

## **Observations of volcanic cloud heights and ash-atmosphere interactions**

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### **Abstract**

*We discuss two related problems of critical importance to the International Airways Volcano Watch: the accuracy of cloud height observations, and the variation of volcanic cloud height with differing atmospheric conditions. Both affect the accuracy of volcanic ash dispersion forecasts. Ground, air, and, to a lesser extent, satellite based cloud height observations are subject to a high degree of error which creates a great deal of uncertainty and contributes to substantial over/under warning on occasion, and increased costs and risks to the aviation industry. Reporting can be improved and increased with appropriate education and by providing suitable techniques to observers. The effect of atmospheric conditions on volcanic cloud height can be extreme, and we show examples from Sakurajima (Japan), and Pinatubo (Philippines) of atmospheric convection that leads to radically higher ash transport than would otherwise be the case. To account for these effects, meteorological forecasting techniques should be used to predict the likely altitude of ash in strongly convective situations, and warning strategies adjusted to suit.*

### **Introduction**

One of the most difficult problems associated with International Airways Volcano Watch (IAVW) operations is determining the height of the volcanic ash layers. Even slight inaccuracies in height determination can cause major errors in eighteen-hour dispersion forecasts, causing over/under warning and the associated hazards and costs.

This paper discusses two related fields of ash height determination. Firstly, we briefly describe the accuracy of ground and air based observations, when compared to satellite observations. We then give a more extensive analysis of the observed variation of volcanic cloud heights with atmospheric conditions.

### **Satellite, air and ground-based observations**

Satellite height estimation techniques are well known (Oppenheimer, 1998; Prata and Grant, 2001). For operational use, the most common method of height estimation is correlation of brightness temperatures with atmospheric profiles (Sawada, 1987, 2002), preferably supplemented with wind correlations (Holasek *et al.*, 1996) to overcome underestimates caused by non-opaque clouds, overestimates caused by clouds having emissivity of less than unity, and height ambiguities caused by atmospheric inversions. In many cases, wind correlations alone are sufficient to give a reasonable estimate of cloud height. We are therefore able to achieve a reasonable level of accuracy using satellite techniques. However, the temporal resolution of most satellites means that we will usually be making our first dispersion forecasts for any major event using height information from ground or air based observers, assuming the eruption is observed and reported promptly. For eruptions obscured by overlying cloud or too small to be resolved by satellite sensors, ground or air based reports are the only available estimates of volcanic cloud heights. Such observations are consequently critically important.

Sawada (Sawada, 2002), in an extensive review of eruptions in the field of view of GMS ('Himawari'), found a very poor correlation between satellite heights and other observations, with the majority of ground based observations underestimates. Since Sawada was generally using infrared brightness temperatures to estimate height, many of his own observations could be underestimates (for non-opaque or stratospheric clouds), so the problem could be even worse than his work suggests.

Figure 1 shows Sawada's comparison of ground and satellite based volcanic cloud height observations, based on his work from 1977 to 1996 using GMS brightness temperatures (Sawada, 2002). To this data we have added other cases (Tupper *et al.*, 2003a; Tupper and Kinoshita, 2003), where ground based observations are compared to all available data including wind drift correlations, pilot reports, and radar (for Miyakejima). The composite analysis shows a very substantial group of eruptions, labelled as group '5' by Sawada, which have reached altitudes of 10 – 20 km, but had their heights under-reported from the ground. Sawada partially attributed this to 'vapor clouds over eruption clouds induced by strong ascending currents with eruption-onset'. Tupper and

Kinoshita (2003), however, suggested that geometrical considerations were the main reason; it is virtually impossible to make a good ground-based estimate of cloud height for clouds above about 5km, from anywhere near the volcano during an eruption. In many cases, no report can be made at all; for example an eruption from Raung on 25 August 2002 to an altitude of 7-9 km was unobservable from the ground even in daylight (Tupper *et al.*, 2003b). Tupper & Kinoshita (2003) also suggested that any eruption for which a ground based report of eruption clouds above 5 km altitude is received should be assumed to have developed to tropopause height, until evidence is received to the contrary.

