VOLCANIC ASH

CONTENTS

1.1 INTRODUCTION

"Ladies and gentlemen, this is your captain speaking. We have a small problem. All four engines have stopped. We are doing our damnedest to get them going again. I trust you are not in too much distress." Capt. Eric Moody, BA Flight 009, 27 June 1982

Volcanic ash clouds lofted into the atmosphere can spread around the world and remain for months or longer. The ash and accompanying gases are damaging and hazardous to aircraft especially those close to the eruption where concentrations of ash and gases are high.

Detection of ash clouds by aircraft in flight is difficult since they cannot easily be distinguished from normal cloud. Hence the importance of meteorological forecasters who utilise ground and remote observations to determine the presence of ash clouds prior to assessing and forecasting their height, movement and dispersion.

The aviation industry utilises ash-plume forecasts to guide aircraft clear of any threat.

1.2 DEFINITION

Volcanic ash clouds are composed of fine pulverised rock, predominately silica (in the form of tiny glass shards) in most cases, and corrosive gases that convert into droplets of sulphuric acid and other substances.

1.3 EFFECTS

The most critical effect on aircraft occurs when ash melts in the hot section of the engine, and fuses into a glass-like coating on components further back in the engine, causing loss of thrust and possible "flame out" (engine failure). In addition, there is abrasion of engine parts, the airframe, windscreen and parts protruding from the aircraft, and possible clogging of the fuel and cooling systems.

The first recorded significant aviation encounter with volcanic ash occurred over Indonesia on 24 June 1982. A British Airways Boeing 747 en route from Kuala Lumpur to Perth flew through an ash cloud from Indonesia's Mount Galunggung at night. The aircraft lost power to all four engines, and descended from 37000 ft to 12000 ft, before the pilot was able to restart three engines and make an emergency landing at Jakarta, Indonesia.

The pilot's report indicated that an acrid electrical smell had been noticed in the cockpit at the time of the engine malfunction, with very fine dust or smoke entering the cockpit. St. Elmo's fire was observed on the leading edge of the engine nacelles and around the cockpit windows, and a "search light" effect was visible shining out of the engines through the fan blades. When making the emergency landing at Jakarta, most of the cockpit windows were almost completely opaque, and the landing had to be completed by the pilot looking through a small side section of the cockpit window that had remained relatively clear.

Inspection of the damaged aeroplane showed a "sand-blasted" appearance to the leading edges of the wing and engine inlet surfaces, the radome and the cockpit windows. Subsequent strip-down inspection of the aircraft engines revealed "sand-blasting" erosion of compressor rotor paths, rotor blade tips, and the leading edges of high-pressure rotor blades. Fused volcanic debris was found on the high-pressure nozzle guide vanes and the turbine blades (Figure 1).

Examination of all the evidence showed that the aircraft engines had stalled due to the ingestion of volcanic ash, with engines only restarting once the aircraft had descended out of the volcanic ash cloud and into clear air.

Figure 1 Photographs of damage caused to the British Airways Boeing 747 that encountered ash from the Mt. Galunggung eruption [courtesy Capt. Eric Moody] Top row, from left - Stator blades from turbine; Close up of melted ash on stator blades; Magnified image of ash from pitot system. Bottom row, from left - Lens from landing light windscreen; Windows after washing clean.

Three weeks later a Singapore Airways Boeing 747 en route to Melbourne reported a similar incident. Power was lost on two of its engines, and the aircraft had to divert to Jakarta for emergency landing.

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1.4 INTERNATIONAL AIRWAYS VOLCANO WATCH

To meet the volcanic ash threat to aviation, the International Civil Aviation Organization (ICAO) implemented the International Airways Volcano Watch (IAVW) to establish practices and procedures covering the observing and reporting of volcanic activity and ash cloud emissions, and the issuance of advisories and warnings to aircraft[8]. Nine regional Volcanic Ash Advisory Centres (VAACs) have been established worldwide to detect, track and forecast the movement of volcanic ash clouds and provide advice to meteorological watch offices (MWOs) in their areas of responsibility (Figure 2). These are located in Anchorage (Alaska), Buenos Aires (Argentina), Darwin (Australia), London (UK), Montreal (Canada), Tokyo (Japan), Toulouse (France), Washington (US) and Wellington (NZ).

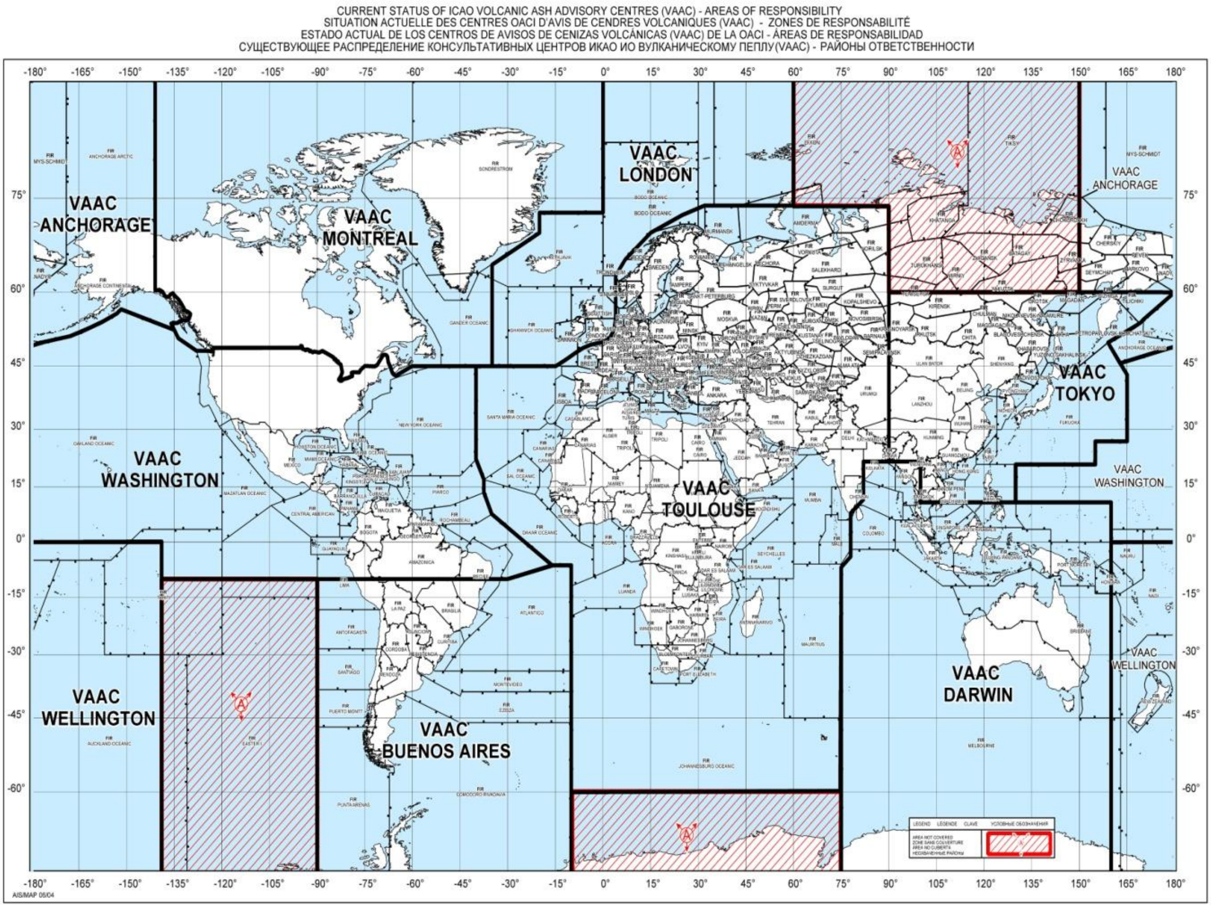


Figure 2 Areas of responsibility of the VAACs

1.5 VOLCANIC ACTIVITY

The highest concentration of active volcanoes lies along the rim of the Pacific Ocean, the so-called “Ring of Fire” (Figure 3), which stretches northwards along the western edge of South and North America, across the Aleutian and Kurile Island chains, down through Kamchatka, Japan and the Philippines and across Indonesia, Papua New Guinea and New Zealand to the islands of the South Pacific. Other active regions are in Iceland, along the Great Rift Valley in Central and East Africa, and in countries around the Mediterranean.

Within the Darwin VAAC area of responsibility, the high number of active volcanoes through Indonesia, Papua New Guinea and the Solomon Islands pose a significant threat to international air routes from Australia to Europe and Asia.

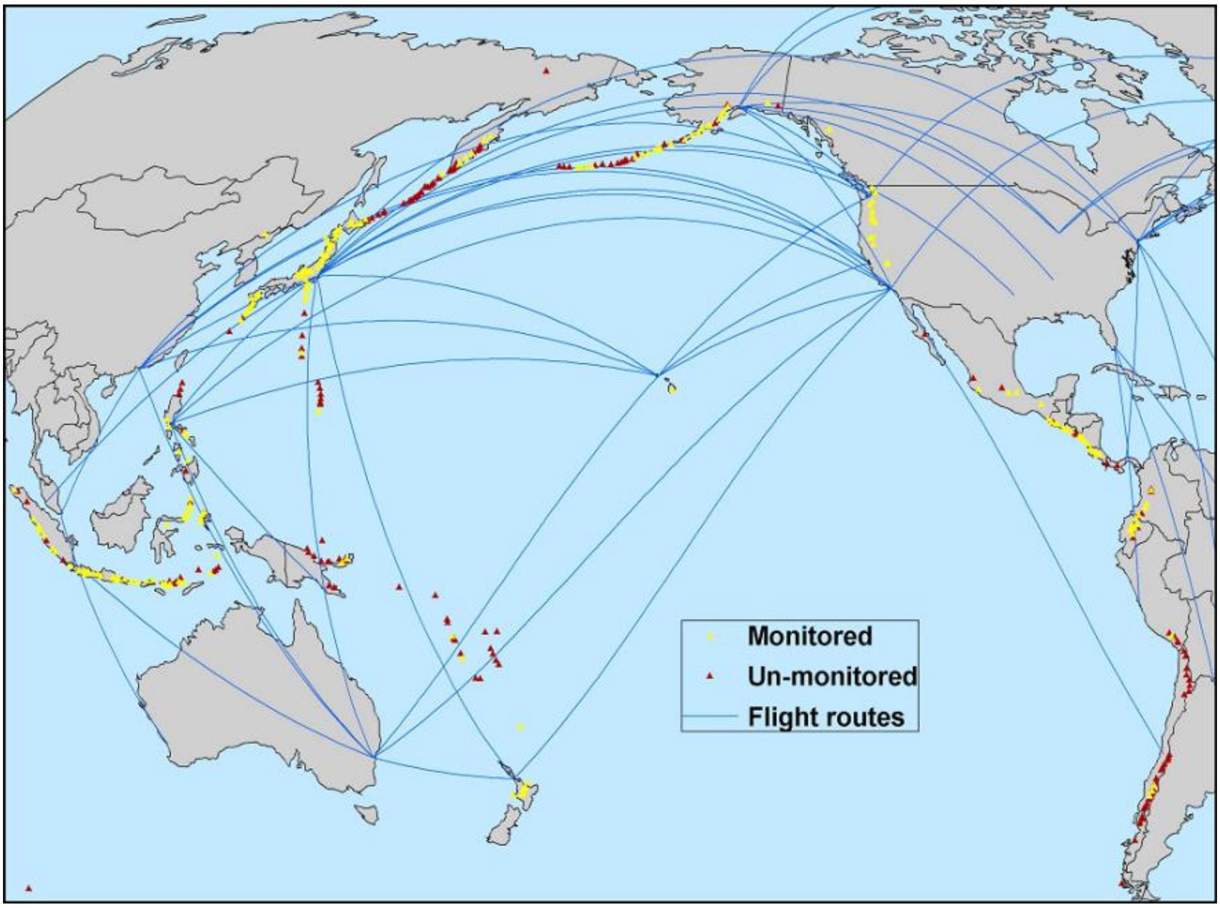


Figure 3 Major international air routes that pass through the Pacific "Ring of Fire", with monitored (yellow) and unmonitored (red) volcanoes indicated (courtesy United States Geological Survey).

1.6 TYPES OF VOLCANIC ERUPTIONS AND SOURCES OF ASH CLOUD

The behaviour of erupting volcanoes ranges from the quiet, steady effusion of lava at one extreme to highly explosive eruptions at the other which blast several cubic kilometres of glass particles and pulverised rock (volcanic ash) and corrosive gases high into the atmosphere and over a wide area for several days. This explosive activity is of greatest concern to aviation, mainly because of the great volume of ash and the heights that the ejecta can reach in these types of eruptions. An ash cloud from a large volcanic eruption can remain in the atmosphere in dangerous concentrations for many days. Over this time, it can travel many thousands of kilometres with the prevailing winds affecting aircraft and aerodromes.

The intensity of a volcanic eruption depends mainly upon the composition of the magma in the volcano. Generally, the most explosive eruptions come from magmas that have high gas levels and high viscosity (resistance to flowing).

The size of a volcanic eruption is sometimes measured by its Volcanic Explosivity Index (VEI, Table 1). Eruptions affecting aircraft cruising levels are generally VEI 3 or greater. These include the explosive eruption types *Plinian* (Figure 4) and *Vulcanian*, as well as *co-ignimbrite plumes* caused by the "ground hugging" *pyroclastic flows* (sometimes referred to as 'nuees ardentes'). Note that steam driven *Phreatic* eruptions may be either small or large. However, smaller eruptions (e.g. *Strombolian*) should not be ignored, with some consideration given to the proximity of the volcano to airports, the height of the volcano, and whether the ash plume is entering convective cloud (which may transport ash to higher levels in the atmosphere).

