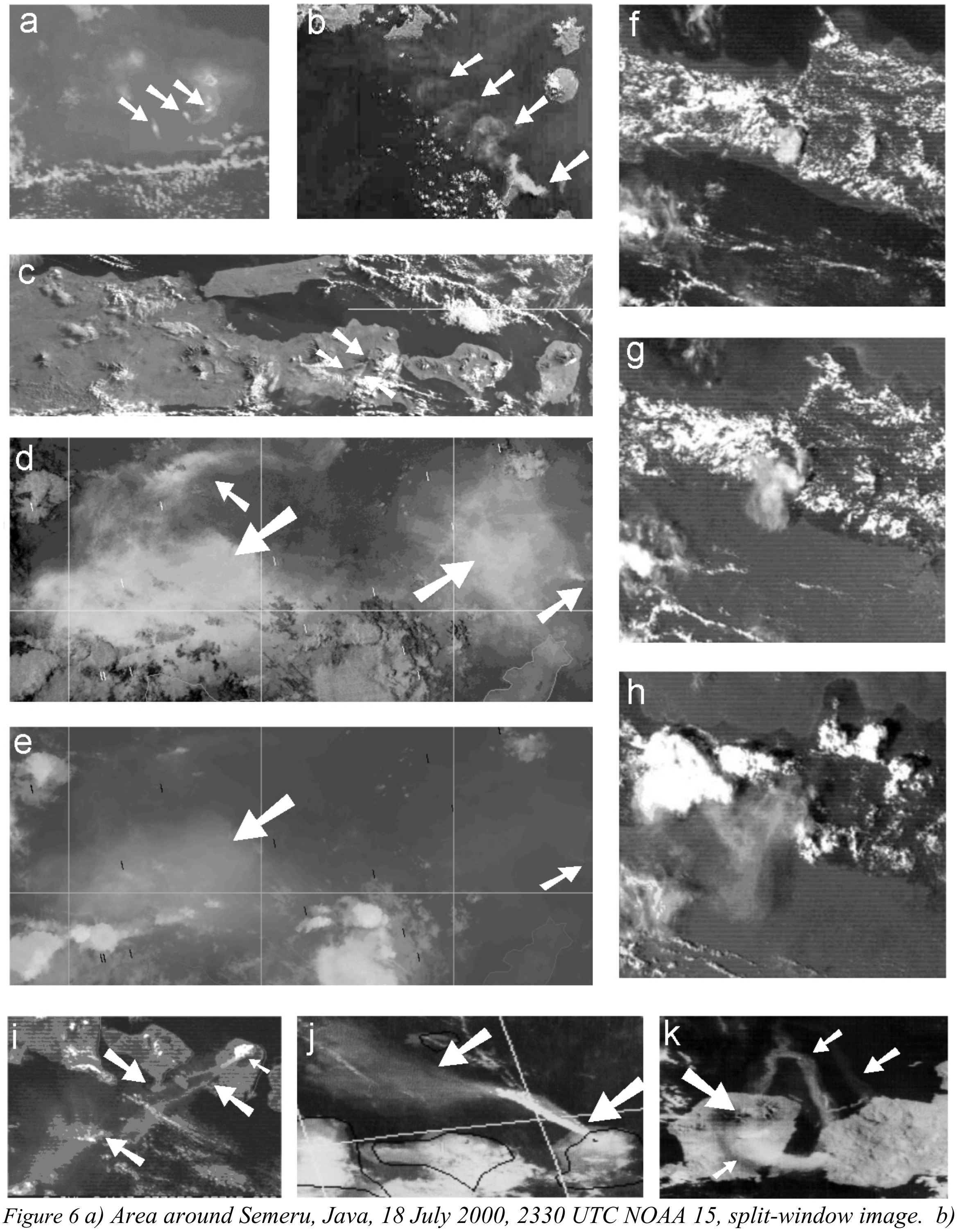


Figure 6 a) Area around Semeru, Java, 18 July 2000, 2330 UTC NOAA 15, split-window image. b) Plume drifting northwest from Anak Krakatau towards southeast Sumatra, seen on SPOT imagery on 27 June 1999, at 0325 UTC Image copyright CNES 1999, made available on CRISP – SPOT