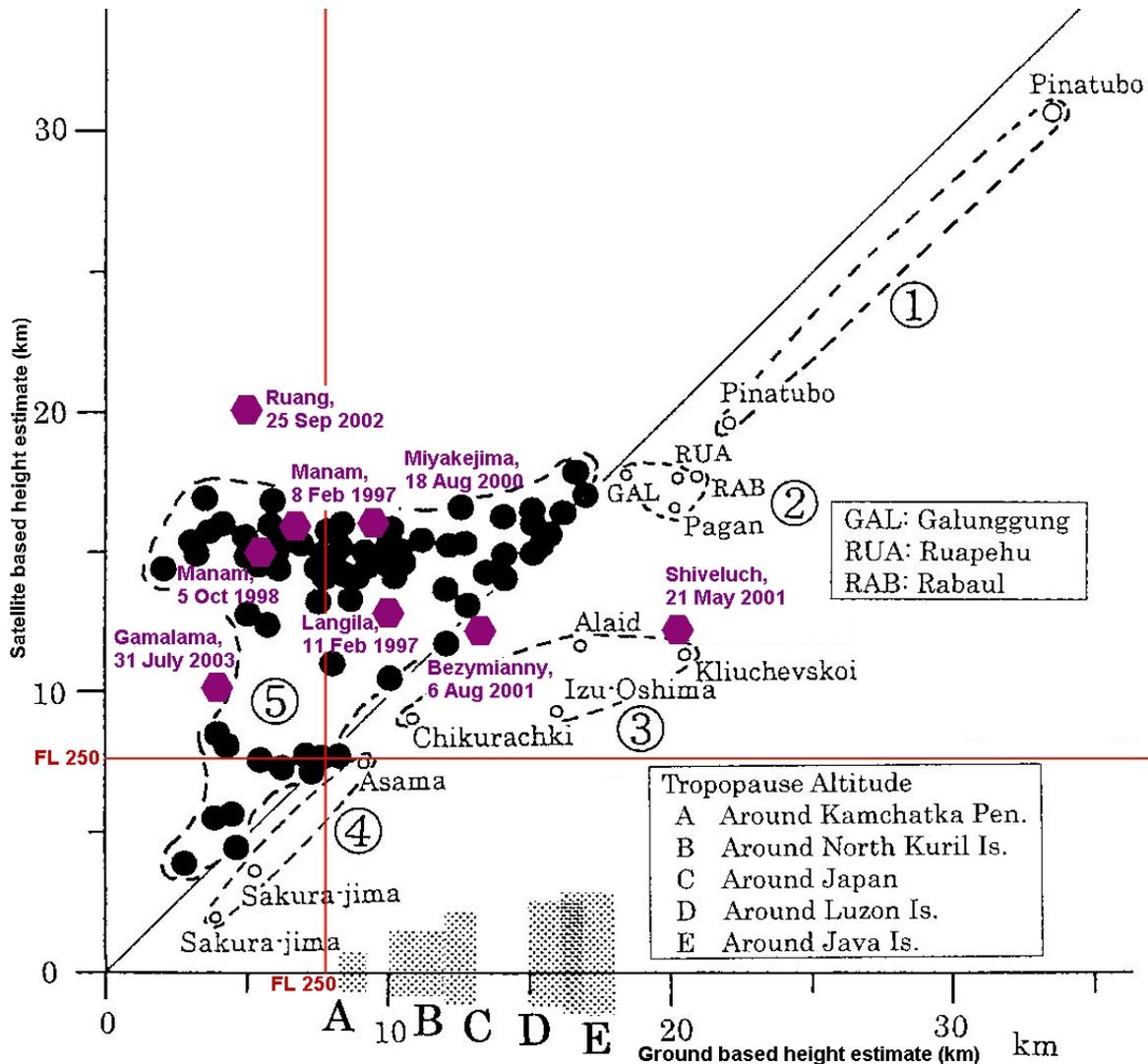


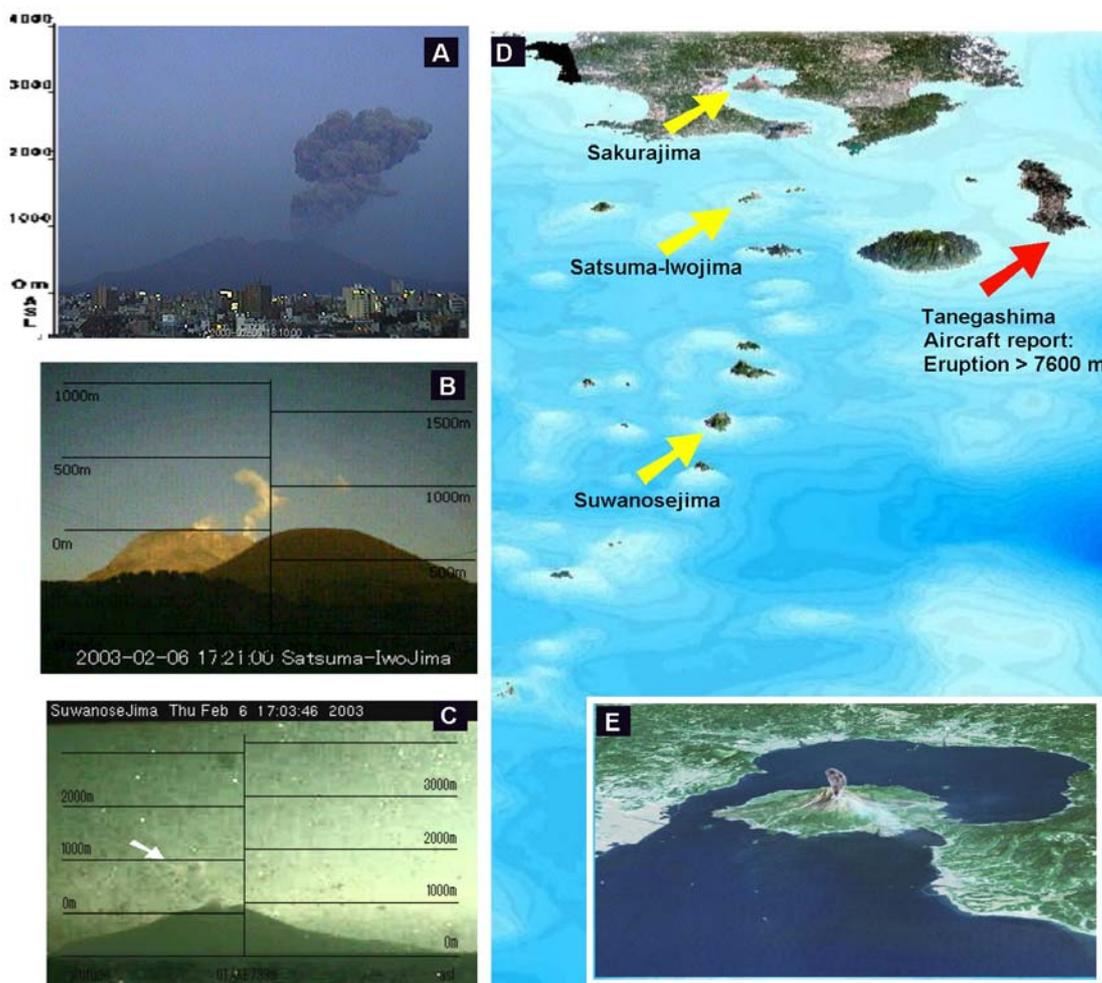
Figure 1 - Satellite / ground based height estimates, after Sawada (2002, black circles and text) and with additional observations (purple hexagons and text).

Many of the satellite underestimates in Fig. 1 are for high latitude volcanoes. It is worth noting that, for an eruption cloud ascending in a dry atmosphere, far less water is likely to be entrained into the eruption plume than in the tropics, resulting in less opaque clouds which are not amenable to brightness temperature based satellite analysis. When ancillary data such as stratospheric winds or radar observations are not present, then cloud heights can be difficult to ascertain.

Importantly, one of the critical pieces of information for ‘colour code’ assignment by volcanic observatories (ICAO, 2000) is the height of eruption, and particularly whether it is above or below FL250 (approx 7.6 km). We have marked FL250 on Fig. 1; if colour codes were to be based solely on ground observations, then 38% of these eruptions would be misclassified. For this reason, it is critical that satellite, radar, and other data are used in volcanic cloud height analysis; this may mean that Meteorological Watch Offices and/or Volcanic Ash Advisory Centres should be involved in the colour code assignment process for events in progress and post-analysis.

Pilot reports are also subject to considerable error (Tupper and Kinoshita, 2003), with the most frequent example being the over-reporting of the height of low level eruptions from aircraft at cruising levels. Often eruptions reported to FL250 or even higher are apparently much lower based on surface observations. Because these eruptions are usually below satellite resolution, such events are more difficult to verify.

Figure 2 shows a typical example of a report from a pilot unused to volcanic cloud, from a European airline over Japan.



**Figure 2 - Pilot report on February 6, 2003, relayed to Tokyo VAAC, of an eruption to 7 km from Tanegashima (not an active volcano). A-C: Kagoshima University camera images from Sakurajima, Satsuma-Iwojima and Suwanosejima respectively, D: location map, E: 3D SiPSE simulation of Sakurajima plume from SSW, altitude 13 km, horizontal distance 50 km from volcano.**