Some volcanoes eject modest ash clouds on a regular basis, whereas others are generally quiet until a big eruption event. Semeru (Java), Dukono (Halmahera) and Rabaul (New Britain) are examples of volcanoes that are known to be regular emitters of modest amounts of volcanic ash. Some switch between modes very easily (for example Rabaul, and Manam in PNG).

The composition of the eruption column is also important, with ash-rich plumes obviously of greater danger to aviation. Eruptions from Semeru are generally ash-rich, whereas those from Bagana (Bougainville Island) tend to be ash-poor. An eruption column from Ulawun (New Britain) is likely to be ash-rich, but when it is degassing (expelling gases) the plumes (which can sometimes be seen on satellite imagery) are ash-poor.

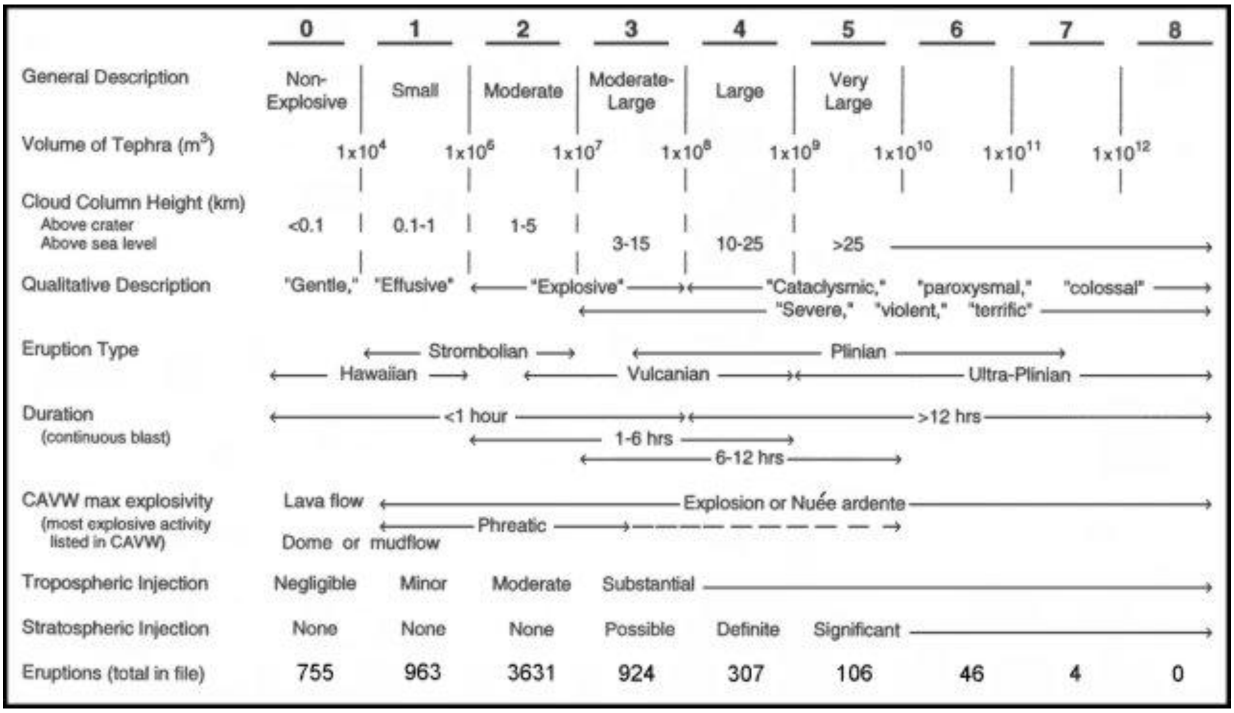


Table 1 Volcanic Explosivity Index (VEI)[12](from Siebert and Simkin (2002)

1.7 Observing, Monitoring and Diagnosing

The Darwin VAAC is responsible for the monitoring of various sources of information for volcanic activity (e.g. ground reports, satellite imagery, pilot and ground reports, online news stories etc). It is also responsible for the issuance of Volcanic Ash Advisories (VAA) within the Darwin VAAC area of responsibility and SIGMETs for the Brisbane and Melbourne Flight Information Regions (FIRs). An important part of both these procedures involves liaison with other agencies such as vulcanological authorities, airlines, other VAACs and meteorological offices.

1.7.1 Forecasts and Ground Reports from Vulcanological Authorities

Vulcanological observatories near active volcanoes are the first line of defence in the monitoring of volcanic activity. Staff working at these locations can build up a very useful knowledge of the typical behaviour of the volcano and can give very valuable observations on any day-to-day changes.

Figure 4 Sub-Plinian (small Plinian) eruption of Manam volcano at 7:15am on 24 November 2004 (also see Fig. 7), courtesy of Rabaul Volcano Observatory.

While long-term forecasting of volcanic eruptions is not possible, vulcanologists are able to give short-term forecasts based on their own monitoring techniques (e.g. seismic activity, ground deformations etc.). Although primarily used to provide warnings for local communities, this information can be used by VAACs in providing advice to the aviation industry on imminent eruptions and their expected nature (e.g. whether an eruption is likely to reach cruising levels).

Ideally, once an eruption is known to have occurred, information from observatories will be sent quickly through to meteorological agencies and civil aviation authorities. In practice, information flow may be delayed due to:

- Poor communication links;
- The priority of warning the local public of impending danger; and
- The eruption affecting communications or the observatory itself.

Estimates of the height of the ash cloud above the ground are often:

- Under-estimated, especially for large eruptions when observers are located close to the volcano;
- Difficult to make when the ash enters (or generates) meteorological cloud;
- Misleading if remote cameras (web cams) are set up too close to the volcano to observe the full extent of a large eruption cloud.

1.7.2 Pilot Reports (AIREPs and Volcanic Activity Reports)

Pilot reports are an important source of information of volcanic activity. Such reports can include an observation of a distant eruption cloud, or an encounter with volcanic ash.

Estimating the height of low-level ash eruptions from high-flying aircraft is difficult, with many observations of ash plumes below cruising levels often exaggerated. Height estimates from aircraft that are some distance from the ash plume are also difficult. Observations of ash at or above the cruising level of the aircraft are likely to be more accurate. Hence it is important to know the aircraft's cruising altitude, and the approximate distance of the aircraft from the plume.

1.7.3 Satellite Imagery

Volcanic Ash Advisory Centres primarily use meteorological satellite systems (both geostationary and polar orbiting) for monitoring volcanic ash clouds. However these are generally not optimised to detect volcanic ash, so detecting an eruption from satellite data can be difficult. It is often easier to detect and monitor volcanic ash if it is already known that an eruption has occurred, so information from volcano observatories is extremely important.

The main advantage of the geostationary satellites is that they allow hourly monitoring of any volcano within their field of view, whereas a polar orbiter typically has only two passes a day near a specific volcano in the tropics. However, due to their lower earth orbit, the polar orbiting satellites produce higher resolution images than their geostationary counterparts. Satellite data used by the Darwin VAAC includes:

- Geostationary satellite imagery: MTSAT-1R;
- Polar orbiter imagery: NOAA AVHRR;
AQUA and TERRA MODIS;
SPOT; and
- SO_2 imagery: OMI and AIRS.

1.7.4 Pattern Recognition

Using unenhanced satellite imagery, pattern recognition techniques rely on being able to recognise the visual differences between an ash cloud and a normal meteorological cloud. However, detecting a volcanic eruption on satellite imagery can be difficult when there is a lot of meteorological cloud in the vicinity.

Some patterns to look for include:

- A line or plume extending from the volcano (Figure 5);
- Discolouration on true-colour (e.g. MODIS) visible imagery (Figure 6) below freezing level; and
- Cloud blow-up over a volcano that is inconsistent with the normal diurnal convective timing (Figure 7).

It is good practice to loop images. What looks like a high-level eruption cloud on one image might turn out to be a thunderstorm that has drifted over the volcano. Care should be taken to not rely exclusively on this method, as ash can be obvious at some levels but diffuse and hard to see at others. Where possible, split-window imagery should be used in conjunction with pattern recognition.

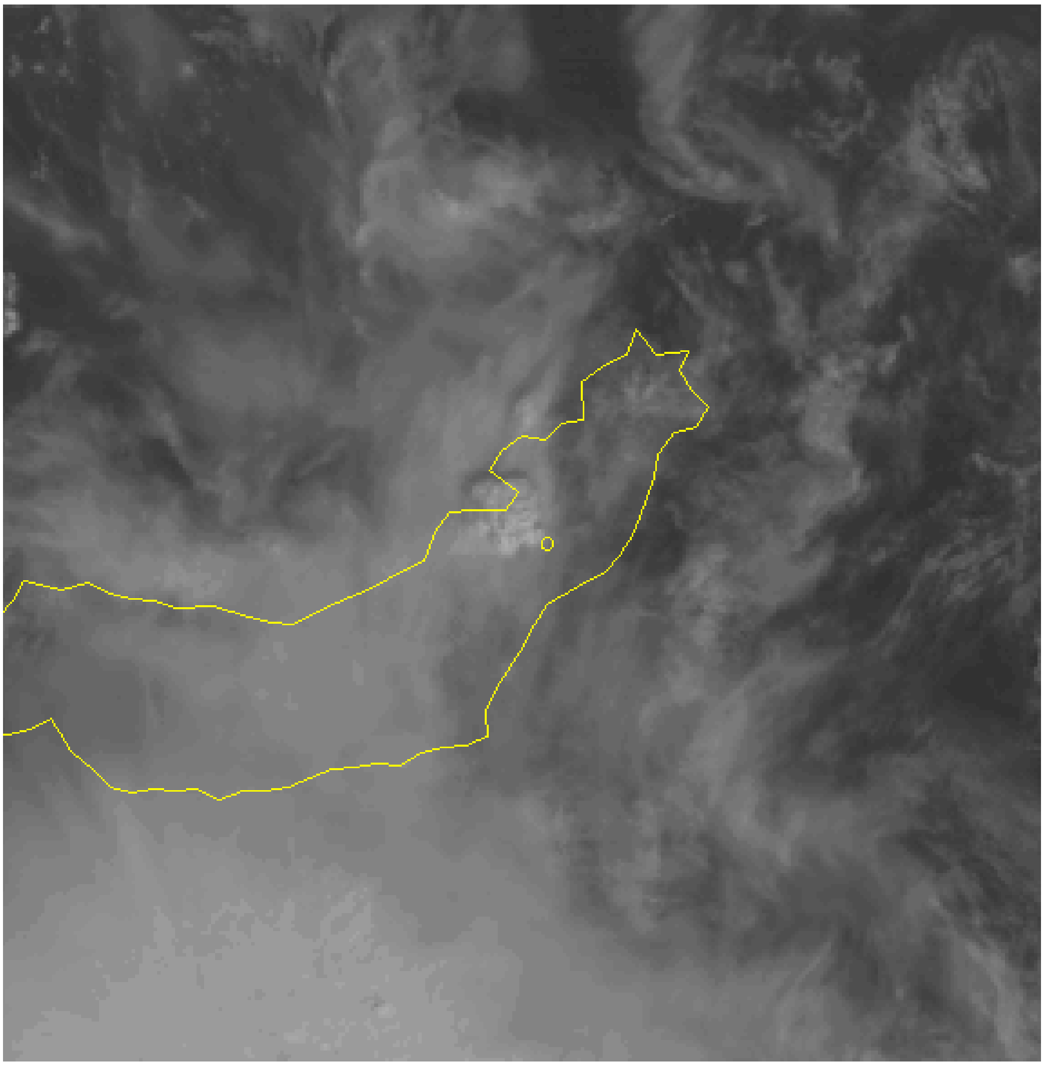


Figure 5 The distinguishing feature on this MTSAT-1R visible image of 27 December 2005 is the wedge-shaped cloud emanating from Soputan (small circle), Sulawesi, which is indicative of an on-going eruption.

Eruptions through overcast cloud are very difficult to etect, particularly as they will often be ice-rich and look similar to other clouds. Proximity to an active volcano is helpful, and should the volcano be reported to be in eruption, might be taken as reasonable evidence of eruption in real-time operations. The eruption in Figure 7 (the same eruption shown in Figure 4) was a noted success in real-time operations, as VAAC staff detected the eruption through the overcast without ground-notification. In this case, the key feature of imagery was 12 hours of continuous deep convection (to 18km or FL600) over the volcano during the night; it was correctly presumed that this atypical pattern resulted from strong volcanic forcing.

