Volcanic cloud monitoring issues at the Darwin VAAC

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Abstract

We discuss recent eruptions from Ruang, Semeru and Rabaul, and some mysterious aircraft encounters over Micronesia, in the context of current Darwin VAAC operations. Ruang was generally monitored successfully, with some qualifications such as a high level, eastward moving SO_2 cloud that was only clear in post-analysis, and the complete lack of aviation 'SIGMETs'. Rabaul and Semeru are both long running, generally low level eruptions where little can be seen on satellite imagery. Three aircraft encounters occurred over Micronesia without the source of the volcanic cloud being identified. While International Airways Volcano Watch performance is steadily improving, there are still significant scientific and procedural concerns highlighted by the above cases.

1. Introduction

The Darwin Volcanic Ash Advisory Centre (VAAC) was established in 1993 within the Northern Territory Regional Office of the Commonwealth Bureau of Meteorology, Australia. This was part of the early development of the International Airways Volcano Watch (IAVW) following some near-catastrophic aircraft encounters in the region (Johnson and Casadevall, 1994) . Prior to the establishment of the Darwin VAAC, ash warning functions were performed by the National Meteorological and Oceanographic Centre in Melbourne, Australia, which now acts as the Darwin backup (Potts and Whitby, 1994). Meteorologists who perform the VAAC duties also work in the Regional Forecasting Centre providing forecasts and warnings for the Northern Territory, and in the Regional Specialised Meteorological Centre, which provides specialist meteorological analysis and numerical weather prediction over the tropical Western Pacific and eastern Indian Oceans. The VAAC is therefore strongly grounded in the meteorological environment that most of its eruptions occur in, although the involvement of 20-25 operational forecasters in VAAC operations creates a training burden.

The Darwin VAAC area of responsibility includes all of Indonesia and Papua New Guinea, and parts of the Philippines and Solomon Islands. Geophysical and meteorological agencies are generally separated and under-resourced through the region, and a significant part of VAAC resources are directed towards developing and maintaining diplomatic networks in the region, to increase the relatively poor information flow (Tupper and Kinoshita, 2003). Climatologically, the region has the warmest average sea-surface temperatures, highest atmospheric moisture and greatest high cloud cover in the world, so there are also considerable remote sensing challenges.

In this paper, we briefly describe the operational remote sensing techniques used in the region, present some significant recent eruptions, and discuss some approaches to current scientific problems affecting the IAVW.

2. Remote Sensing Methodology

The basis of Darwin VAAC operations has been the reverse absorption technique (Prata, 1989a, b), which has been successful for most significant eruptions in the region since 1993, the notable exceptions being Rabaul in 1994 (Rose *et al.*, 1995) and eruptions in New Britain in February 1997 (Tupper *et al.*, 2003b). GMS, NOAA/AVHRR, and recently GOES-9 data is generally used in VAAC operations, with the temporal resolution of geostationary satellites a particular asset for operations. Higher spectral and spatial resolution makes NOAA/AVHRR data a valuable complement to geostationary imagery despite the lower temporal resolution. There are a number of issues associated with observational accuracy from aircraft and from the ground (Sawada, 1987, 2002: Tupper *et al.*, 2003a: Tupper and Kinoshita, 2003), but the most important remote sensing limitations relate to overlying cloud and to volcanic cloud with innate or entrained water (Rose *et al.*, 1995). In the usual application of reverse absorption in the region, ΔT thresholds are adjusted according to brightness temperature, to reduce the false alarm rate from poor calibration (especially of AVHRR) and stratospheric cumulonimbus tops (Potts and Ebert, 1999: Tupper *et al.*, 2003c). Various other strategies are employed to enhance imagery for intensive analysis.

The recent introduction of GOES-9 has expanded the opportunity of taking advantage of the short-wave infrared channels already present on AVHRR for volcanic ash detection, (Ellrod *et al.*, 2003), or for detection of ash-poor, sulphate rich clouds (Kinoshita *et al.*, 2003). Better use of these channels is an immediate priority for development. MODIS data is currently used in near-real time through NASA's Rapid Response System, and for post-analysis. Local reception and processing of MODIS data is seen as a high priority although it requires substantial capital investment and may be some years off.