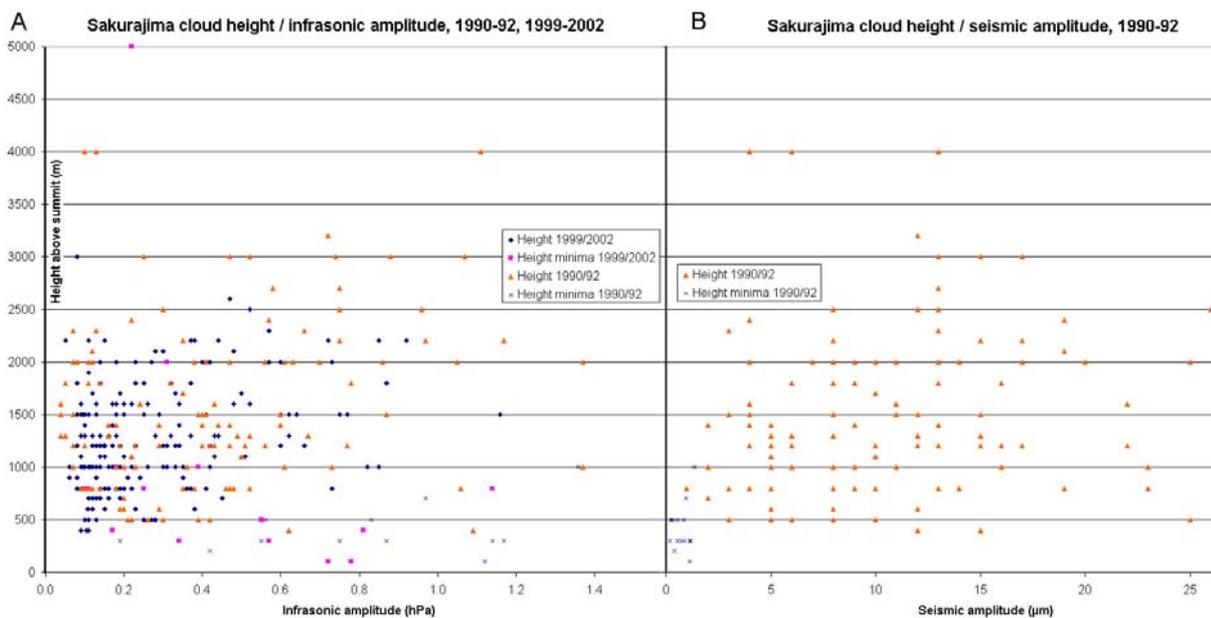
On this day, the pilot reported an eruption from Tanegashima at 09:30 UTC, with smoke and ash cloud reaching ‘at least FL250’ at 09:30 UTC. Tanegashima is not volcanically active, but lies to the east of the Ryukyu islands, where three volcanoes were emitting plumes on that afternoon. The most likely of these to have triggered the report was Sakurajima, which had an explosion at 09:04 UTC to an altitude estimated by Kagoshima Local Meteorological Observatory as 3.3 km. The eruption cloud dissipated relatively quickly (Kagoshima University archives, <http://volceye.edu.kagoshima-u.ac.jp/webcam/archive/030206/>) in clear skies, but pilot observation may have been slightly impeded by the approaching twilight. Fig. 2E shows a simulation of the appearance of the Sakurajima eruption from an altitude of 13 km, 50 km SSE of the volcano or halfway between Sakurajima and Tanegashima, using the ‘Satellite image Presentation System for Education’ (SiPSE), <http://sipse.edu.kagoshima-u.ac.jp/sipse-e/index.htm>, which can simulate the appearance of a topographic feature from any angle and has basic volcanic cloud representation capabilities. Using systems such as this, we can train pilots and volcanic observers to provide more accurate volcanic cloud reports.

The frequency of receipt of pilot reports is another major issue. An analysis of reports received by Tokyo VAAC during the past year shows that of the 35 reports, 27 came from a single aviation operator (Japan Air Commuter, mostly flying YS-11 turboprops), with Japan Air Systems contributing 4. Larger airlines are either rarely making reports, or rarely forwarding them. While it is commendable that short-haul airlines, which can make relatively accurate reports from low altitudes, contribute so heavily to the International Airways Volcano Watch in this area, there is clearly room for improvement of the amount of information being received overall. Japan Air Commuter occasionally experience damage from volcanic clouds (I.Yoshimura, YS-11 pilot, personal communication), and have therefore established a mandatory reporting system that includes Tokyo VAAC. In the Darwin VAAC region the situation is similar, with particular operators (notably QANTAS and Air Niugini) contributing the bulk of reports.

### Atmospheric interactions

The essential dynamics of eruption clouds are well known (Sparks *et al.*, 1997; Woods, 1998). In particular, the effect of atmospheric wind and moisture have been investigated with detailed modelling, and found to significantly affect the height of rise and level of maximum ash concentration of eruptions (Graf *et al.*, 1999). The complications posed by volcanic cloud / atmosphere interactions are non-trivial, and they affect our ability to presume volcanic cloud height from explosion amplitude.

(Kamo *et al.*, 1994) describe infrasonic recordings at Sakurajima. The Japan Meteorological Agency has an extensive infrasonic network at Sakurajima, used for real-time monitoring. High hopes are held for the utility of the Comprehensive Nuclear Test Ban Treaty monitoring network for volcanic eruption detection (Chen and Christie, 1995). For remote *height* estimation, however, the situation is complicated.



**Figure 3 A) Infrasonic amplitude / cloud height above Sakurajima summit, January 1999 - August 2002, and July 1990 – January 1992, B) Seismic amplitude / cloud heights, July 1990 – January 1992. ‘Height minima’ indicates that the cloud top was obscured. Data courtesy Japan Meteorological Agency, Kagoshima Local Meteorological Office**

Figure 3 A) shows the wide variation of plume height at Sakurajima, against infrasonic amplitudes recorded at a single station. Part of this variation will be because the shock waves propagate differently as the atmosphere changes, part is certainly due to the changing cloud height with different wind speed and humidities. An additional complication is that, of 5589 non-zero cloud height observations during the 1999/2002 period, only 209 (4%) were associated with detectable explosions. Fig. 3 B) is a similar figure, this time against seismic amplitude in 1990/92. The lack of correlation between plume height and seismic amplitude appears inconsistent with earlier work by McNutt (1994), but may be partially explained by the focus on smaller eruptions, which are more affected by environmental conditions and which were excluded by McNutt.