'Quicklook' facility. c) Early morning NOAA-15 image over eastern Java, Bali, and Lombok, 6 June 2002, 2334 UTC, channel 2. d,e) The eruption of Ruang on 25 September 2002, seen on Terra-MODIS imagery at 1415 UTC, in split-window imagery (d) and channel 31 infrared imagery (e) f,g,h) Merapi, Java, erupting on 22 November 1994. GMS-4 visible images, at 0440 UTC, 0545 UTC, and 0745 UTC, respectively. i,j,k) Eruptions from Rinjani, Lombok, during 1994. GMS-4 visible, 2 July 1994 0345 UTC, NOAA enhanced split-window 5 July 1994, and NOAA channel 2, 5 September 1994 at 2330 UTC

3-9. Krakatau

Like Semeru, activity from Krakatau is usually very difficult to discern on satellite imagery. However, the slight height of the active cone, Anak Krakatau, makes small ash clouds much less dangerous for aviation than from tall volcanoes such as Semeru and Raung. Fig. 6 b) shows a plume drifting northwest from Anak Krakatau towards southeast Sumatra in June 1999. The even 'clumping' of clouds in the plume probably reflects wave motions in the atmosphere rather than variations in the eruption intensity.

Activity from Krakatau is reported sporadically. In August 2000, plumes were reported by aircraft to about 2000 metres height, but the plumes could not be seen on meteorological satellite imagery. The volcano is somewhat remote and not always easy to monitor. For example, for most of 2002, the Indonesian Directorate of Volcanology and Geological Hazard Mitigation (often known as 'VSI' as a contraction of the previous name of the organisation) was reporting that the seismograph there had not been working since 13 September 2001 (e.g. VSI 'Hot News' 663, 2002).

3-10. Raung

Although most of the activity from Raung has been relatively minor, the volcano causes problems because of its height and proximity to the busy air-routes connecting Bali with Java and surrounding countries. Aircraft on descent into Denpasar Airport from the west or northwest pass close to Raung and run the risk of encountering ash or gases from the volcano at an altitude of 3000-4000 metres. Noxious odors were reported to Darwin Volcanic Ash Advisory Centre by an international flight passing close to Raung on 14 July 2001 at an altitude of approximately 2.5 km; on that occasion there was nothing identifiable from the volcano on GMS, AVHRR, or TOMS satellite imagery.

Fig. 6 c) shows an early morning NOAA-15 pass over eastern Java, Bali, and Lombok. In these conditions of exceptional 'dry season' visibility, many features can be distinguished, including most of the prominent volcanoes of the region. A weak bifurcated plume can be seen (arrowed) from Raung. TUPPER *et al* (2003) show a larger eruption from Raung on 25 August 2002.

3-11. Ruang

Ruang, in the Sangihe Islands north of Sulawesi, had a large eruption on 25 September 2002 (Fig. 6 d,e). The volcano itself (arrowed) was still visible as a hot object in infrared channels. This is quite common, for example the lava flowing from the Manam eruption in May 2002 was clearly visible in NOAA channels 3, 4 & 5. OPPENHEIMER (1998) describes the conditions necessary for hot areas to be visible for various infrared sensors.

In these Terra-MODIS images, two areas of volcanic cloud are visible, deriving from the same eruption. The western part, visible as a bright, diffuse area in both images, is thought to have been middle level atmospheric and have a high ash content, while the eastern portion nearer the volcano is thought to have been drifting in very light, high altitude winds (15 – 20 km), and, from multispectral MODIS analysis, to have a much higher gas content. TUPPER *et al* (2003) shows the dispersion of these clouds in a little more detail.