3. Case Studies

a) Ruang, Sangihe Islands, Indonesia

Ruang volcano began erupting at 1700Z on 24 September 2002 (Directorate of Volcanology and Geological Hazard Mitigation, personal communications and bulletins). A major eruption occurred at 0350Z on the 25th, with the eruption cloud reaching about 20km in altitude (Tupper *et al.*, 2003b). The event occurred soon after Aqua/MODIS became operational, and high quality imagery was available from GMS-5, Terra, Aqua, and the NOAA polar orbiters, with relatively clear weather conditions.

For real-time VAAC operations, the success of the split-window technique on the hourly GMS-5 imagery was notable, providing the most valuable tool for tracking the ash. Using this method ash could be detected for approximately 40 hours following the main eruption (Tupper *et al.*, 2003b). This was considerably longer than for the single band visible or infrared images. The residence time of the ash cloud and high density of suitable polar orbiting passes allowed close comparison of satellite calibrations and the exploration of multispectral techniques (Tupper *et al.*, 2003c).

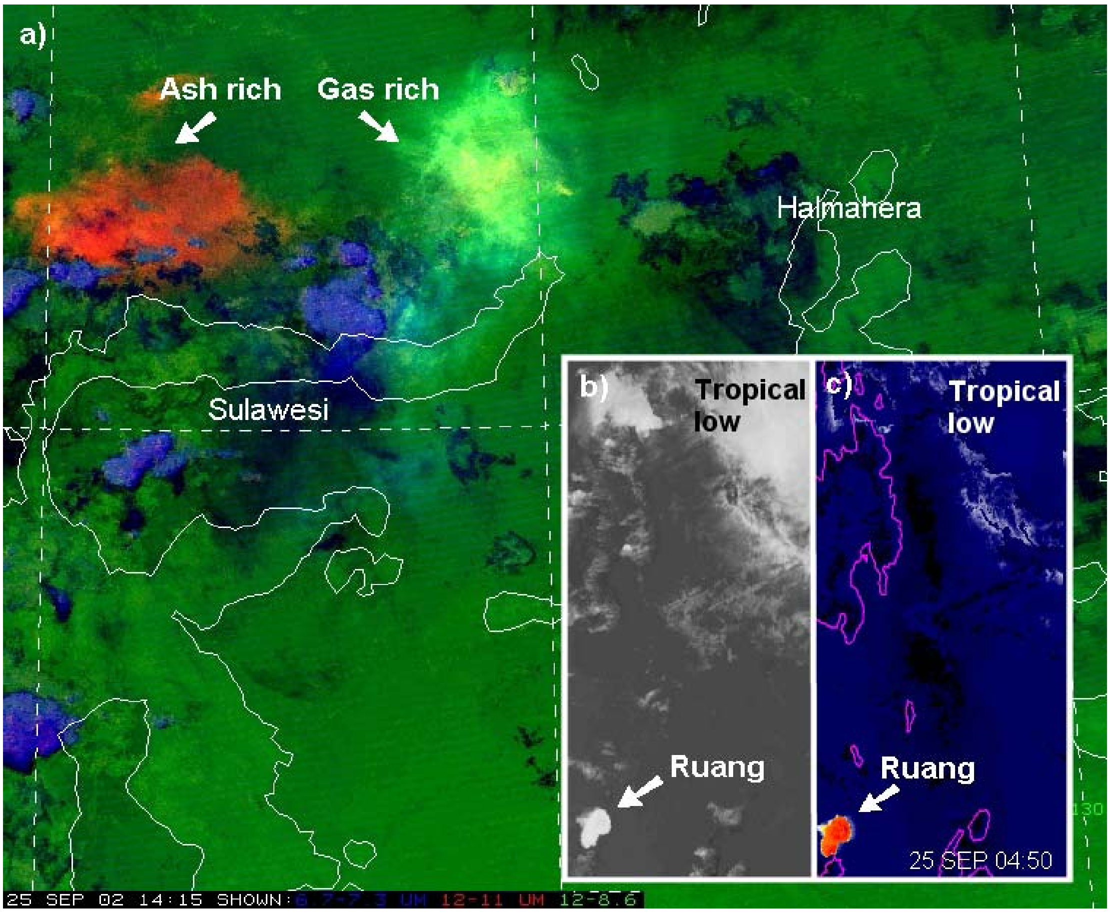

Figure 1 - a) Terra/MODIS multispectral image over clouds from Ruang eruption, 14:15 UTC, 25 September 2002, using 6.7, 7.3, 8.6, 11 & 12 µm channels. The western (red) cloud was at approximately 5-14 km altitude and appeared to mostly consist of ash, while the pale green cloud was gas rich but also contained ash, at an altitude of 16-18 km. A higher (approx 20 km) SO_2-rich cloud was over Halmahera and moving eastwards at this stage, but only detected on earlier GMS-5 imagery and GOME imagery over Papua New Guinea from the 27th. Water/ice clouds appear blue in this enhancement.
b) Aqua/MODIS, 04:50 UTC, 25 September, 11 µm, and c) 0.415 & 11 µm enhancement, exploiting the very low reflectivity of the eruption cloud compared to thunderstorm tops at 0.415 µm.

Figure 1 shows MODIS multi-spectral images created during post-analysis. The availability of MODIS data in real time would improve operations principally because of the extra information available from the 7.3 and 8.6 µm bands (Prata *et al.*, 2003b: Realmuto *et al.*, 1994), but also because of the potential for improved use of the visible and near-infrared bands (Ellrod *et al.*, 2003: Kinoshita *et al.*, 2003: Tupper *et al.*, 2003a), and for the monitoring potential of the high resolution 250 and 500 metre bands.