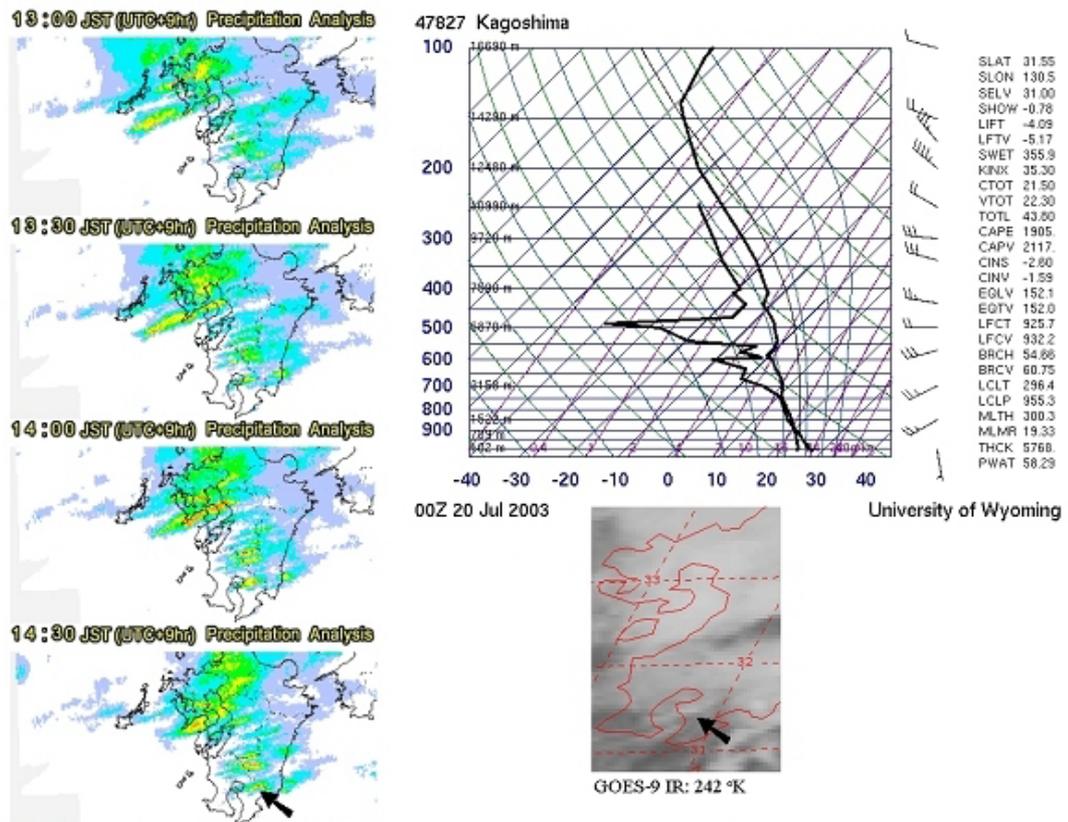
Especially for small eruptions, wind has a very large effect on plume development. Figure 4 shows a case of high winds, in this case associated with a typhoon, forming a lee wave on Sakurajima, with vertical development of the explosion cloud severely restricted. On this day heavy ashfall and high SO<sub>2</sub> concentrations were recorded in Tupper *et al.*, **Observations of cloud heights and ash-atmosphere interactions.**

Sakurajima town. Other effects such as bifurcated plumes (Ernst *et al.*, 1994) are commonly observed on satellite imagery.



**Figure 4** Lee wave carrying SO<sub>2</sub> and ash directly over Sakurajima town in high winds, 3 August 1999.

In the absence of high winds and in unstable environments, convection is commonly observed over Sakurajima, allowing the transport of even passive degassing high into the atmosphere (Tupper and Kinoshita, 2003). Certain wind profiles can also support continuous orographic convection. Figure 5 shows such a situation for Sakurajima.