This eruption was reported in real-time to an altitude of 5 km, but was in fact at least 15 km high, and possibly 20 km or higher on satellite evidence. Almost certainly, the height of the eruption was under-reported from the ground because the one volcanological observatory for Ruang is within three kilometres of the volcano, and an observer stationed there cannot estimate the height of a high ash cloud with any degree of accuracy (Dali Ahmad, Indonesian Directorate of Volcanology and Geological Hazard Mitigation, personal communication).

3-12. Merapi

Another major eruption during the last decade was at Merapi, Java, on 22 November 1994 (Fig. 6 f,g,h). This visible imagery shows the ash cloud has a darker colour than the surrounding meteorological clouds. However, the extent of deep convective development later in the afternoon over Java (h) suggests that, had the eruption occurred a few hours later, it would have been much harder to detect using satellite imagery alone.

This eruption and the associated casualties are described by the SMITHONIAN INSTITUTION (1994). No estimate of the cloud height was reported by VSI. Air reports put the height of the cloud as being about 10 km. Brightness temperature analysis on GMS-4 infrared imagery gives a minimum temperature on the dense eruption cloud of approximately –67 °C, consistent with a cloud height of approximately 14 km.

3-13. Rinjani

1994 was a very active year in the southwest Pacific and Indonesian area for volcanic eruptions. Figs. 5 i,j, and k) show eruptions from Rinjani, Lombok, Indonesia during 1994. Fig. 5 i) shows a low level bifurcated plume, with the northern branch passing over or just south of Denpasar International Airport. Fig. 5 j) has a more substantial plume passing to the north of Bali and Java, with the heaviest concentrations of ash highlighted by the split-window algorithm in white. Fig. 5 k) has a complex plume structure resulting from multiple eruptions to different levels of the atmosphere.

The eruptions of Rinjani occurred during the driest time of the year in conditions of good visibility, and consequently were relatively easy to track with satellite. Like the activity from Raung, their proximity to Denpasar International Airport caused difficulties for international carriers, with many diversions and increased costs.

3-14. Eruptions not observed from satellite

Many eruptions are not observable from satellite due to overlying cloud or resolution difficulties. These tend to be the less significant ones (SAWADA, 1987), but occasionally noteworthy events are not seen from space. Fig. 7 shows an eruption from Merapi, Java, 10 February 2001. This eruption was estimated from the ground (at night) to an altitude of about 8 km above sea-level, and distributed 1 cm thickness of ash 5 km from Merapi, with the ash plume spreading 60 km away from the volcano. The time of the photo was not noted, but it appears to be close to dawn judging from the observatory lights (although extensive ash cloud may produce these conditions throughout the day), and well after the start of the eruption at 0330 local time. Nothing unusual was observed on meteorological satellite imagery due to overlying cloud.

February is a very cloudy month in the region. Since the eruption started at night, no aircraft observations would have been possible. This was a dangerous eruption for aircraft that could only be observed from the ground, at night, and in poor visibility conditions.

Figure 7 Eruption from Merapi, Java, 10 February 2001. Image taken at VTRC Babadan post observatory and provided courtesy Indonesian Directorate of Volcanology and Geological Hazard Mitigation

4. Discussion

4-1. Meteorological interactions

As noted earlier, we believe that the photographic and satellite record of eruptions is biased towards eruptions that have occurred in exceptional visibility conditions. Many of the most interesting and problematic volcanic clouds occur in hazy, cloudy or moist environments.

Often, volcanic activity can be masked by what we shall term 'semi-volcanic' clouds. Fig. 8 is a view of cloud over Sakurajima, Kagoshima, Japan, which as discussed later is a highly observed volcano. Here, we see the complexities of volcano / atmosphere interaction. The atmosphere had high humidity on this day and was convectively unstable. The volcano is emitting mainly steam, which rises convectively and begins to spread out at its level of neutral buoyancy. However, the entrainment of water vapour allows a deeper convective cloud to begin to develop. As for most volcanoes, the effect is enhanced by the topography of the volcano. It is not possible to completely distinguish between meteorological and volcanic cloud.