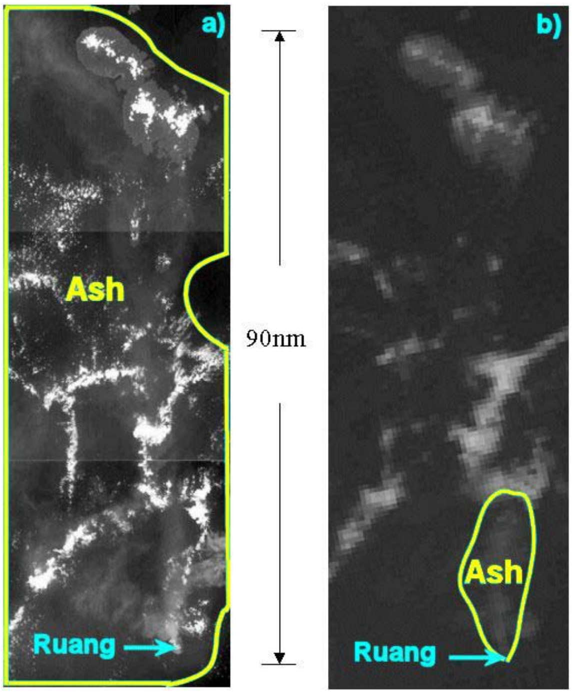

Figure 2 - SPOT-5 0.65 µm (left) and GMS-5 0.65 µm (right) images, at 0201 UTC and 0240 UTC respectively on 26 September 2002. Approximate areas of visible volcanic cloud are outlined in yellow. [SPOT image © CNES 2002, courtesy CRISP 'Quicklook' facility (http://www.crisp.nus.edu.sg/)]

The temporal resolution and spatial coverage of geostationary imagery is vital for real-time monitoring and tracking of ash dispersion, but unfortunately the poorer spatial resolution can potentially lead to underestimation of the ash extent. Figure 2 shows images from GMS-5 and SPOT-5 over Ruang the day after the main eruption, when ash was still being emitted to around 6000 m (based on cloud drift observations), but the ash was too diffuse to be confidently detected on 5 km resolution GMS-5 infrared imagery. A small ash plume is faintly visible on the GMS-5 visible imagery, but was much clearer and more extensive on the SPOT-5 images. The image frequency of SPOT-5 is too low for routine operational use, but can occasionally provide great insight into activity at a volcano (Carn and Oppenheimer, 2000). Recently, the 250 metre mode of MODIS imagery from NASA's Rapid Response site (http://rapidfire.sci.gsfc.nasa.gov/) has been used successfully in operations despite the delay of several hours in obtaining imagery.

For the Ruang event, Darwin VAAC forecasters had the common problem of how long to continue dispersion forecasts after ash ceased to be detectable on GMS-5 imagery. There have been recorded instances of aircraft encounters with ash long after the main eruption and even at great distances from the volcano (Casadevall, 1994: Rose *et al.*, 2003), so advisories tend to be conservative. Under the procedures of the IAVW (ICAO, 2000), the term "ash dissipated" may be used in the forecast section of the advisories. When this term was used by the Darwin VAAC a query was received from an airline about whether is was safe to fly through the area. The VAAC can only report that ash is no longer detectable but cannot advise that an area is absolutely safe. This and other related issues are summarised in Table 1.