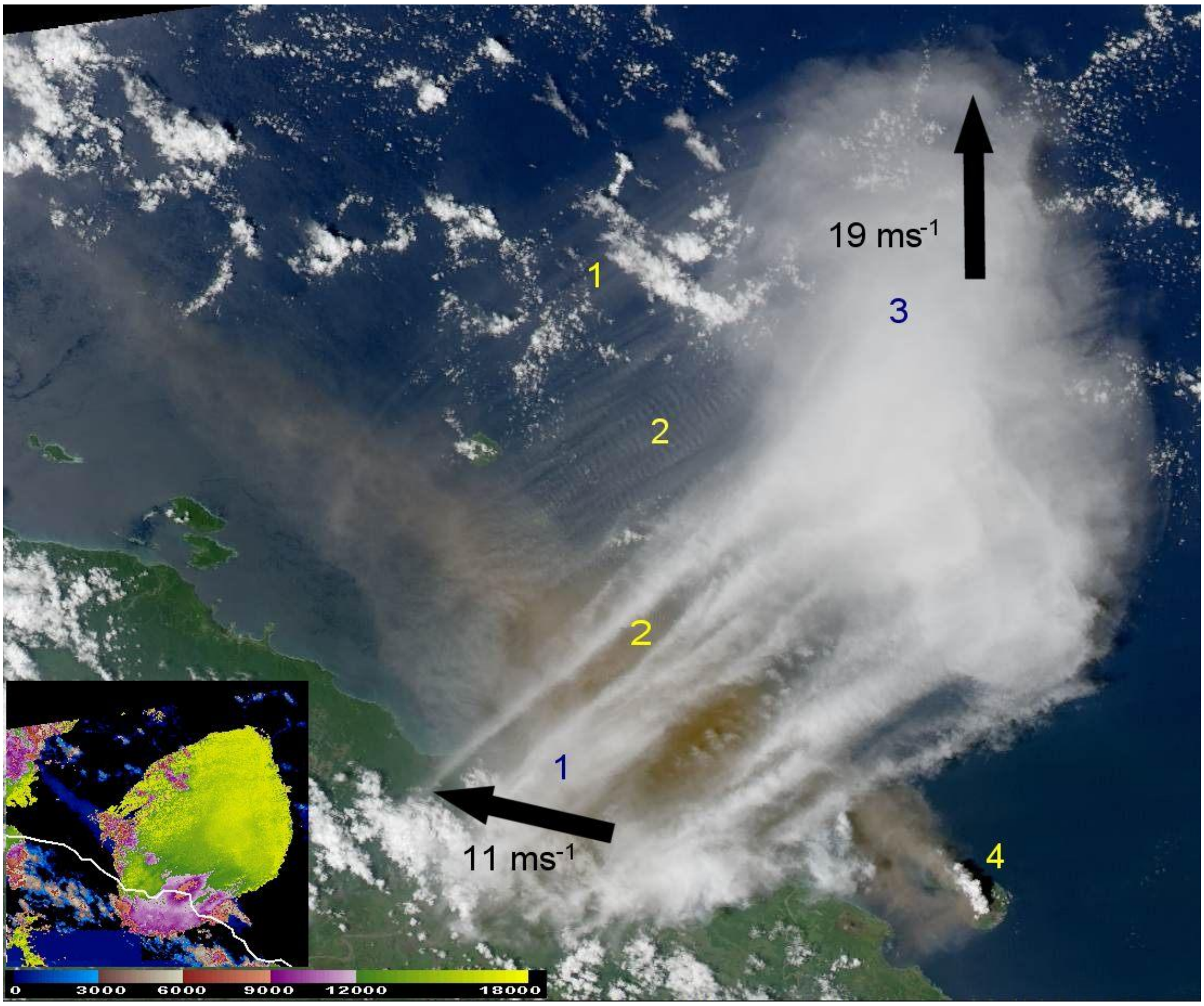


Figure 6 Complex clouds. Aqua/MODIS true colour image of a dissipating high level cloud over a continuing eruption of Manam, Papua New Guinea, 0355 UTC 24 October 2004. The inset shows matching cloud height (in metres) using a technique known as CO_2 slicing. On the main image, note the white appearance of the glaciated parts of the cloud, compared to the dirty brown below the freezing level. Labelled features are the observed drift of the clouds (arrows), wave features in the cloud (1,2), the main body of ice and SO_2-rich cloud that subsequently moved rapidly northwards across the equator (3), and the continuing eruption (4). The CO_2 slicing image here analyses the increasing height of the cloud towards the north, consistent with our understanding of the wind fields.[14]

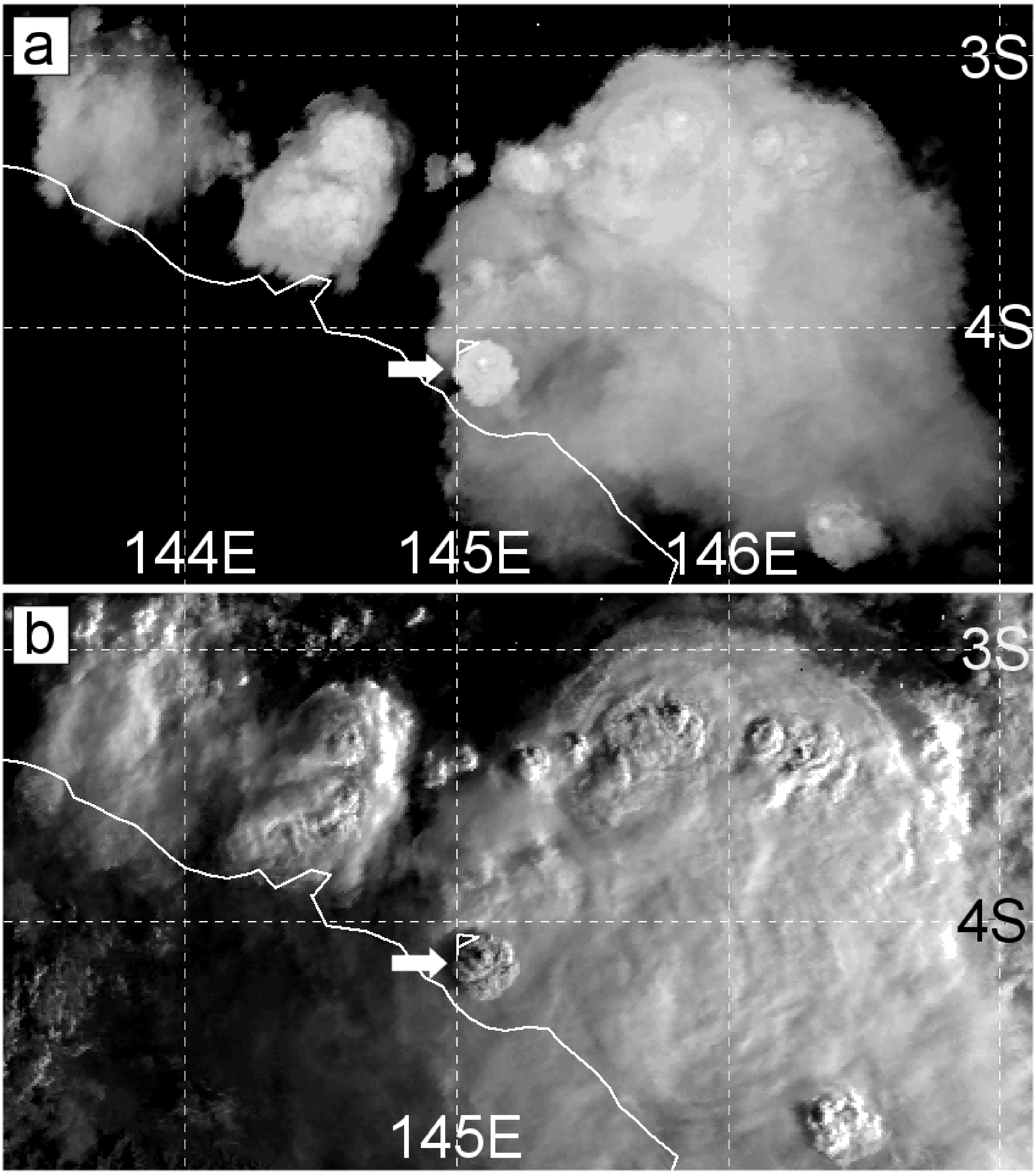


Figure 7 Eruption through cloud: the same eruption of Manam as in Figure 4, seen from above. a) NOAA-15/AVHRR 11 µm contrast stretched infrared image, 2039 UTC 23 November 2004 (6:39 am on 24 November local time) showing eruption (arrowed) bubbling through cirrus overcast from overnight cumulonimbus convection. White dot in centre is 'undercooled' overshooting top at -96°C (undercooling occurs when the cloud has cooled through expansion on ascent and not adjusted to the environmental temperature). b) Matching visible image: undercooled top casts 7 km shadow on umbrella cloud, suggesting ~ 1 km extra height. Note in both a) and b) that other overshooting tops from non-volcanic convection are apparent.[14] A 12 hour satellite loop of this event also shows the overshooting cloud tops associated with the volcanic eruption are inconsistent with the normal diurnal convective timing.

1.7.5 Channel Differencing (The 'Split-Window' Technique)

Many satellite infrared instruments observe at multiple wavelengths. The most widely used and effective technique for detecting ash-rich clouds exploits the fact that *a transparent ash cloud absorbs ground-emitted infrared radiation more strongly at 11μm than at 12μm, whereas ice/water-rich clouds absorb more strongly at 12 μm.*

This was first explored by Prata[18] and termed 'reverse absorption', as the 'normal absorption' effect of water vapour was already well known. However, the technique is usually referred to as the 'split window' technique after the two infrared windows used.

Exploiting the different absorption characteristics of ash and water vapour clouds in the 11μm and 12μm wavelength bands, split-window imagery can distinguish between volcanic ash and surrounding cloud, and potentially allow the tracking of ash long after it has ceased to be detectable in single wavelength imagery. This technique of finding the temperature difference between two channels, ΔT, is used in this case by subtracting the 12μm band from the 11μm band to create a split-window image. This typically produces negative values for ash and positive values for water vapour clouds. Results can be displayed as a scatter diagram (Figures 8, 9, 11), an infrared image with the negative difference values superimposed (Figure 9), or as a raw-difference image (Figure 10).

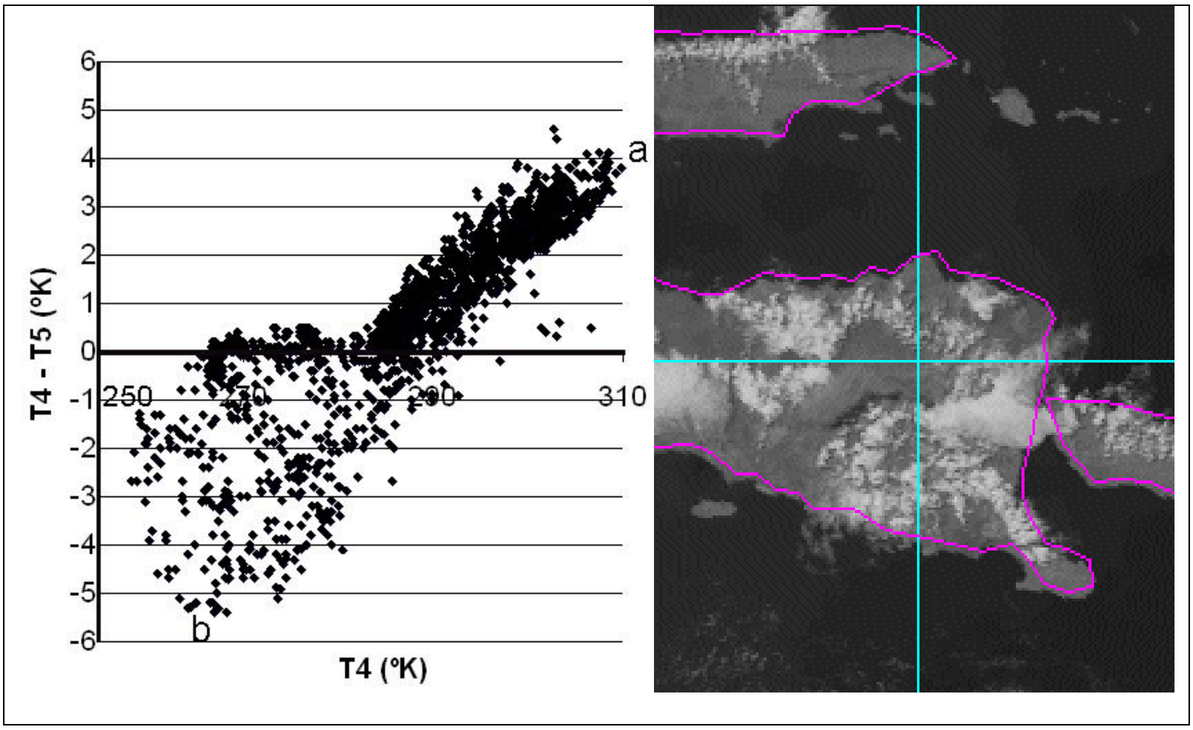


Figure 8 Scatter diagram (left) of an ash-rich eruption (right). On the left is temperature difference (ΔT) between channels with wavelengths of 11μm and 12μm (ΔT = T(11μm) - T(12μm)) plotted against T(11μm) brightness temperatures from NOAA-16/AVHRR images of the eruption of Raung, east Java, Indonesia, on August 25 2002 (right). On the scatter diagram, the distinctive "u" shape of the transparent, ash-rich cloud (label 'b') is evident, while the positive values at higher temperatures(label 'a') represent warm, probably opaque cloud in a positive ΔT environment caused by high water vapour.[15]

The strength of the split window signal depends on a number of factors, including ground temperature, cloud opacity, satellite resolution, satellite viewing angle, particle size, and relative ash and ice content in the cloud. In Figure 9, two satellite views of an eruption cloud from the Russian volcano 'Shiveluch' are shown (small inserts), together with their matching scatter diagrams. The Figure compares ΔTs for VISSR and AVHRR data at 1537 UTC and 1547 UTC respectively on 21 May 2001, and shows the relevant IR and ΔT images. At this stage, the cloud was thinning and shearing, with the central portion still relatively opaque and giving near-zero ΔTs. The GMS-5 data is distorted due to parallax effects that are exaggerated with the height of the cloud, but overall the two sensors compare extremely well. The GMS points clustered just below the zero line on the scatter diagram reflects the lower resolution of the data, especially at high latitudes.