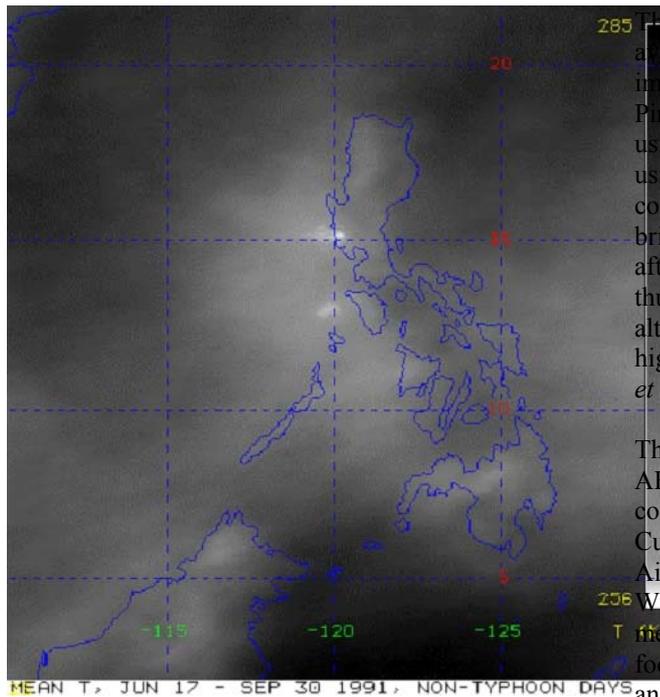
**Figure 5 -** Orographic convection continuously induced over Sakurajima (arrowed) in southern Kyushu, allowing continuous transport of volcanic emissions to approximately 10 km altitude.

In this case, deep westerly winds provided a continuous source of moisture and orographic convection, resulting in deadly mudslides over much of western Kyushu. The radar images (courtesy Japan Meteorological Agency) show convection developing over Sakurajima continuously through the afternoon, to a height of about 10 km, and extending well out to sea to the east. In this situation, while the flux of emissions is probably low (there

were no explosions recorded on this day), the *height* of transport is to aircraft cruising levels without any explosive input.

The most remarkable case of volcanic / atmosphere interactions was witnessed by US military observers after the paroxysmal eruption of Pinatubo in 1991 (Oswalt *et al.*, 1996), who observed volcanic storms developing over low level emissions, as a result of secondary phreatic explosions, or over the hot ground. (Holasek *et al.*, 1996) gave a cursory examination of the secondary explosions, but the details and implications of these three kinds of interaction have been largely unexplored.

Figure 6 shows a 3.5 month composite of GMS-4 hourly infrared images from two days after the paroxysmal eruption to the end of September 1991, with bad data, and images where Typhoons were affecting the Philippines, excluded from the analysis.



The area around Pinatubo is clearly the coldest on average during this period. Analysis of individual images shows repeated deep convection over the Pinatubo region, with 77 discrete events identified using GMS-4 imagery. Cloud heights were derived using brightness temperatures, cloud drifts, and comparison to radiosonde data. Hourly mean brightness temperatures also showed a pronounced afternoon maximum, which can be attributed to thunderstorms produced by diurnal heating processes, although it is also consistent with the suggestion of higher eruption heights in unstable afternoon air (Graf *et al.*, 1999).

The events were then examined using NOAA 10 & 11 AVHRR 1 km data. Twenty-one of these events could be seen on the AVHRR data, and compared to Cubi Point and Clark Air Base radars (US Navy, US Air Force, 487 observations, courtesy J.Scott Oswalt). We found great variation in the radar and satellite measurements of each event, attributable to the radar focus on the area immediately over the Pinatubo vent, and the lower spatial and temporal resolution of satellite data. Also, for some events there was unmistakable evidence of material being carried aloft by convection.