Figure 8 View of cloud over Sakurajima, Japan, from Kagoshima University, 12 August 2002, 7:50 UTC. Image taken by Kagoshima University's web camera

The subject of meteorological interactions in a moist atmosphere is complex and largely unexplored. On the theoretical side, SPARKS *et al* (1997), discuss convective enhancement of the volcanic eruption column through moist eruptive processes. GRAF *et al* (1999) reinforced this with more detailed modelling. For observational evidence, OSWALT *et al* (1996) describe 'volcanic thunderstorms' in the post-Pinatubo environment, when thunderstorm clouds could be triggered by small eruptions (in which case rain containing ash resulted) or even hot surfaces. In Papua New Guinea also, volcanic ash clouds from small eruptions have also been observed lifted higher than they should be by convective actions (I. ITIKARAI, Rabaul Volcano Observatory, personal communication). The implications of this in terms of the International Airways Volcano Watch are important for the southwest Pacific as the atmosphere is almost always conditionally unstable over much of the area, and therefore any eruption could conceivably generate a cloud to above tropopause height. In order to quantify these effects, much more observational work is required.

4-2. Difficulties with height estimation

Estimation of the height of volcanic clouds is one of the most critical pieces of information for the International Airways Volcano Watch, because the winds at the levels that the cloud attains determine the subsequent drift direction of the ash. SAWADA (2002) shows a comparison of eruption heights estimated from the ground and with satellite data, showing considerable variation. Table 3 summarises the problematic eruption height observations mentioned here. On first glance some of the differences are extraordinary. The reasons for this deserve discussion and need to be widely understood.

Eruption	*Report type*	*Report*	*Likely height of cloud top*	*Comments*
Rabaul 1994	Pilot report relayed by Air Traffic Control Centre	Height of aircraft given (FL290) but not plume	20 km	Ambiguity in wording
Manam 1997	Ground report	7 km	15+ km	Night eruption
Manam 1998	Ground report	5-6 km	15+ km	
Langila 1997	Pilot reports	8 km	11+ km	Monsoonal
Ruang 2002	Ground report	5 km	18+ km	Observer at difficult viewing angle
Merapi 1994	Pilot report	10 km	14 km	

Table 3. Notable under-reporting of eruption heights, in order discussed in this paper.

In satellite remote sensing and when conducting direct observations, it can be difficult to estimate the height of an ash cloud. Satellite estimation techniques are summarized in OPPENHEIMER (1998). For operational work, estimation using brightness temperatures and wind correlations are the most common methodologies. Both are subject to substantial error in unfavourable conditions. Stereoscopy is not used operationally because of the rareness of available images, and shadow height estimation, which requires corrections for satellite angle, curvature of the earth, and position of the sun, is used only for post-analysis. In many cases, particularly for a diffuse ash cloud, it is extremely difficult to obtain more than an approximate idea of the height the cloud has reached.

Height estimation from the ground can also be difficult. For small eruptions in good visibility, the height can be estimated using basic trigonometry, with the assumption that the eruption column is directly over the volcano or at a known distance. This technique is commonly used in the region.

However large eruptions will tend to tower over the observer and be difficult to estimate (D. AHMAD, Indonesian Directorate of Volcanology and Geological Hazard Mitigation, personal communication), and may have ash fall obscuring the cloud. Above a cloud height of about 5000 metres, ground-based height estimation can be difficult (Y. FUJIWARA, Japan Meteorological Agency, personal communication). The examples in Table 3 support this view.