Another point of interest from Ruang eruption was the distribution of high level SO_2, detected in GOME imagery (University of Bremen, http://www-iup.physik.uni-bremen.de/gomenrt/). The SO_2 cloud persisted for longer than the detectable ash, moved eastwards in the stratosphere, and covered a greater area than the detectable tropospheric ash and gas. The separation of SO_2 and ash is commonly observed (Constantine *et al.*, 2000), but it is also reasonable to assume that any SO_2 cloud also contains low concentrations of fine ash particles, and that a detected SO_2 cloud implies the probability of an ash cloud at lower levels which might not be explicitly detected (Tupper *et al.*, 2003b). If any concentration of ash is considered a hazard to aviation, then using this argument the SO_2 distribution should be incorporated into the volcanic ash advisories and SIGMETs[1]. Aside from the potential association with ash, SO_2 is also a hazard to aviation, as a cause of human respiratory failure and aircraft corrosion (Casadevall and Rye, 1994). Explicit, real time detection of SO_2 is possible with the use of data from TOMS (Krueger *et al.*, 1995), TOVS (Carn *et al.*, 2002: Prata *et al.*, 2003a) and MODIS (Prata *et al.*, 2003b: Realmuto *et al.*, 1994). A related issue is whether airlines are prepared to fly underneath

[1] *No SIGMETs were received or apparently issued for the Ruang eruption, so the Darwin VAAC advisories were the only warning source. At least one international commercial operator was known to be operating through the ash clouds over Borneo, although no reports were received of ash encounters. Both the lack of SIGMETs and the varying response of airlines are consistent with previous eruptions in the region.*

stratospheric SO_2, which may be judged an acceptable risk if aerosols are precipitating down from the SO_2 cloud at a very slow rate.

b) Rabaul, New Britain, Papua New Guinea

The eruption of the Tavurvur cone at Rabaul began at 0347 UTC on 20 October 2002 (Rabaul Volcano Observatory, volcanic activity reports and personal communications), and has continued until the present. The main issues with this event for Darwin VAAC were the low-level nature of the eruption, the lack of detection of ash on satellite imagery, the duration of the activity, the frequency of ash reports, and the problem of when to cease issuing advisories.

Faxed reports were received from Rabaul Volcano Observatory on a regular basis during the first few months of the eruption, becoming more intermittent as the activity gradually decreased. The vulcanological prognosis throughout the event was that the current eruption was expected to continue, although an increase in eruptive activity was unlikely. Ash was reported to 3 km above the summit (688 m) during the first two days, 1-2 km for the following two weeks, and then several hundred metres to time of writing, with occasional periods of increased emissions to 1-1.5 km. There were very few occasions during this event where ash was identifiable on satellite imagery.

During this event advisories were generally issued every 24 hours, with more recent updates whenever significant new information was received. The IAVW requires that advisories be issued every 6 hours, however in some situations, such as when ash is not detectable on satellite imagery and new information is only received daily or less frequently, airline consultation has suggested that issuing advisories once a day is sufficient. This helps to keep the workload of the VAAC manageable, while not compromising the VAAC service.

As the duration of this event extended from weeks to months there was considerable debate within the VAAC as to whether or not advisories should be continued. Arguments for continuing to issue advisories stemmed from the IAVW guidelines (ICAO, 2000), which makes no distinction between low and high level eruptions and states that advisories should be continued until no further reports of volcanic eruptions are received. Arguments against issuing advisories involved the low level nature of the eruption, the lack of detection on satellite imagery, and a perceived lack of value of the advisories. Industry consultation initially affirmed the need to continue with advisories, then approved their cessation later in the event.