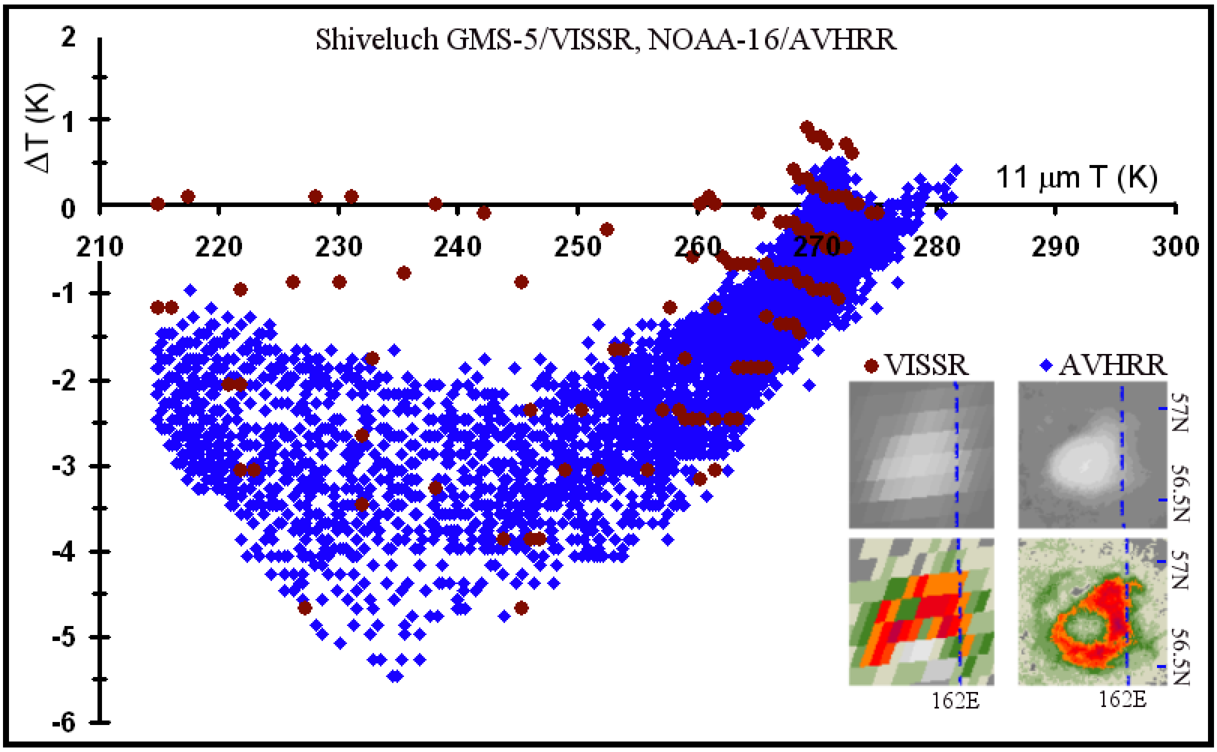


Figure 9 Temperature difference scatter diagram over a high level (16 km) eruption cloud from Shiveluch, Kamchatka on 21 May 2001 for GMS-5 /VISSR (brown) and NOAA-16/AVHRR (blue). Images shown are (top row) GMS-5 /VISSR, IR1, 1537UTC (left) and NOAA-16/AVHRR T4, 1547 UTC (right). Bottom row is the corresponding temperature difference images. The data used in the scatter diagram is from the same area as the images. [19]

1.7.6 Problems with Split-Window Imagery

Some of the problems encountered with split-window imagery are:

- It only works for (semi) transparent clouds, as it relies on some of the emitted thermal energy from the earth's surface passing through them. This may result in ash not being detected in early stages of the eruption when ash may be too dense or when the cloud is water or ice laden (common during the early parts of an eruption);
- The results tend to be reversed (i.e. positive values are produced) when the surface below the clouds (either the land/sea surface, or under-lying clouds) is cooler. This is more of a problem at higher latitudes, but can happen if an ash cloud penetrates the stratosphere and is observed against a cold overcast sky;
- Very cold cloud tops or badly calibrated IR channels can produce false alarms;
- A slight misalignment between the two infrared channels can produce false alarms at the edges of clouds; and
- High water vapour and water/ice content in volcanic ash clouds can reduce the effectiveness of the technique[20]. This is a common problem in tropical areas.

In 'raw' split-window imagery, the emphasis is less on set 'cut-off' temperatures but on subjective interpretation of the patterns created. This can be extremely valuable and yield unexpected results. Figure 10, shows the dissipating high-level cloud from the 24 October 2004 Manam eruption (Figure 6). The dark areas in figure 10 indicate the possibility of ash, but with relatively moist clouds and a moist atmosphere, the dark plume coming from the volcano is difficult to distinguish from other non-volcanic dark pixels. Examination of the matching scatter diagram (Figure 11) shows almost no negative split-window pixels, but a strong ambiguity arising from poor AVHRR calibration of the lower temperatures[21], so that very cold opaque cloud can give the same split-window signal as an ash cloud.

The most interesting feature of this image and scatter diagram, and a consistent feature of eruptions from this volcano, is the strongly positive signal associated with the high-level eruption cloud. This is because volcanic aerosols introduced into a water/ice cloud will tend to result in a larger effective particle radius in the cloud (effectively creating a cloud of ice-coated ash particles that look like ice), and the smaller particles have different absorption properties. In the Manam eruptions and some others, this result can be used to track the ice-rich portions of the cloud, in some cases for many hours before the signal loses strength and the clouds are indistinguishable from Cb tops. The smaller particles can also be used in some reflective techniques (see section 1.7.7).

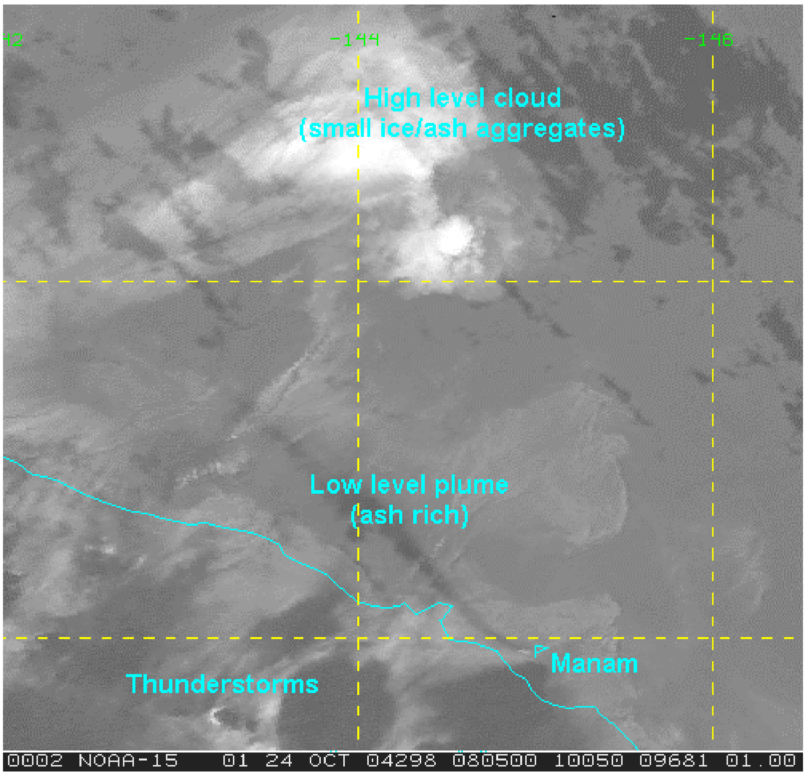


Figure 10 This NOAA-15/VHRR split-window image from October 24 2004 of eruption clouds from Manam, Papua New Guinea shows the ash-rich low level plume as a dark (negative) line to the northwest of the volcano[14]. The technique did not analyse the higher-level eruption cloud as containing ash, probably due to the high ice content, but the strongly positive (bright) values could still be used to track the cloud.

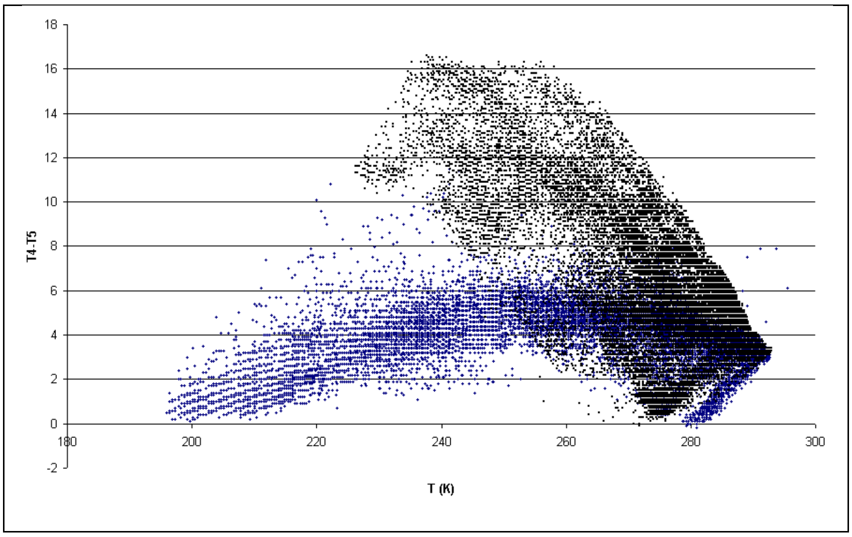


Figure 11 Scatter diagram to go with figure 10. The blue pixels represent areas of storms and part of the low-level plume, and the black pixels represent the dissipating ice-rich eruption cloud as well as another part of the low-level plume.

1.7.7 Short-Wave and Mid-Wave Infrared Imagery

Short-wave (e.g. 1.6μm) and Mid-wave (e.g. 3.9μm) infrared wavelengths can be highly useful for ash detection during the day, especially in situations where the split-window technique doesn't work because of ice or water in the cloud or because the cloud is opaque. As these wavelengths are comparable to cloud particle diameters, the reflection of solar radiation from cloud tops becomes important. Large particles absorb more and reflect less than small particles. Therefore, on 1.6μm imagery glaciated clouds (large ice particles) appear dark, while meteorological clouds below freezing level (smaller water droplets) are brighter as they are more reflective. High level volcanic ash clouds may contain a lot of ice, but ash-ice aggregates tend to have a smaller particle size and hence reflect more strongly than a glaciated cloud (Figure 12).

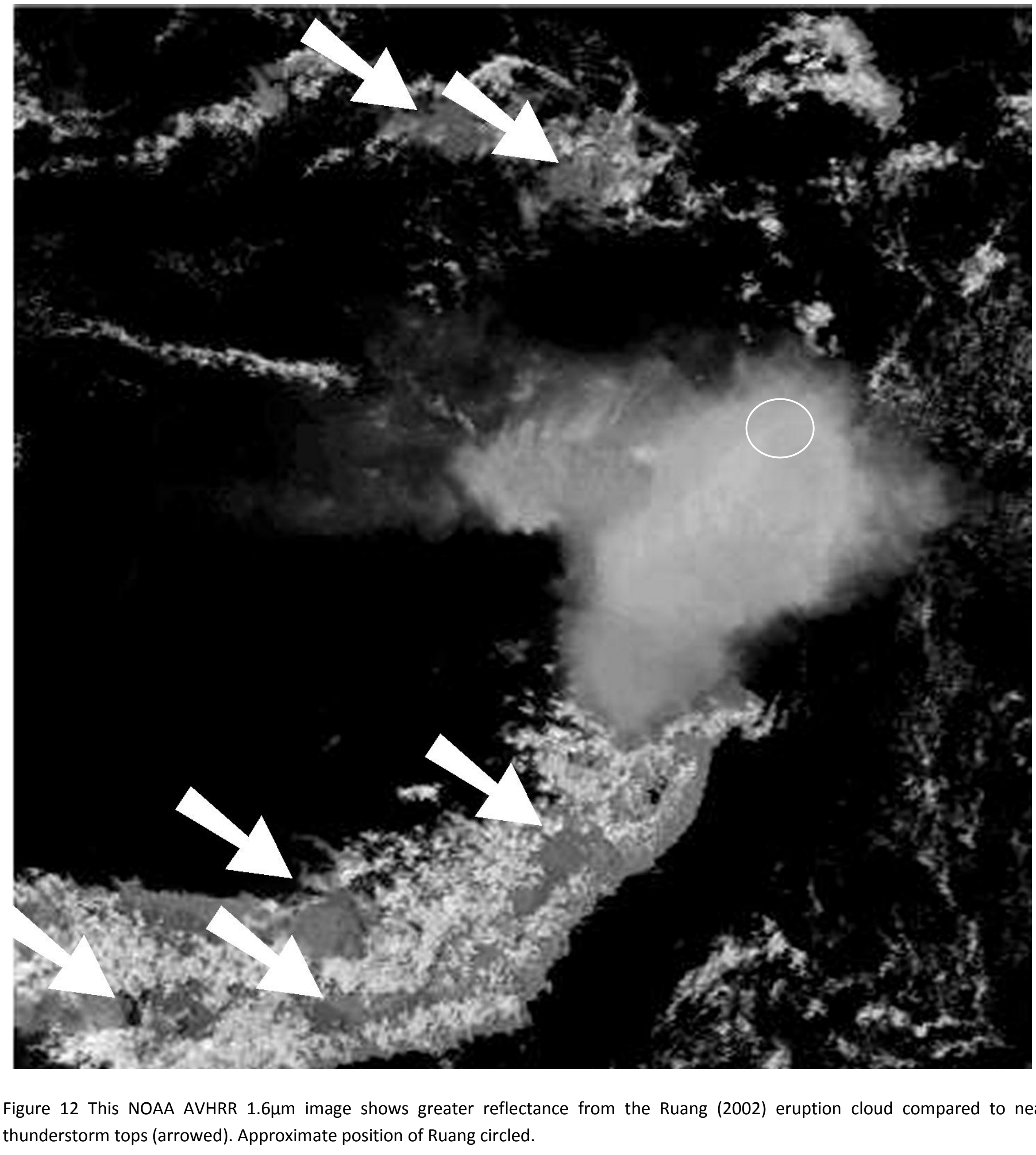


Figure 12 This NOAA AVHRR 1.6μm image shows greater reflectance from the Ruang (2002) eruption cloud compared to nearby thunderstorm tops (arrowed). Approximate position of Ruang circled.