Poor visibility can make even confirmation of an eruption difficult – for example in August 2001, Makian volcano in Halmahera, Indonesia, was reported to be erupting by the local observer, when in fact the red glow at the summit was caused to be a bushfire (D. AHMAD, Indonesian Directorate of Volcanology and Geological Hazard Mitigation, personal communication). This is an understandable mistake to make in conditions of poor visibility. There should be no reason, therefore, why we should expect any particular skill in volcanic cloud height estimation except in conditions of exceptional visibility.

However, even in perfect conditions, we should expect differences in observation methodology to result in different height estimates. For example, Indonesian observers consider the height of the ash column directly over the volcano (as they must for trigonometic measurement), and do not include associated meteorological cloud or any subsequent plume evolution (D. AHMAD, personal communication). A pilot looking at the same volcanic cloud will consider the very top of the cloud (G.RENNIE, R.CANTOR, QANTAS, personal communications), which may be obscured from the ground observer or be considered not part of the eruption column. This explains to a degree why pilot observations from aircraft at cruising level over Indonesia are invariably to a higher height than ground observations.

Pilot observations are also widely acknowledged to have variable skill. For example, D. INNES, (Air New Guinea, personal communication), writes:

"There is a pretty wide margin of error for pilot reports based on what we get from the crews. One crew will describe what they see as ash, while another might report it as only smoke, and a third may decline to report what they see as they don't consider it noteworthy...With a typical cruise level of between 24000 to 28000 feet (approx 7 – 8.5 km) on the routes passing active volcanoes, a really high emission is easy to gauge as far as height and spread is concerned, but for a lower level event that stays below about five to eight thousand feet (1.5 - 2.5 km), the view we get is almost two dimensional. For these ones, a report from commuter planes would probably be more accurate given their cruise level of around the ten thousand foot mark…"

"At altitude, I have to use landmarks and an idea of the height of the volcano to guess tops and bottoms, and as for spread and range, there is a blurring between what we see as volcanic emissions and general haze resulting from an inversion or even grass fires in the area. It's very much a case of what the pilot in question chooses to interpret…"

It can be seen then, there is no single operational method that will reliably estimate the height of ash clouds from each eruption. Therefore, no observation of cloud height should be assumed accurate without careful checking of the circumstances under which the observation is made, and comparison with other data.

For ground-based observations of substantial eruption clouds in the southwest Pacific, and bearing in mind the possibility of moist convective enhancement of the eruption cloud, we tentatively suggest the following guideline for operations and post-analysis:

Ground-based reports of eruption clouds above 5 km a.m.s.l. should be taken as being to tropopause height unless there is evidence to the contrary.

4-3. Eruption detection

The first priority of a volcanological agency during a volcanic crisis must be to the local population, especially in a situation of limited resources. Therefore, even when there is a smooth relationship between local authorities and the Volcanic Ash Advisory Centers in normal circumstances, events can dictate that eruption notifications are not made or are delayed during a volcanic crisis.

Meteorological satellite detection times are not sufficient for operational use, even though they can be the first method of detection in many cases. In the case of the relatively high frequency geostationary satellites, if an eruption occurs just before the satellite scans over the area, it may still be 20 minutes or more before the image will be examined by meteorologists. In the worst case, the delay may be hours. Because of the speed of aircraft movement, faster eruption detection is essential for an adequate warning service.

In addition, if meteorologists are not focusing on a particular area (because of lack of forewarning of eruption), the eruption may be missed entirely, and only discovered on satellite imagery when the ground report comes in. The detection rates reported by SAWADA (1987) are for satellite analysis in hindsight. Real time detection is even more difficult, and real-time detection rates can be very low. In many cases, especially for Papua New Guinea, which has an excellent reporting network of locally based pilots, pilot reports are the first report of a major eruption cloud. However pilot reports are not adequate either in poor visibility conditions.

Hence, for the International Airways Volcano Watch to work smoothly requires prompt notification of eruptions by volcanic agencies. However, the capacity of the volcanic agencies to undertake this must be considered in the context of the resources available to them.