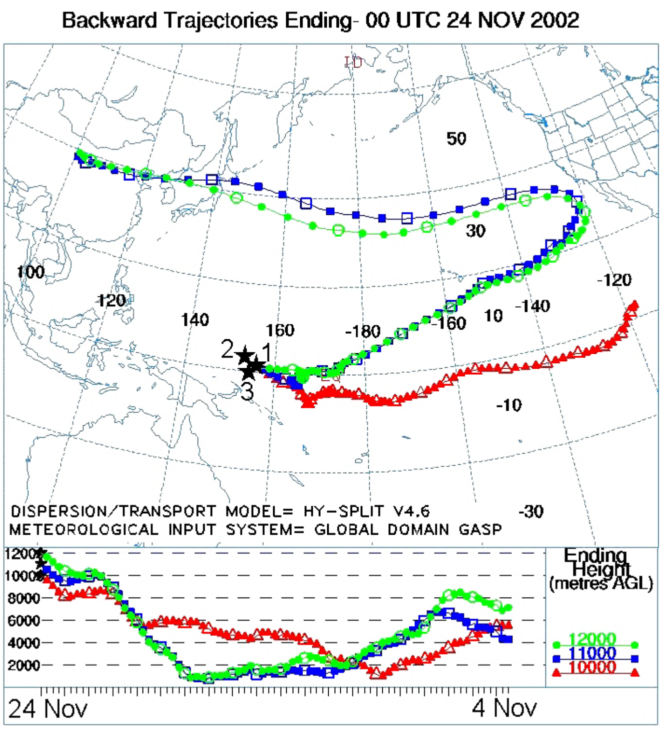

Figure 3 - Positions of aircraft encounters over Micronesia, and 20-day GASP/HYSPLIT back trajectories from encounter #1 (courtesy P.Stewart, NMOC, Melbourne).

c) Mysterious Micronesian encounters

Three puzzling aircraft encounters with volcanic cloud have occurred within a very small area over Micronesia; the first two within 12 hours of each other, the third months later. Figure 3 shows the locations of these encounters:

At 1728 UTC on 23 November, 2002, an aircraft at FL330 reported volcanic ash while 'flying in a CB cloud',
At 0717 UTC on 24 November, 2002, at FL360 an aircraft reported 'not conclusive but possible slight haze and a little smell.'
At 1745 UTC on 8 March 2003, a pilot reported ash at FL330.

No volcanic cloud was found in real-time imagery in any of these cases. An interesting detail was that a report from Tokua Airport near Rabaul was received on the 24 November 2002, with ash observed entering the base of a CB at around 3000ft at 0330 UTC. Satellite imagery at this time shows convection moving slowly to the west.

The first two reports were investigated by a loose collective including Jean-Marie Carrière (Toulouse VAAC), René Servrankcx (Montreal VAAC), Barbara Stunder (NOAA), Paul Stewart (Bureau of Meteorology NMOC), and Darwin VAAC staff, using the relevant national dispersion and numerical weather prediction models. Figure 3 shows the NMOC HYSPLIT/GASP 20-day back trajectories from encounter #1. Two possible hypothesis were considered; 1) that the volcanic clouds were from Rabaul, entrained into cumulonimbus and transported to cruising levels, and 2) that the clouds were from the eruption of Reventador in Ecuador, South America, on 3 November 2002. After comparison of model output, GMS and MODIS imagery, and TOMS imagery (courtesy Simon Carn), the Rabaul possibility was thought to be very unlikely, and the Reventador hypothesis could not be proved and was in any case inconsistent with the third encounter in March 2003. The source(s) of these encounters thus remains a mystery, although the opportunity to promote international investigation of these and similar incidents was very welcome.