Mid-wave infrared channels such as 3.9μm sense both solar reflection and thermal emission, meaning they should be interpreted differently during the day compared to at night. During the night (when there is no solar reflection component), mid-wave IR behaves similarly to the thermal IR (11 or 12μm) bands, but is useful for detecting thermal anomaly areas, such as those caused by volcanic activity (see 1.7.8 - Hot Spots).

During the day, the solar reflection component becomes dominant. However, a strong reflective signal from an ash cloud is interpreted in the mid-wave infrared band as a warmer cloud, resulting in a darker looking cloud than a thermal infrared image would produce (Figure 13).

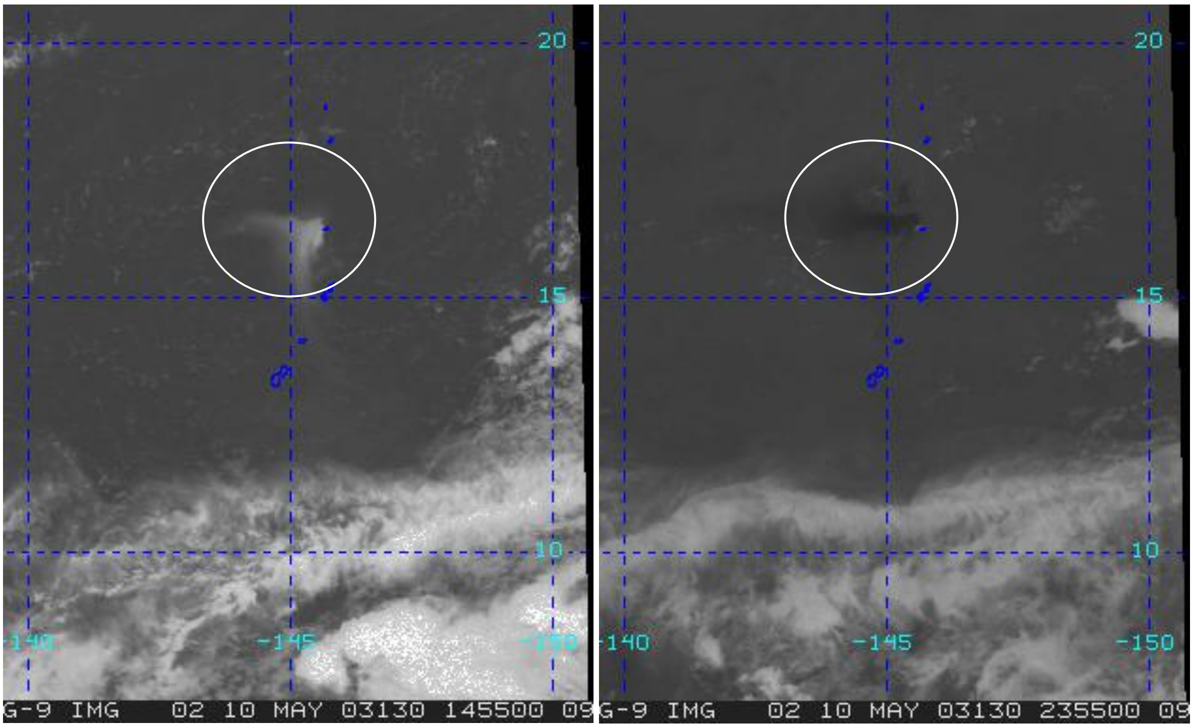


Figure 13 This eruption of Anatahan on 10 May 2003 shows up on GOES-9 3.9µm imagery as bright during the night (left), and dark during the day (right). See circled regions.

1.7.8 Hot Spots

Hot spots are generally detected in the 3.9µm wavelength band (for both geostationary and polar orbiting satellite instruments). Hot spots do not directly imply the presence of ash, but may signify activity at a volcano that could be associated with ash emissions. Potential causes of hot spots at a volcano include lava at the surface and high temperature emissions (including pyroclastic flows or fires) which may or may not be associated with volcanic activity (Figure 14).

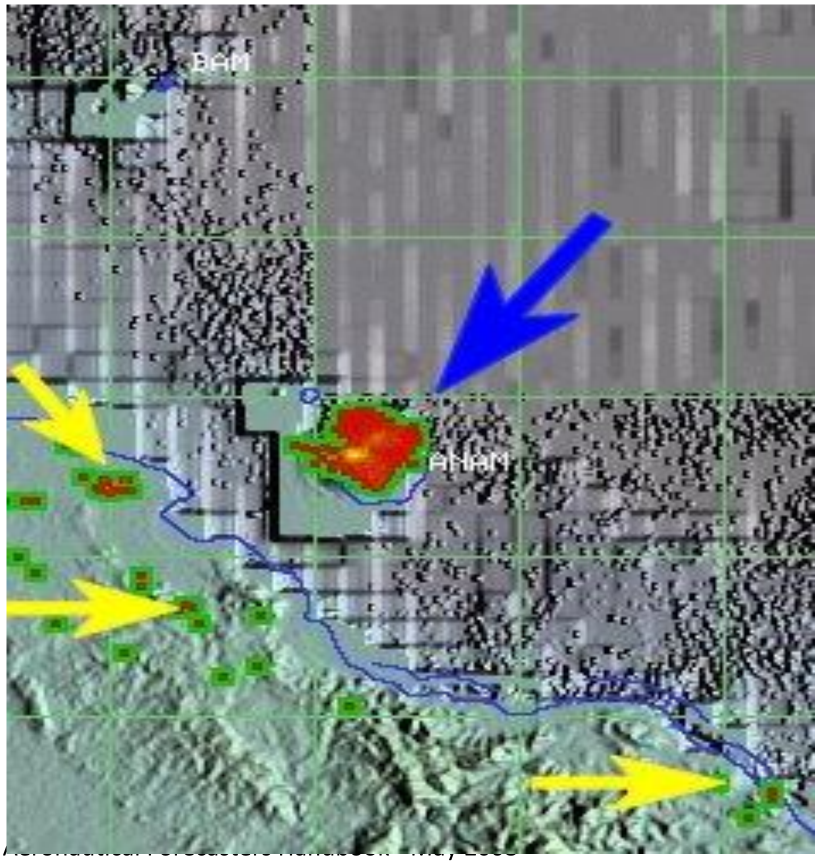


Figure 14 Hotspots accumulated over a year (7 March 2004 – 7 March 2005) in northern Papua New Guinea, produced by fires (yellow arrows), and pyroclastic flows from the eruption of Manam volcano (blue arrow).

1.7.9 SO_2 AND AEROSOLS

Sulphur dioxide (SO_2) is often released in large quantities during a volcanic eruption. While SO_2-rich clouds and ash-rich clouds are not always co-located, there is no evidence of complete separation of gas and ash in a volcanic cloud, so SO_2 associated with a volcanic eruption may be used as a proxy for the presence of ash. There are two basic satellite methods of detecting SO_2 in the atmosphere, using infrared (IR) (Figure 15) and ultraviolet (UV) (Figure 16). Volcanic ash in the atmosphere is an aerosol, and so may also be detectable in aerosol imagery. Currently OMI SO_2 images are available via the web in near-real time. However, the images from a polar orbiting satellite, are only available once per day.

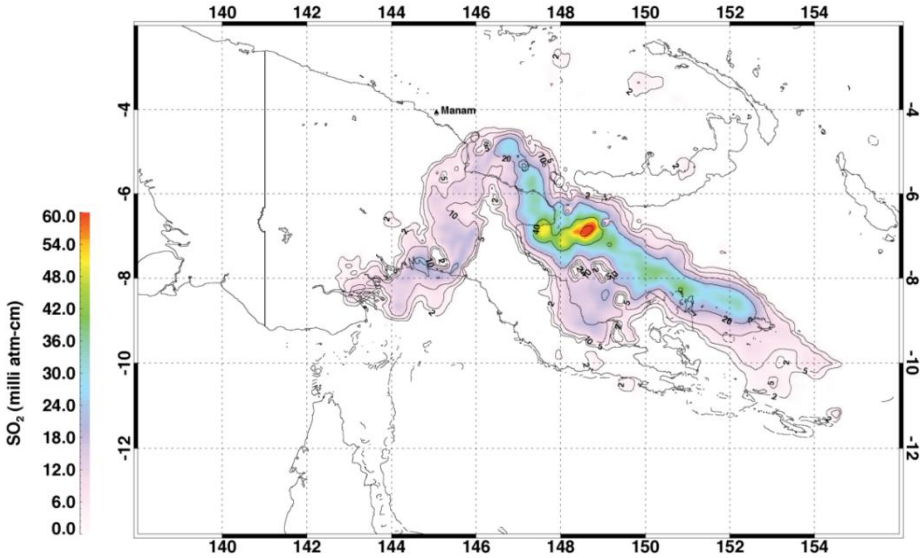


Figure 15 AIRS Derived SO_2 distribution after 12 hours of high level eruption of Manam on 23/24 November 2004 (see figures 4 and 7 regarding this eruption)[14]. Areas of SO_2 also potentially contain ash.

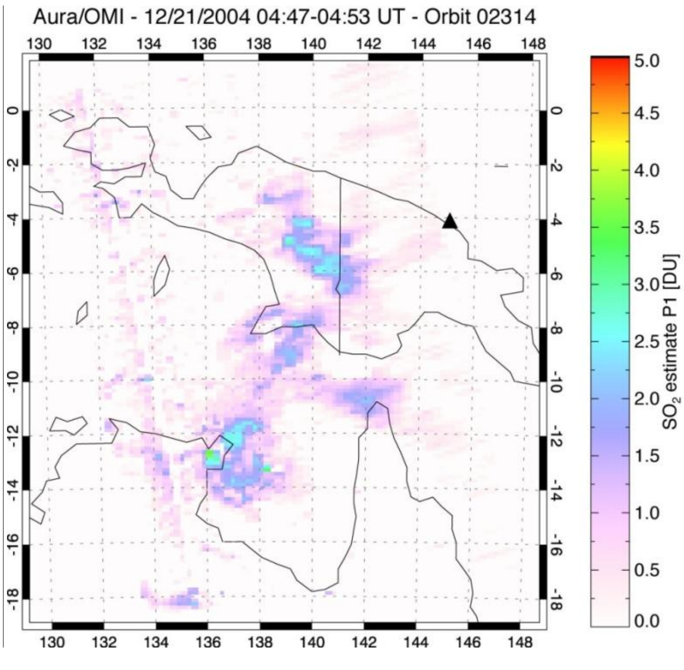


Figure 16 OMI Derived SO_2 distribution from Manam eruptions of 20 December 2004, showing drift of cloud (thought to be at cruising levels) over Australia. Courtesy Simon Carn (Joint Center for Earth Systems Technology). Volcanic Ash Height Estimates

1.7.10 Volcanic Ash Height Estimates

It is important to determine a reasonable estimate of the height of any ash because it:

- is important for aircraft operations; and
- will greatly influence the forecast of ash dispersion.

Whenever possible, ash plume height estimates from aircraft and the ground should be double-checked using satellite imagery, due to the limitations of these observations as discussed previously.

There are various ways to estimate volcanic cloud height from satellite imagery[22,23], three of which are common in operations, as described below. Temperature and wind should preferably be used in combination, supplemented by shadow height estimates where available.

If no information is available but a large eruption has been reported, use your meteorological knowledge. In a convectively unstable situation, a large eruption cloud should get at least as high as a thunderstorm would in the same environment[24]. In a situation with strong tropospheric inversions, you should anticipate the cloud spreading out at that inversion as well as at the tropopause (Figure 21).

1.7.11 Brightness Temperature

If the cloud is opaque, the coldest brightness temperature measured from an infrared satellite image of an ash cloud can be compared to a nearby temperature sounding or model data to get a height estimate. Ash cools rapidly to the temperature of the surrounding air, so this method can produce reasonable results.

<u>CAUTION</u>: If the ash cloud has penetrated into the stratosphere, the brightness temperature might correspond to a level in the atmosphere both below the tropopause as well as above the tropopause. This needs to be kept in mind to avoid under-estimating the ash height. If the ash cloud is more than an hour or two old, the cloud will likely be non-opaque and the height estimated using this method should be treated as a minimum height.

An example of a fresh eruption cloud with a significant stratospheric overshoot is shown in Figure 17.