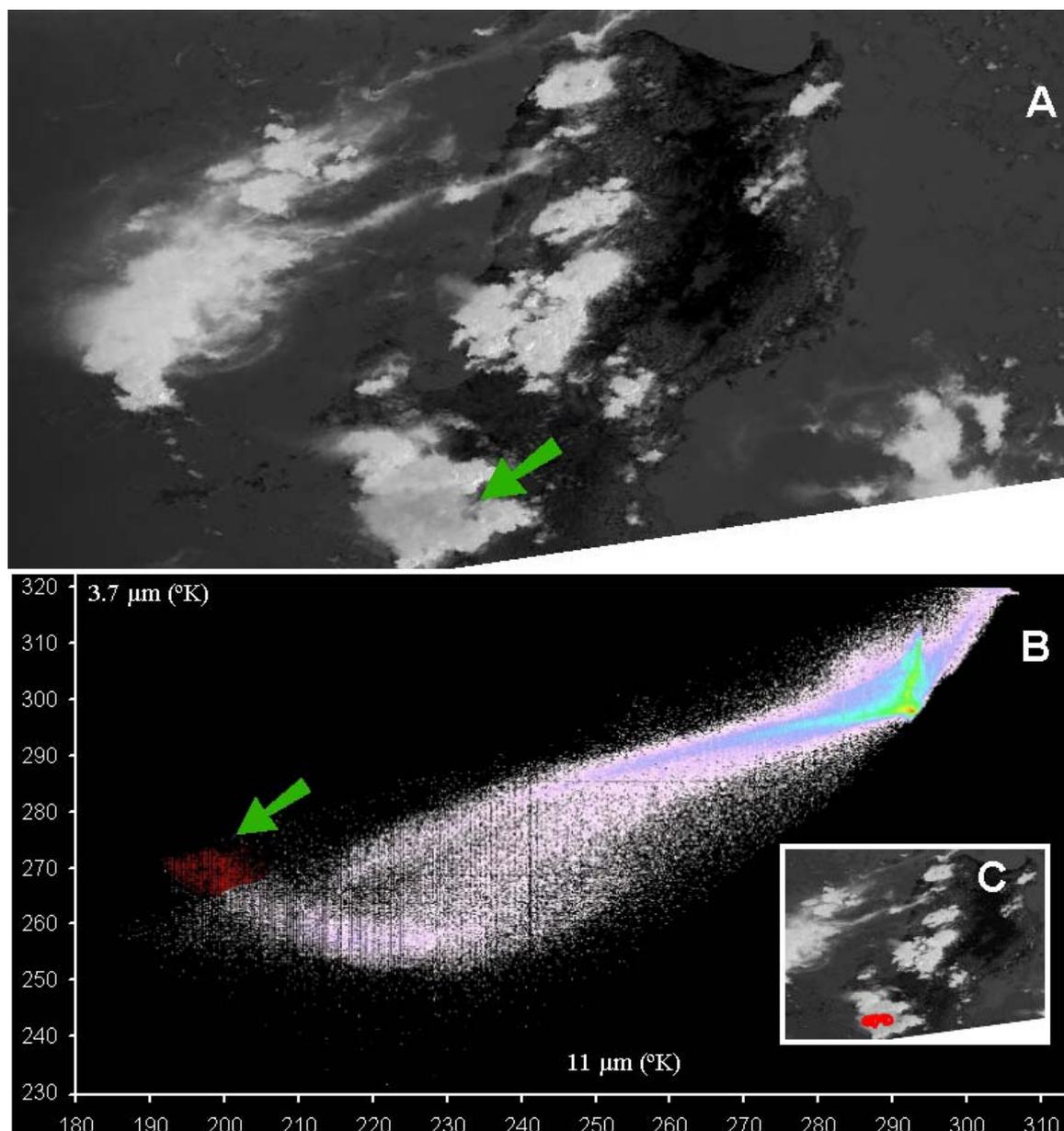
**Figure 6 Mean brightness temperature, Philippines, June 17 - September 30, 1991, using hourly GMS-4 data. Bad data and typhoon-affected hours excluded.**

It is well known that the reverse-absorption technique (Prata, 1989a, b) is unsuitable for detecting ash in opaque or water-rich clouds (Rose *et al.*, 2000: Rose *et al.*, 1995). (Ellrod *et al.*, 2003) used short-wave infrared channels to make up for the loss of the second infrared channel on the GOES satellites, in an approach that emphasises the absorption characteristics of ash at 3.9  $\mu\text{m}$ . The recent move of GOES-9 to the western Pacific, and the forthcoming introduction of MTSAT offer an opportunity to expand the use of short-wave infrared channels in the Asia-Pacific. In particular, there is scope to focus on detection of decreased ice particle size (as opposed to ash particles) using the increased reflective component of small particles in these wavelengths. This effect has already been used to observe ash-poor, sulphate rich plumes from Miyakejima (Kinoshita *et al.*, 2003), and has been exploited for some years in algorithms used to determine cloud particle size on the assumption that the clouds are composed of water/ice and that certain assumptions can be made about their reflectance properties (Kawamoto and Nakajima, 2003; King *et al.*, 1997; Nakajima and King, 1990).

In recent years, there has been intense discussion in climatological circles about the role of aerosols and aerosol-affected cloud in the global climate budget, particularly after the Pinatubo eruption, when changes in the reflective properties of cirrus were noted, (Charlson *et al.*, 1992; Chuang *et al.*, 2002; Kaufman and Fraser, 1997; Minnis *et al.*, 1993). Examinations of very cold tropical cumulonimbus, using short wave particle size algorithms, have shown an apparently smaller particle size in areas where there are high aerosol concentrations in the boundary layer (Sherwood, 2002). Imagery of the 'Chisholm fire', where smoke was lifted into the

stratosphere by a supercell (Fromm and Servranckx, 2003), and of the 'pyro-cumulonimbus' of the Australian 2002/03 summer<sup>1</sup> have shown distinctive short-wave signatures in very cold cloud tops polluted by smoke aerosols.

We followed Sherwood's (2003) method of examining very cold cumulonimbus tops at 3.7  $\mu\text{m}$  for evidence of unusually small particle size in deep convection, but restricted ourselves to AVHRR LAC 1 km on an event-by-event basis for simplicity. Because we are assuming the possibility of volcanic ash in these clouds which has markedly different reflective properties to ice particles, it is not appropriate to attempt an actual particle size derivation based on ice particle assumptions, as has been done in other aerosol/convection studies (Rudich *et al.*, 2003).