d) The perpetual Semeru eruption

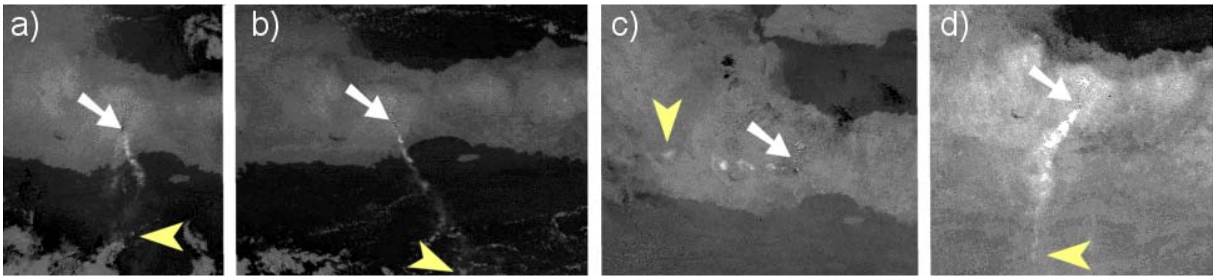

Figure 4 - Ash clouds visible from Semeru during the 2003 dry season, shown as contrast stretched 12-11 μm images. The white arrows indicate the position of Semeru, the lemon arrowheads the farthest visible extent of ash. a) NOAA-15, 1 June 2003, 2317 UTC, bifurcated plume extending 56 km to S, b) NOAA-15, 2 June 2003, 2252 UTC, 183 km plume to SE, c) NOAA-15, 1 July 2003, 2313 UTC, explosion 'puffs' extending 100 km to W, and d) NOAA-17, 6 August 2003, 1454 UTC, bifurcated plume 122 km to SSW.

There are several volcanoes in Indonesia that are known to be in a state of constant eruption; of these, the most problematic is Semeru, in eruption since 1967 with sometimes hundreds of explosions every week (Directorate of Volcanology and Geological Hazard Mitigation reports). Ground-based observations are usually received on a weekly basis, and hence are considered too old to trigger advisories, severely limiting the number of advisories issued. Aircraft reports are generally received in clear weather only, and usually greatly overestimate the height of the plumes when compared to ground reports: typically a plume reported as 600 m above the summit height (3676 m) from the ground might be reported as FL200 (6000 m) or even FL300 (9000 m) high from aircraft. This issue is discussed elsewhere (Tupper *et al.*, 2003a: Tupper and Kinoshita, 2003). Figure 4 shows four plumes observed using NOAA/AVHRR. It can seen that the ash from Semeru can sometimes be detected well over 100 km away from the volcano, in good conditions.

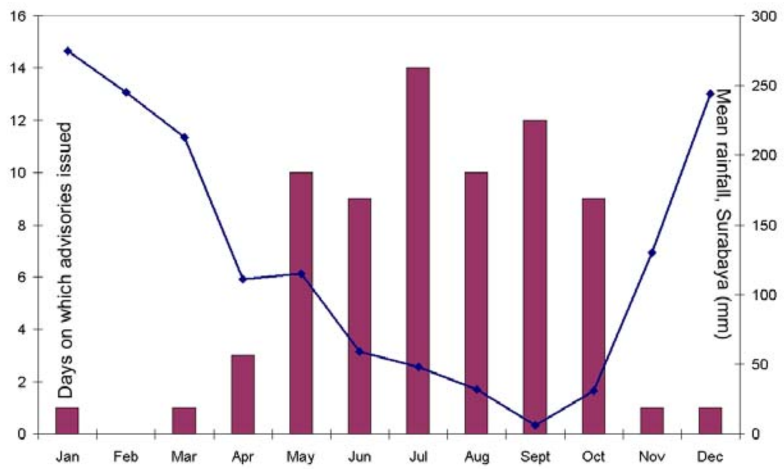

Figure 5 - Total days on which advisories have been issued for Semeru, July 1993 - June 2003, by month (solid columns), and monthly average rainfall from Surabaya, eastern Java (blue line).

Figure 5 shows how the advisories issued for Semeru have been highly dependent on satellite and aircraft visibility, by comparing the months in which advisories have been issued with the average monthly rainfall from the nearby city of Surabaya. It can readily be seen that the weather conditions most conducive to safe flying, with the least amount of cloud cover and convection, are also those that generate the most number of volcanic ash advisories. The actual activity from Semeru can be assumed to be constant throughout the year. SIGMETs and NOTAMs are seldom received for Semeru.

4. Discussion

It is difficult to completely isolate scientific from procedural issues. Table 1 summarises the operational effect of selected issues for the Darwin VAAC, and some suggested actions.