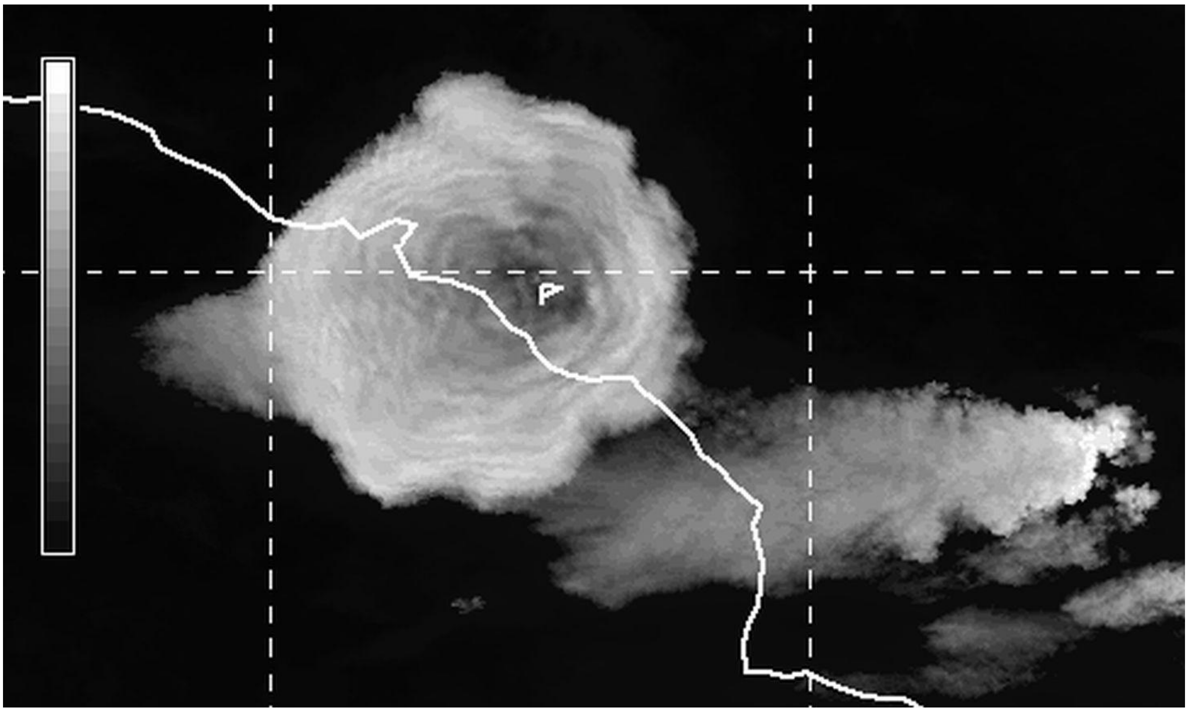


Figure 17 Stratospheric overshoot. Contrast stretched image of umbrella cloud from eruption of Manam, Papua New Guinea. Aqua/MODIS 11 µm image at nominal 1 km resolution, 1535 UTC 27 January 2005[14]. In the umbrella cloud, we see the top of a stratospheric eruption column at an altitude of 23-24 km in the centre (dark), warmed to -63°C. The rings around the centre are gravity waves. The cloud slopes downwards and warms towards the umbrella cloud edge, which is at an altitude of ~19 km and a temperature of -82°C, still a few degrees above the tropopause temperature of -85°C. 19-22°C overshoot into stratosphere. A small 'tongue' to the west of the umbrella cloud is blow-off from the upper-tropospheric part of the eruption column. To the southeast are thunderstorm tops showing a bright (cold) near-tropopause anvil dissipating (and apparently thinning) towards the centre of the image. The features described come from comparison of different satellite techniques with each other and with lidar observations[14].

1.7.11.1 Comparison of Ash Movement with Upper Winds

Ash heights can be estimated by comparing the direction of movement of the ash cloud with the upper winds in the area (Figures 18, 19 and 20). The winds may give you a range of heights that the ash is contained within, or an upper-estimate of the height of the ash.

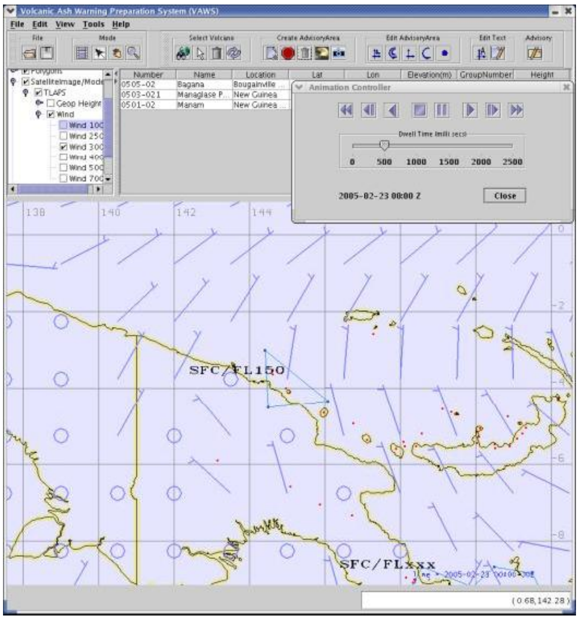


Figure 18 Upper wind display in VAWs

Dispersion and trajectory model output can be compared with the ash movement and distribution to assist with height estimates. These models can be run with different starting heights to see which best corresponds to the observed ash cloud.

Be aware that when comparing low-level eruptions (below FL150) that the winds may be influenced by the mountainous terrain characteristic of volcanic regions.

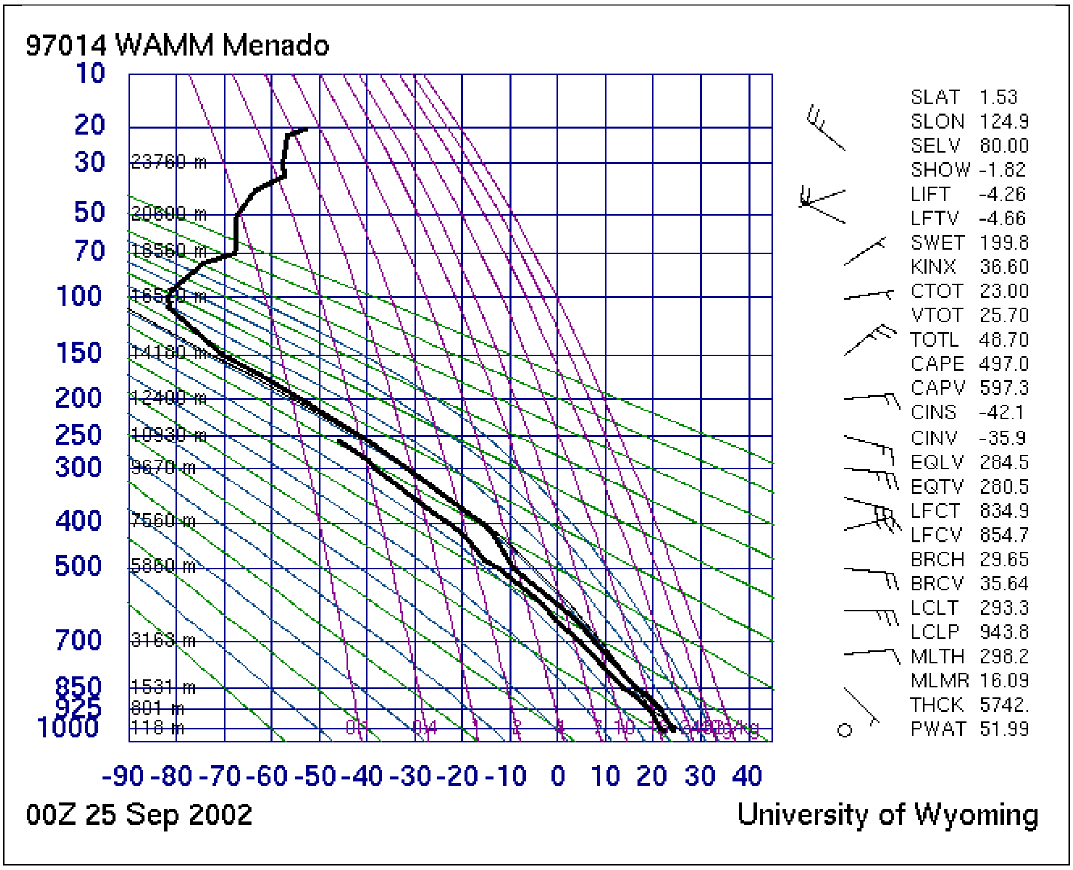


Figure 19 Sounding from Menado, Sulawesi, on the morning of the eruption of Ruang (see Fig. 12, 20). This is a summary view to 10 hPa, but the basic features (mid-tropospheric easterlies, a thin layer of northeasterlies near the tropopause, and westerlies further aloft) are evident.

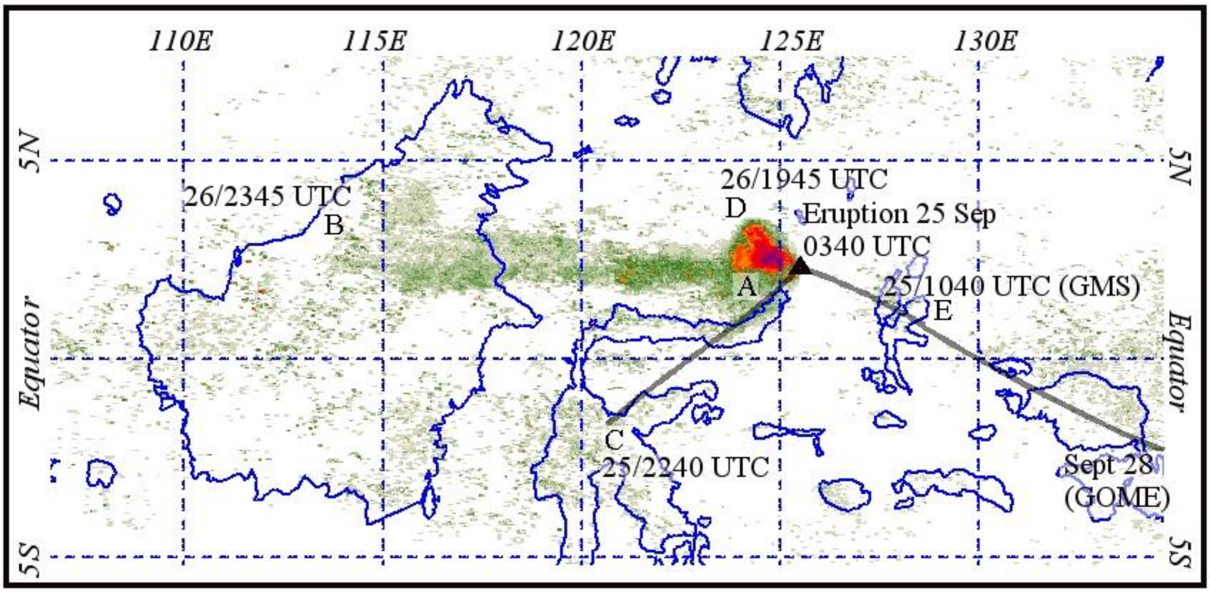


Figure 20 Cloud separation in a sheared environment: summary image of cloud spread of 2002 Ruang eruption, based on combination of temperature, wind, and shadow height estimates. This is a temporal composite of GMS-VISSR infrared ΔT images from 22:40 UTC 24 September 2002 to 1945 UTC 26 September 2002 (created in McIDAS). The colours shown are minimum ΔT (maximum ash signal strength). Some parts of the cloud were too ice-rich / ash-poor to give a signal. Labelled features are: A, a plume 3-5 km high, drifting westwards at 5-8 m/s, B, a 5-14 km layer, drifting steadily west at 16 m/s, C, a 14-16 km layer, moving southwest at 16 m/s, D, a partially stratospheric layer between 16-18 km, drifting westwards at 2-3 m/s, and E a stratospheric SO_2-rich cloud moving eastwards at about 16 m/s, at 18-22 km in height.

1.7.11.2 Comparison of Shadow Widths for Height Estimates

If the ash cloud is casting a shadow, a rough height estimate may be obtained by comparing the width of the shadow with the width of a shadow cast by a nearby meteorological cloud at the same longitude (Figure 21). The height of the meteorological cloud is taken from its brightness temperature. The ratio of the ash cloud height to the width of its shadow should roughly equal the ratio of the meteorological cloud height to the width of its shadow. A height estimated in this way is most likely to provide a lower bound, as the height of the portion of the cloud casting the shadow may not be the highest part of the cloud.

Be aware that when comparing low-level eruptions (below FL150) that the winds may be influenced by the mountainous terrain characteristic of volcanic regions, and also be aware that model output in the tropics can be very poor due to the poor observational network across the region. For example, the SW drift of SO_2 shown in Figure 16 was not matchable to any model analysis or dispersion trajectory. Where observed soundings and winds are available, use them in combination. For example, the vertical temperature and wind profile shown in Figure 19 (taken just south of the eruption of Ruang in 2002, as the eruption began), helped provide a very detailed analysis of the cloud heights and directions, through careful, combined wind and temperature analysis.