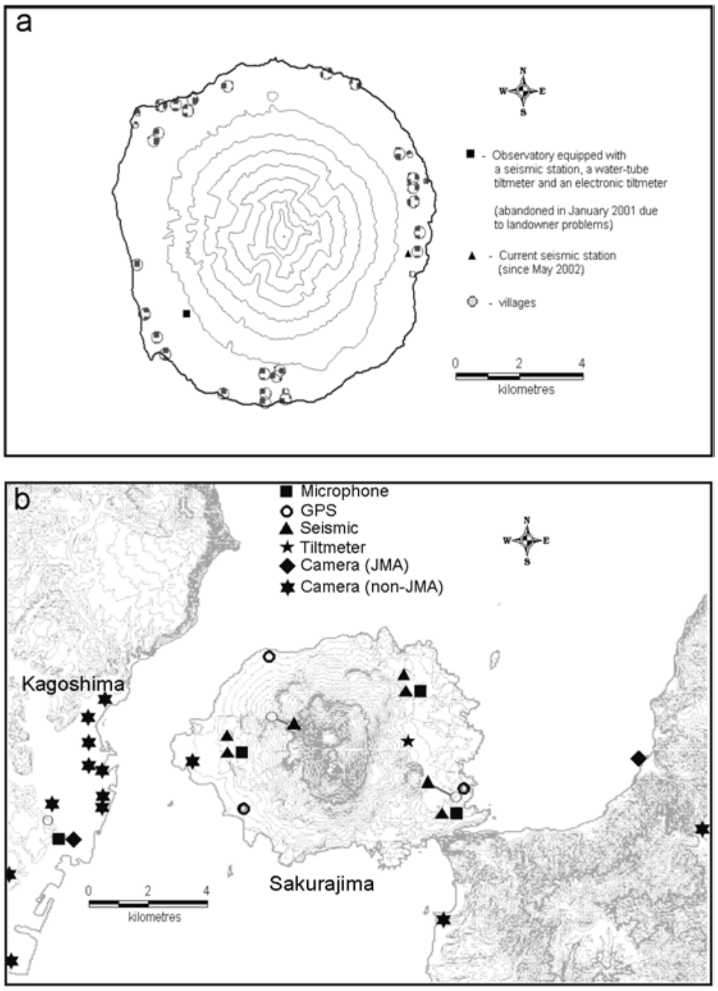


Figure 9 a) Monitoring resources at Manam Island, a populated island and one of world's most active volcanoes. Courtesy Rabaul Volcano Observatory .b) approximate locations of observation points around Minamidake, the active peak of Sakurajima, Kagoshima, Japan. Only public web-camera and official Japan Meteorological Agency locations are shown; Sakurajima Volcano Observatory and other stations are omitted for clarity. Base map and location information courtesy Japan Meteorological Agency.

4-4. Resource Issues

There are large variations in the resources available to volcanological agencies, which must impact on their ability to provide eruption notification. Communications costs and reliability, vandalism, theft, equipment failure, and even army occupation have all been known to hinder volcanic monitoring in the southwest Pacific.

Figs. 9 a) and 9 b) compare the monitoring resources available at Manam Island, Papua New Guinea, and Sakurajima, Japan. For clarity in Fig. 9 b), only the monitoring instruments of the Japan Meteorological Agency, and known public cameras, are shown. The extensive network of Sakurajima Volcano Observatory, ashfall measurement stations operated by the local government, and other various other observation points are omitted. The network at Sakurajima, with many public web-cameras, thermal cameras, many instrument locations, and so on, reflects a technologically developed society and high levels of government funding. At Manam there is no less expertise but a great difference in resources for volcanic monitoring. Communications from Manam are by radio only, with reliability varying according to the time of day (I. ITIKARAI, Rabaul Volcano Observatory, personal communication), and the status of the instruments is precarious:

"Following the eruption, a temporary seismograph was installed on the southeast side of the island. The installation of the seismograph will once again enable Rabaul Volcano Observatory to monitor the seismicity of the volcano and provide appropriate and reliable information to relevant agencies on the status of the volcano. Before the eruption this vital information was lacking because landowners of Manam Volcano Observatory shut down the Observatory on 16th January 2001 due to land compensation issues, making it very difficult for RVO to conduct any form of forecasting." (I. ITIKARAI, Rabaul Volcano Observatory, personal communication, 2002, following the May 2002 eruption)

The availability of seismograph information is critical for the International Airways Volcano Watch because it enables the prediction and notification of major eruptions independently of direct observations of a volcanic cloud. In geographical terms Manam Island is remote; however in aviation terms it is close to the main aviation routes between Japan and Australia.

The Rabaul Volcano Observatory is one of the world's pre-eminent volcano centres (SIMKIN and SIEBERT, 1994) which, like the Indonesian Directorate of Volcanology and Geological Hazard Mitigation, has a proven track record of saving lives on the ground. Yet it is difficult to suggest that the Rabaul Volcanological Observatory, with the difficulties it faces and the resources available to it, should provide the same level of observations to the International Airways Volcano Watch that are potentially available from a highly monitored volcano such as Sakurajima.

4-5. Political Issues

The problem of differing resources can be helped through aid projects. However, there are issues of sustainability and national sovereignty that immediately affect the way that this is implemented.

IAVCEI (1999) lay out the expected standards of conduct for visiting researchers to use at volcanic crises. Many of the issues raised can be extended to apply to participants in the International Airways Volcano Watch, for example:

- The need to respect cultural differences in scientific discussion and decision making.
- The need to interact with the primary authority or scientific team before making public statements about the volcano. In practical terms, the Meteorological Watch Offices, Volcanic Ash Advisory Centres, Airlines, and Aviation Authorities are extended members of the group observing the volcanoes and have specialist data to contribute to the understanding of what the volcano is doing during a crisis. However, the remoteness of these offices, the difficulty of communications, and the newness of these arrangements can often impede effective interaction during the volcanic crisis.
- Funding decisions from foreign countries for equipment to help in the watch for volcanic clouds should come at the invitation of the local authorities, which then should have full control of how they are used. Aid should be sustainable and appropriate.

As the International Airways Volcano Watch develops, these issues will continue to be important and will directly affect the quality of volcanic observations received.

4-6. Organisational issues.

The International Airways Volcano Watch is still a relatively new network and it is taking some time for the bureaucracies and commercial organisations in both developed and developing countries to adjust. For example, there are no historical interactions between the meteorological and geophysical agencies in most countries, although the functions do co-exist in the Japan Meteorological Agency.

There is also a great need for raised levels of awareness throughout the region. The 'Vulcan-Aus' committee (a committee of representatives from relevant institutions and companies) has made efforts in this direction in the southwest Pacific, particularly for Papua New Guinea and Indonesia.

The International Civil Aviation Organisation also educates and co-ordinates its member states, and provides some training materials. However there is much more work to do.

5. Summary and Conclusions

In this paper, we have shown some of the breadth of observations of volcanic clouds in the region, and discussed scientific and political issues that affect observations of volcanic clouds.
We conclude that:

1) Volcanic clouds can be well observed by satellite, from the air, and from the ground. However, all of these observations are subject to error or obscuration.
2) Ground based height reports for large eruptions are particularly subject to underestimation, and should be treated with great caution.
3) Errors arise from a variety of sources and cannot be immediately eradicated. Eruptions at night and in conditions of poor visibility are particularly difficult.
4) The overall amount and quality of volcanic cloud observations can be improved by making appropriate resources available to volcanological observatories. Better remote sensing techniques, and better training and organisation will also improve the operations of the International Airways Volcano Watch.

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