Issue	Consequence for IAVW	Action required
Lack of information flow; pilot reports, NOTAMs, SIGMETs often non-existent. Ground reports patchy and weather/communication dependent. Satellite imagery often obscured by extensive tropical thunderstorm tops at 15-17 km.	General under-warning, depending on area and season. Difficulty in verifying ash distribution. Possible over-warning if observations of clear air in warning zones are not performed.	Continued development of 'holistic' multi-sensor approach for ground, air and satellite-based observations. Education, diplomacy, aid projects.
No defined safe concentration of ash. Satellite techniques may not be sensitive enough for airline requirements.	Uncertainty when to cease advisories. Problems of over-warning, under-warning, variation in practises, impossibility of verification.	Major research into ash effects on aircraft, definition of 'safe' level, more sensitive satellite techniques, refinement of procedures.
SO_2 and inferred ash; little operational detection.	SO_2 is not explicitly mentioned in advisories – aircraft can fly through SO_2 clouds with low concentrations of ash with no warning unless the ash has also been detected.	Begin real time processing of TOVS, TOMS, MODIS. Introduce geostationary TOMS type UV instrument for day-time detection of SO_2 and aerosols. Agree on procedures for handling SO_2 clouds in IAVW.
Low level plumes generally only sensed from polar orbiting, visible imagery.	Information flow for advisories is sporadic, difficult to maintain currency of 6 hourly advisories.	Assumption of constant activity, education of aviation clients about information flow (geological versus aviation ideas of time).
Many volcanoes constantly in low-level eruption. Possibility of upward convective transport of ash.	Difficult to prioritise eruptions with a high mass flux into the atmosphere, because all warnings have the same relative weight.	Further develop aviation colour code or similar system to become universal and to be interpreted as a prioritisation system.

Table 1 – Darwin VAAC monitoring issues, consequences for the IAVW, possible actions.

Acknowledging the limitations of ash detection, the Darwin VAAC adopts a conservative strategy when forecasting the distribution of ash. If ash is detectable on visible satellite imagery towards the end of the day, but not on infrared imagery, the ash distribution will generally be extrapolated overnight until visible images are received again the next day. In the case of large eruptions where ash has been evident on satellite imagery, such as the Ruang example, forecasts may again be extrapolated as the ash ceases to be detectable over time. The length of time that forecasts are continued for in these circumstances is subjective, but as a general guideline forecasts will be shuffled forward with subsequent advisory issues without extending the overall forecast period. For example, the previous 18 hour forecast will become the current 12 hour forecast, with no new forecast being given for the 18 hour time step. In this way forecasts may be continued for up to 24 hours from the point ash has ceased to be detectable (less for smaller eruptions, at the discretion of the forecaster).

In an attempt to manage information that is not received in real time the Darwin VAAC has implemented the following guidelines for when to issue VAAs:

1) Ash at or above FL150 (4.5 km) is reported or detected on satellite imagery, providing the information is less than 24hrs old.
2) Ash below FL150 (4.5 km) is reported or detected on satellite imagery, providing the information is less than 12hrs old.

FL150 (4.5 km) has been chosen to distinguish between high and low-level ash. The highest volcano in the Darwin VAAC area of responsibility is Kerinci at 3800 m. A higher priority is given to high-level ash as it is generally assumed that it poses a greater threat to aircraft, particularly with its potential to affect international air routes. High-level ash is generally considered to be associated with larger volumes of ash, a longer residence time in the atmosphere, and a greater dispersion potential than ash at low-levels.

Age limits on the information that advisories are based on have been imposed to maintain the real-time focus of Advisories. The choice of 12 and 24 hour age limits is designed to minimise the issuance of advisories in situations where the ash has already dissipated, while still allowing for a degree of conservatism. The ability of the VAAC to provide information on the distribution of ash is limited when ash is not identifiable on satellite imagery, particularly when ash has not been detectable for 24 hours.

In addition to these criteria, advisories are also issued:
1) Upon notification from a volcanological agency that a volcano has the potential to erupt within days. These precautionary advisories, although not required specifically by the procedures outlined for the IAVW (ICAO, 2000), are considered to provide valuable forewarning to the aviation industry.
2) Upon receipt of new information that is not adequately covered in an existing advisory.
3) At the reissue time specified in a current advisory.

These criteria are of course subject to review, depending on future research on volcanic ash and the requirements of the aviation industry.

5. Conclusions

The IAVW in the Darwin VAAC area has developed considerably in the decade since its inception, with many successful examples of major eruption monitoring, such as the eruption of Ruang in 2002. Low level eruptions are less easy to manage, especially in conditions of poor visibility. There are still scientific and procedural issues that require addressing even in the context of successfully detected eruptions such as Ruang, and also obvious problems to deal with, such as our inability to detect volcanic clouds associated with three aircraft encounters over Micronesia.

Continued remote sensing research, expansion of remote sensing programs, ground and air based detection are all required for improvement of the IAVW. Procedural and scientific issues are closely intertwined and should be progressed together.

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