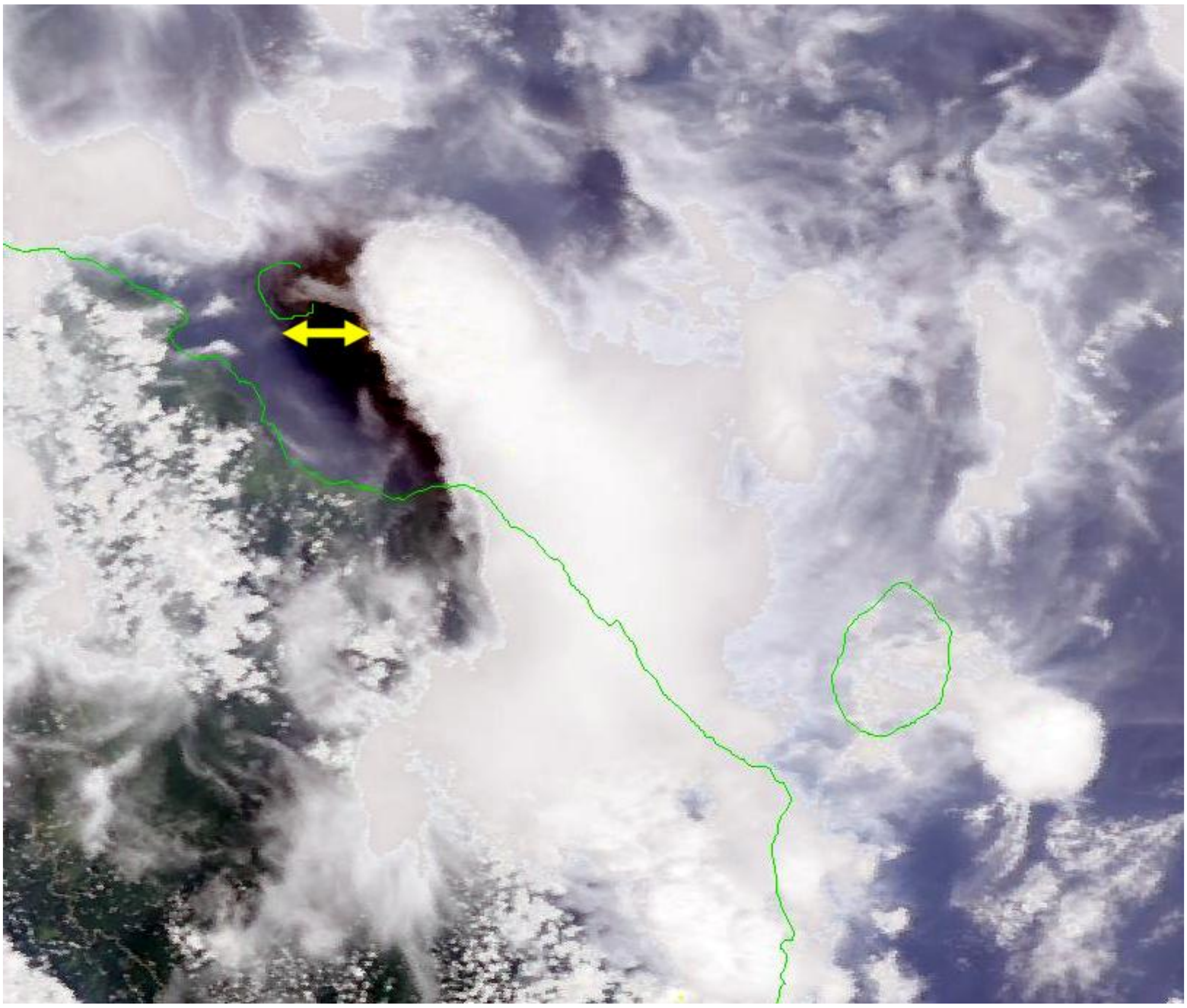


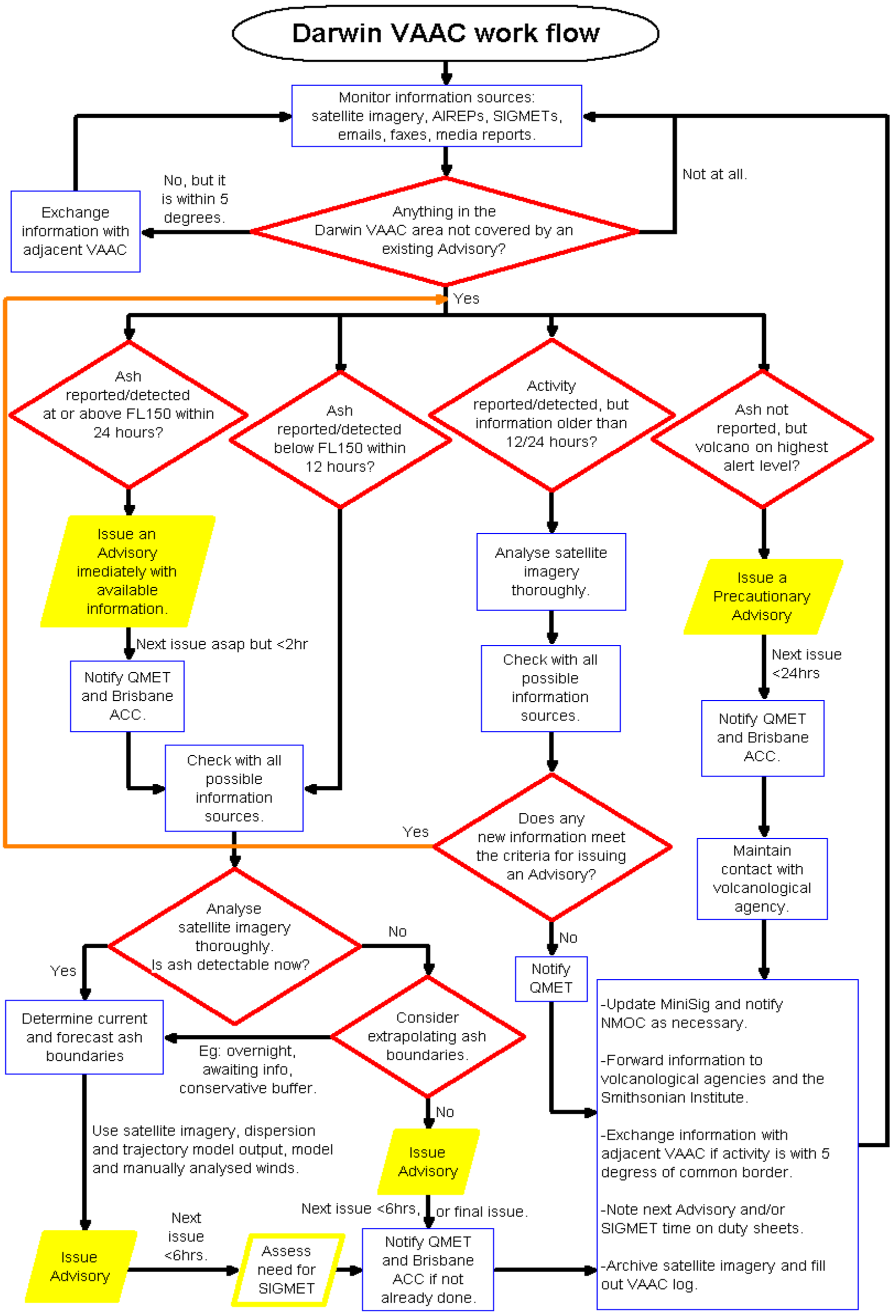
Figure 21 Cloud shadow from spreading at the tropopause: An extraordinary Terra/MODIS true colour image of a Manam eruption, showing the side of the eruption column and a very well defined 15 km shadow (in yellow). The image is taken at a ~45° angle to the vertical, on 0110 UTC 31 October 2004. Infrared temperatures, 'CO_2 slicing' height estimation[14], and comparison to shadows from thunderstorms in the area (not shown) gives a height estimate of 15-17 km (most likely around 16.5 km).

1.8 Forecasting

The Darwin VAAC is responsible for the issuance of Volcanic Ash Advisories (VAA) within its area of responsibility and for issuing SIGMETs for the Brisbane and Melbourne Flight Information Regions (FIR).

1.8.1 Priority

Volcanic Ash Advisories are high priority aviation weather products (refer to the Aeronautical Services Handbook). The variable size of volcanic eruptions means that some escretion is allowed for reprioritisation of smaller events, where it is definitely established that the eruption is minor.



1.8.2 Forecasting the Movement of Volcanic Ash Clouds

An important function of the VAAC is to produce volcanic ash forecasts and to provide advisory information to MWOs for the SIGMETs they issue for volcanic ash.

The movement, spread and dispersion of volcanic ash clouds depends upon:

- the nature of the eruption;
- the meteorological condition of the atmosphere;
- the strength of the eruption;
- the altitude reached by the ash cloud (of primary importance);
- ash concentration and its size distribution of particles;
- atmospheric stability;
- wind shear; and
- precipitation (as ash particles can be "rained out").

Numerical atmospheric transport prediction models are used to provide an outlook on how airborne ash would move and spread in the prevailing winds. These models depend on initial input of eruption data (e.g. location and time of eruption, height of eruption column, etc.), analysed and forecast meteorological fields and, depending on the model, various assumptions of parameters such as ash concentration. The typical output of the models provide two- or three-dimensional information about the volcanic ash cloud, at specific times in the future.

Dispersion and trajectory model output is utilised by the Darwin VAAC to assist with the preparation of forecast ash boundaries. The models should be initiated as soon as possible after ash is detected, or an eruption reported, to allow timely preparation of forecast positions. The model output may also assist with the detection of ash on satellite imagery, as it can give an idea of where the ash may be expected to be on the image. Satellite data helps to "ground truth" the model output data.

1.8.3 Dispersion and Trajectory Models

The dispersion and trajectory models available to the Darwin VAAC, include:

- HYSPLIT (Australian version), which is the primary model used (Figure 22)[25]; and
- The University of Alaska's 'Puff' volcanic ash tracking model (Figure 23)[3], which provides regular predictions for several volcanoes throughout the world and can also be initiated for other volcanoes with parameters specified by the user.

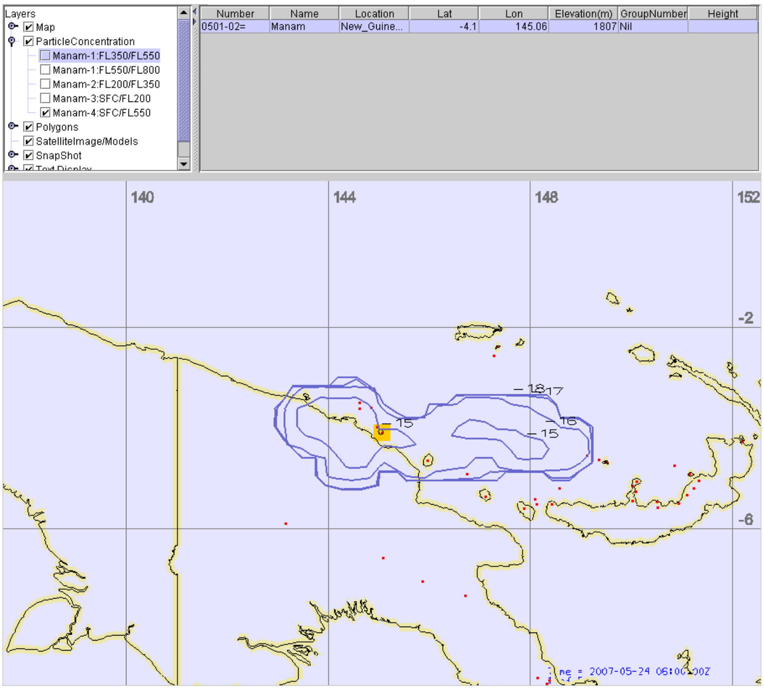


Figure 22 HYSPLIT dispersion model output for an eruption at Manam, displayed using VAWS (see 1.8.5). The blue contours represent different concentrations of ash.

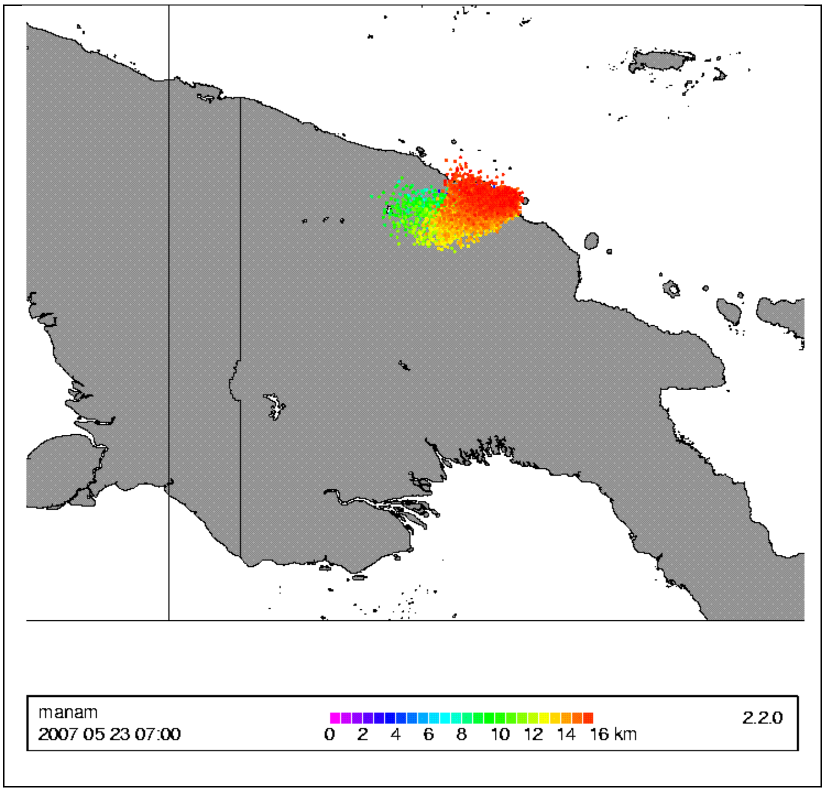


Figure 23 Puff model output for an eruption at Manam showing ash dispersion at different heights.