**Figure 7 - Convective event over Pinatubo, 06:24 UTC, 15 July 1991, A: NOAA-11 3.7  $\mu\text{m}$  image calibrated as an infrared image, apparently warmer area over Pinatubo arrowed, B: scatter diagram of calibrated 11 and 3.7  $\mu\text{m}$  temperatures, anomalous area (in red) arrowed, C: position of red scatter diagram pixels on original image. The anomalous area is apparently caused by high reflectivity from small particles in the CB tops over Pinatubo.**

<sup>1</sup> During the 2002/2003 summer in Australia, several thunderstorms were observed to be generated over bushfires, and to carry smoke particles into the upper troposphere or lower stratosphere. Work is in progress (Fromm, Servranckx & Tupper) to analyse these events.

Figure 7 shows one of the more interesting cases found following the Pinatubo eruption. It is conventional in meteorology to calibrate 3.7  $\mu\text{m}$  as an infrared channel, even though it also has reflected solar components during the day. For strongly reflective particles 3.7  $\mu\text{m}$  in cumulonimbus tops, the 3.7  $\mu\text{m}$  temperature will appear disproportionately warm (darker); the arrowed red area on the scatter diagram corresponds to the red area exactly over Pinatubo in Figure 7C. On this day, Cubi Point radar logs (Oswalt, personal communication) recorded venting from the volcano to an altitude of just less than 10 km, but 'ash mixing with CBs in the vicinity' to an altitude of 19 km or more (high but not impossible for normal deep convection in the area). The 3.7  $\mu\text{m}$  temperature anomaly is then attributable to smaller than usual cloud particle size caused by ash advected high by convective activity.

### *Discussion*

The prevailing attitude towards volcanic ash avoidance in the responsible parts of the aviation industry is conservative (Grindle and Burcham, 2002; Rossier, 2002). As a result of documented serious incidents of encounters with ash clouds even over 5000 km from the source (Casadevall, 1994), and in ash-sparse clouds (Grindle and Burcham, 2002), aviation operators repeatedly and unambiguously affirm the need to know of minor eruptions and of old ash clouds.

In this context, the uncertainties of cloud height observation from the ground, and the knowledge of convective transport of ash particles, are critical issues. The current IAVW procedures (ICAO, 2000) place heavy emphasis on regarding each eruption as a discrete, observable event, with the role of volcanic observatories, VAACs, and Meteorological Watch Offices well defined. The examples presented suggest that some adjustments may be necessary to IAVW principles:

- i. A certain number of eruptions are largely unobservable or are badly observed, so ash emissions and transport should be assumed from known activity characteristics.
- ii. The atmospheric convective regime around volcanoes should be regarded as part of any volcanic risk assessment. Ash may be transported high into the atmosphere by discrete or continuous orographic convection, normal or enhanced diurnal convection, convection caused by secondary explosions, or convection forming on smaller eruptions.
- iii. In some cases, convective ash transport can be inferred through satellite techniques such as short-wave infrared analysis; however most of the time ash-bearing convection will probably appear as normal thunderstorms using satellite techniques.

If these principles were used to justify the issue of extensive, warnings of high level volcanic ash every time a volcano was emitting in a convectively unstable environment, then the end result would probably be an increase in over-warning, consequent cynicism in the aviation community and an inevitable downplaying of the risk caused by eruptions with a high flux of ash to cruising levels. This could be offset by:

- iv. Major research into the ash concentrations considered dangerous for aircraft, with subsequent definition of the IAVW 'duty of care'.
- v. Detailed modeling of the convective transport of ash under the situations described above, with results to serve as source terms for ash densities in dispersion model initialization.
- vi. The extension of the aviation colour code system into regions of the world not currently using it, with high altitude/low flux events assigned 'yellow' or 'orange' codes rather than the current 'red' suggested for events above FL250. This would allow aviation operators to program different response patterns for highly dangerous eruptions (colour code red) while still allowing the possibility of lower concentrations of ash at high altitudes for volcanoes releasing ash into deep convection. Graduated warnings systems and threat classifications have been found appropriate in many natural hazard situations (for example, tropical cyclones), and could be further developed in the IAVW.
- vii. Because of the extensive meteorological considerations involved and the poor accuracy of many ground observations, aviation colour codes should probably be assigned jointly between volcanic observatories and meteorological watch offices /VAACs, rather than solely by volcanic observatories as is currently the case. The degree of specialisation required in this field suggests that VAACs could play a strong role in this process.

### *Conclusions*

There is great variation between volcanic cloud heights estimated from the ground or aircraft and satellite measurements. The development of observing systems, and observer/pilot education will improve the quality of

observations, but IAVW methodology also needs to take into account the uncertainty associated with these observations.

Many observations show the variation of volcanic cloud height with differing atmospheric conditions. In particular, ash transport should be assessed in the context of the convective regime around the source. IAVW participants can take account of this by improved satellite techniques, by detailed modelling to refine conceptual models and ash loading profiles, by research to better define dangerous ash concentrations of ash, and by extensions to the 'colour code' system for aviation.

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