1.8.4 Limitations of Dispersion and Trajectory Models

It is important to understand the limitations of the dispersion and trajectory model output when interpreting results. The output should be compared to the ash distribution on satellite imagery, and the accuracy of the winds used in the models needs to be verified against manually analysed winds.

Some of the limitations of the dispersion/trajectory models are:

- You cannot specify an eruption start-time prior to the analysis time of the current wind model run with HYSPLIT;
- You can only specify a point location rather than an ash boundary in the initial conditions for running the models;
- The models use a number of simplifying assumptions. For example, HYSPLIT assumes that a nominal concentration of ash is released from a uniform column, whereas in reality most ash will be detrained from an eruption cloud at preferred levels such as inversions (e.g. the tropopause for a large eruption); and
- Where an eruption has penetrated well into the stratosphere, the movement of the stratospheric material is often not well described by the models.

1.8.5 Volcanic Ash Warning Preparation System (VAWS)

The Volcanic Ash Warning Preparation System (VAWS) has been developed to streamline the preparation of warnings for volcanic ash[5]. The application is Java-based and enables preparation of the Volcanic Ash Advisory (VAA) using a combination of graphical and text interfaces.

The main steps in the preparation of a VAA are:

- Select the volcano and add it to the volcano table;
- Draw polygons that define the analysed and forecast threat areas (Figure 24);
- Generate the Advisory; and
- Submit the Advisory for transmission.

1. Details on use of VAWS can be found in the VAWS User Guide at:
   http://gale.ho.bom.gov.au/bm/internal/wefor/projects/aviation/VAWSdocs/VAWSHome.html

A useful property of VAWS is the ability to display and loop satellite imagery (Figure 25). This makes the construction of ash boundary polygons easy and much more efficient. In a similar manner, the ability of VAWS to display dispersion model forecasts assists with forecast ash boundaries.

Figure 24 VAWS interface. The polygon over Sumatra defines the forecast or analysed ash boundary (to FL400)

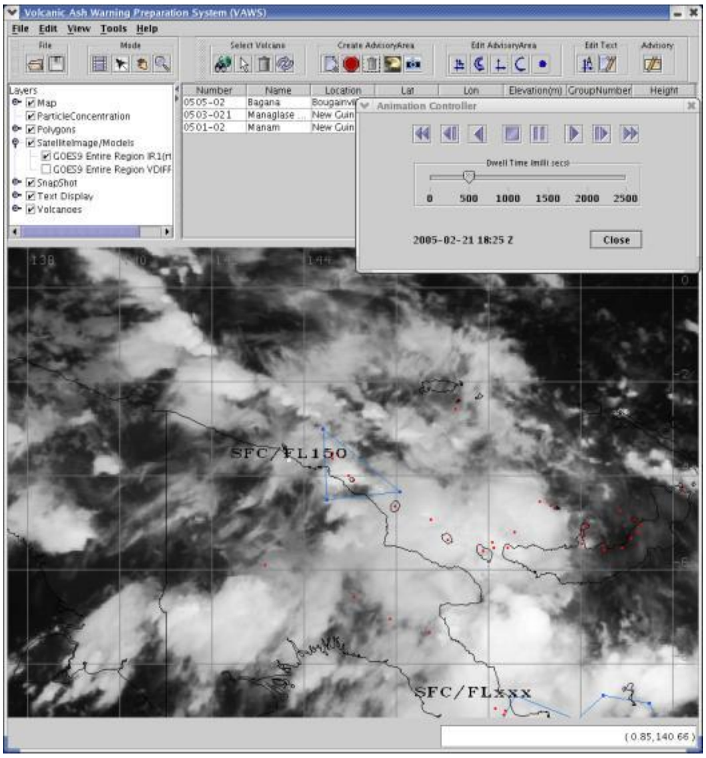


Figure 25 Display of satellite imagery within VAWS. The displayed polygon of volcanic eruption from Manam was defined using imagery.

1.9 VOLCANIC ASH PRODUCTS

The following aviation products can include volcanic ash information:

- Volcanic Ash Advisory (VAA);
- SIGMET;
- Significant Weather Charts (SIGWX);
- Meteorological Reports (METAR/SPECI);
- Volcanic Activity Report;
- Special Air Report;
- Aerodrome Forecast (TAF);
- Trend Type Forecast (TTF);
- Area Forecast; and
- Aerodrome Warning.

Refer to the Aeronautical Services Handbook (ASH) for specific formats and examples. In addition the Darwin VAAC produces a Volcanic Activity Summary for volcanoes in the region, updated daily.

1.10 LIAISON

The Darwin VAAC liaises with other agencies such as vulcanological authorities, airlines, other VAACs and meteorological offices. Darwin VAAC local directives should be consulted for exact procedures and contact details.

1.10.1 AUSTRALIA

The Darwin VAAC has close contact with the air traffic services (particularly Airservices Australia) and airline Flight Dispatch Centres (particularly QANTAS). The aviation industry takes the threat of volcanic ash very seriously, and takes a very conservative approach to air traffic management and flight planning.

1.10.2 INDONESIA

The Centre of Volcanology and Geological Hazard Mitigation (CVGHM) was formerly known as the Volcanological Survey of Indonesia (VSI), and still often goes by this name. The Information Officer at CVGHM may email the Darwin VAAC when there is a significant eruption, and information can also be accessed via their website[10].

1.10.3 PHILIPPINES

The Philippine Institute of Volcanology and Seismology (PHIVOLCS) has a radio room and operations room that may be contacted 24 hours a day[11].

1.10.4 PAPUA NEW GUINEA

Rabaul Volcanological Observatory (RVO) is responsible for monitoring the 14 active and 23 dormant volcanoes throughout Papua New Guinea. RVO is not staffed 24 hours a day, but the Assistant Director at RVO may be contacted out of hours during an emergency. RVO produces activity reports on individual volcanoes, which are emailed to the Darwin VAAC. These reports are received intermittently during periods of low activity, but increase in frequency when the level of activity of a volcano increases.

1.10.5 SOLOMON ISLANDS

There is a seismological department on the Solomon Islands, however there is very little contact with them.

1.10.6 OTHER AGENCIES

The Smithsonian Institute operates the Global Volcanism Programme, which aims to increase the understanding of volcanoes through recording information on volcanic activity. The Smithsonian Institute maintains a database on all of the volcanoes throughout the world and regularly updates the online version of the book *Volcanoes of the World*[12]. The Smithsonian Institute, in conjunction with the U. S. Geological Survey[9], produces a weekly and monthly summary of global volcanic activity.

Other VAACs are contacted whenever a volcanic ash cloud is expected to move from the Darwin VAAC region into theirs or visa versa.

1.11 Glossary of Volcanological Terms

Channel differencing: see *Split Window*.

Co-ignimbrite plume: The volcanic ash plume formed by the convective rise of ash from a *pyroclastic flow*.

Nuee ardente: *Pyroclastic flow*.

Phreatic eruption: Occur when rising magma makes contact with ground or surface water. The extreme temperature of the magma (anywhere from 600 °C to 1,170 °C (1110–2140 °F)) causes near-instantaneous evaporation to steam resulting in an explosion of steam, water, ash, rock, and volcanic bombs.

Plinian eruption: Large explosive eruptions that form enormous dark columns of volcanic material and magmatic gases high into the stratosphere. These are of high risk to aviation due to the height of the eruption column.

Pyroclastic Flow: A ground-hugging avalanche of hot ash, pumice, rock fragments, and volcanic gas that rushes down the side of a volcano as fast as 100 km/hour or more. As the flow races down the volcano, it entrains and heats atmospheric air. The high temperature causes the less dense particles in the upper part of the flow to become buoyant and rise high into the atmosphere. The resultant ash plume is known as a *co-ignimbrite plume.*

Split Window: A technique used to detect volcanic ash that utilises the different absorption characteristics of volcanic ash and water vapour clouds in the 11 and 12µm infrared channels.

Strombolian eruption: Characterised by the intermittent explosion or fountaining of basaltic lava from a single vent or crater. Each episode is caused by the release of volcanic gases, and they typically occur every few minutes or so, sometimes rhythmically and sometimes irregularly. The lava fragments generally consist of partially molten volcanic bombs that become rounded as they fly through the air.

Vulcanian eruption: A moderate-sized explosive eruption that ejects a large proportion of volcanic ash and large lava fragments (‘bombs’ and ‘blocks’). The explosive behaviour of these eruptions is caused by magma with high viscosity that makes it difficult for the dissolved volcanic gases to escape except under extreme pressure.

1.12 ABBREVIATIONS

AIREP	A report from an aircraft in flight
AIRS	Atmospheric Infrared Sounder
AQUA MODIS	Water – Moderate Resolution Imaging Spectroradiometer
ASH	Aeronautical Services Handbook
AVHRR	Advanced Very High Resolution Radiometer
CVGHM	Centre of Volcanology and Geological Hazard Mitigation
Cb	Cumulonimbus cloud
CO_2	Carbon Dioxide
FIR	Flight Information Region
FL	Flight level
ft	Feet
GASP	Global Analysis and Prediction
GMS	Geostationary Meteorological Satellite
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectories
IAVW	International Airways Volcano Watch
ICAO	International Civil Aviation Organisation
IR	Infrared
McIDAS	Man computer Interactive Data Access System
METAR	Routine Aviation Weather Report
MODIS	Moderate Resolution Imaging Spectroradiometer
MTSAT	Multi-functional Transport Satellite
MWO	Meteorological Watch Office
NOAA-15	National Oceanic and Atmospheric Association Satellite 15
NOAA-16	National Oceanic and Atmospheric Association Satellite 16
NZ	New Zealand
OMI	Ozone Monitoring Instrument
PHIVOLCS	Philippine Institute of Volcanology and Seismology
PUFF	*PUFF is a volcanic ash tracking model*
RVO	Rabaul Volcanological Observatory
SIGMET	Significant Meteorological Information
SIGWX	Significant Weather
SO2	Sulphur Dioxide
SPECI	Special Aviation Weather Report
SPOT	Satellite Pour l''Observation de la Terre
TAF	Aerodrome Forecast
TERRA MODIS	Earth- Moderate Resolution Imaging Spectroradiometer
TTF	Trend Type Forecast
TXLAPS	Tropical eXtended Limited Area Prediction System
US	United States (of America)
UTC	Coordinated Universal Time
UV	Ultraviolet
VAA	Volcanic Ash Advisory
VAAC	Volcanic Ash Advisory Centre
VAWS	Volcanic Ash Warning Preparation System
VEI	Volcanic Explosivity Index
VISSR	Visible Infrared Spin-Scan Radiometer
VSI	Volcanological Survey of Indonesia
µm	Microns

1.13 References and On-Line Resources

2. Darwin VAAC external web http://www.bom.gov.au/info/vaac/

3. Darwin VAAC operational web http://www.nt.bom.gov.au/ntregion/operational/volcanic.shtml

4. Puff Volcanic Ash Tracking Model http://puff.images.alaska.edu/world_volcs.shtml

5. http://puff.images.alaska.edu/cgi-bin/login_agu.pl

6. VAWS Home page http://gale.ho.bom.gov.au/bm/internal/wefor/projects/aviation/VAWSdocs/VAWSHome.html

7. ICAO Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds (Doc 9691)

8. Darwin VAAC Volcanic Ash Directive http://www.nt.bom.gov.au/ntregion/volcano/training/Directive2007/directive.htm

9. ICAO Handbook on the International Airways Volcano Watch (IAVW) Operational Procedures and Contact List — (Doc 9766), Second Edition 2004

10. United States Geological Survey: http://volcanoes.usgs.gov/

11. Centre of Volcanology and Geological Hazard Mitigation http://portal.vsi.esdm.go.id/joomla/

12. Philippine Institute of Volcanology and Seismology (PHIVOLCS) http://www.phivolcs.dost.gov.ph/

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17. M. G. Dunn and D. P. Wade, Influence of Volcanic Ash Clouds on Gas Turbine Engines, In T. J. Casadevall (ed.), *First International Symposium on Volcanic Ash and Aviation Safety*, vol. 2047, (1994), pp. 107-118.

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19. A. J. Prata, "Infrared radiative transfer calculations for volcanic ash clouds" (1989) 16 Geophysical Research Letters 1293-1296.

20. A. Tupper, S. Carn, J. Davey, Y. Kamada, R. Potts, F. Prata and M. Tokuno, "An evaluation of volcanic cloud detection techniques during recent significant eruptions in the western 'Ring of Fire'" (2004) 91 Remote Sensing of Environment 27-46, doi:10.1016/j.rse.2004.02.004.

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22. R. J. Potts and E. E. Ebert, On the detection of volcanic ash in NOAA AVHRR infrared satellite imagery, *8th Australasian Remote Sensing Conference, 25-29 March 1996*, (Canberra, Australia 1996).

23. C. Oppenheimer, "Volcanological applications of meteorological satellites" (1998) 19 International Journal of Remote Sensing 2829 - 2864.

24. A. J. Prata and I. F. Grant, "Retrieval of microphysical and morphological properties of volcanic ash plumes from satellite data: Application to Mt Ruapehu, New Zealand." (2001) 127 Quarterly Journal Royal Meteorological Society 2153-2180.

25. A. Tupper, C. Textor, M. Herzog and H. Graf, "Tall clouds from small eruptions: modelling the sensitivity of eruption height and fine ash fallout to tropospheric instability." (2008) Natural Hazards In review.

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