2003 CARIBBEAN VOLCANIC ASH ENCOUNTERS

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On March 17, 2003, Flight Operations received information from the National Weather Service that the Montserrat volcano had erupted, spewing ash and particulate into the atmosphere. East to west upper and lower atmospheric wind patterns shifted north by northwest and volcanic ash was transported into populated areas. Dispatch immediately all contacted all aircraft enroute to San Juan, Puerto Rico, St. Thomas, St. Croix, St. Maarten, Antigua and Santo Domingo in an attempt to divert aircraft away from the adverse effects of this meteorological condition. Flight operations were terminated for almost six hours in San Juan and its surrounding area until a volcanic ash pilot report and Notice to Airmen was rescinded. On July 12, 2003 significant volcanic activity occurred once again at Montserrat. The dome of the volcano collapsed sending ash and particulate into the atmosphere. An Airbus aircraft inbound to San Juan, Puerto Rico encountered an unforeseen cloud of ash at approximately 6000 feet. The encounter subsequently caused damage to the aircraft's engine fan blades and the forward flight deck windows.

ENGINE DAMAGE TO A NASA DC-8-72 AIRPLANE FROM A HIGH-ALTITUDE ENCOUNTER WITH A DIFFUSE VOLCANIC ASH CLOUD

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The National Aeronautics and Space Administration (NASA) DC-8 airborne sciences research airplane inadvertently flew through a diffuse volcanic ash cloud of the Mt. Hekla volcano in February 2000 during a flight from Edwards Air Force Base (Edwards, California) to Kiruna, Sweden. Although the ash plume was not visible to the flight crew, sensitive research experiments and instruments detected it. In-flight performance checks and postflight visual inspections revealed no damage to the airplane or engine first-stage fan blades; subsequent detailed examination of the engines revealed clogged turbine cooling air passages. The engines were removed and overhauled. This paper presents volcanic ash plume analysis, trajectory from satellites, analysis of ash particles collected in cabin air heat exchanger filters and removed from the engines, and data from onboard instruments and engine conditions.

AIRCRAFT ENCOUNTERS FROM THE 18 AUGUST 2000 ERUPTION AT MIYAKEJIMA, JAPAN

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Abstract

Four large commercial aircraft are known to have encountered clouds produced by the 16-17 km high phreato-magmatic eruption of 18 August 2000 at Miyakejima, Japan, which lies close to Japan's two busiest airports at Haneda and Narita. Many other aircraft flew close by the eruption clouds. A near-new Boeing 737-800 and a Boeing 747 both suffered extensive damage and required engine replacement. Another 747 encountered ash and sulphur dioxide, was inspected for three days without any damage found, and a third 747 encountered the cloud approximately 800 km (430 nautical miles) to the southeast, smelt sulphur dioxide but suffered no damage. Costs to the aviation industry are known to exceed US $12,000,000, but this figure is probably a gross under-estimate. The eruption was very well observed from the air and from the ground, and initial warnings were issued quickly, however SIGMETs did not give sufficient detail of the ash cloud dispersion, air-traffic management decisions appear to have been made on the basis of superseded VAAC forecasts for the prior, low-level eruption, and the known encounters all happened to foreign airlines, while Japanese airlines had access to more information about the activity at Miyakejima and made appropriate flight plans. The Miyakejima incidents teach us about the importance of pre-eruption information and planning, of having worldwide rather than country-specific ash-avoidance procedures, of universal and consistent information distribution, and of rigorous post-event investigations. On the positive side, the rapid eruption observation and reporting and the pre-flight planning of local airlines probably contributed to the lack of fatalities from this extremely dangerous eruption.

Introduction

The phreato-magmatic eruption of Mount Oyama, Mikayejima, Japan, on 18 August 2000 was one of the most dangerous volcanic eruptions from the viewpoint of aviation safety in recent years. The eruption began on 8 July 2000 with a crater collapse. Several larger eruptions then occurred, on 10, 18[t] and 29 August (Kinoshita *et al.*, 2002). An evacuation order for Miyakejima residents was announced on 1 September 2000, and high SO_2 fluxes continue to affect the region.

The eruption of 18 August was sudden, but not completely unexpected in the context of the preceding activity. Researchers from the Earthquake Research Institute of Tokyo University had already set up a camera to record the eruptions (Kinoshita *et al.*, 2002), and since the volcano lies only 160 km south of Tokyo, public awareness was already very high. The event was well reported by pilots and ground observers, and seen remotely with hourly satellite imagery and radar (Iino *et al.*, 2001: Tupper *et al.*, 2004). Despite this, two aircraft suffered severe damage from the eruption cloud 90 minutes after the beginning of the eruption, and two other aircraft are known to have flown through the cloud.

Remote sensing issues associated with the eruption, and a brief chronology of events, are given in Tupper et al. (2004). The purpose of this paper is to focus on factors pertinent to the aircraft encounters. We are not seeking to apportion blame to individuals or agencies, but to examine issues associated with what is a complex and still developing warning International Airways Volcano Watch.

Location of Encounters

The 18 August 2000 eruption occurred at 0802 UTC (17:02 JST) Fig. 1 shows the location of Miyakejima, and of the four verified encounters, the first two of which occurred at about sunset:

i) A Boeing 747 had requested a diversion that was only partially allowed because of military airspace ("Octagon" on Fig. 1). The aircraft encountered ash cloud at 34,000 ft (10.3 km) at about 0930 UTC, and exited the cloud at 30,000 ft (9.1 km) 2 minutes later. The aircraft made an emergency landing at Narita. Three engines, the flight deck windshield, and some forward passenger windows were replaced. The fourth engine was to be replaced after 100 hours flying time. The airline made an initial cost estimate of at least US $5 million.

ii) A near-new Boeing 737-800 also encountered the cloud at about 0930 UTC, at 36,000 feet (10.9 km), having received no verbal warnings from Air Traffic Control or nearby aircraft. Just before penetration into the ash cloud, Air Traffic Control had given the flight a radar vector directing the aircraft 40NM (74 km) northeast of Airway B586, an action that was ineffective for avoidance. The flight management computer and electronic engine controls failed, but the engines still functioned. The cockpit filled with 'haze and dust'. The aircraft made an emergency landing. Both engines were damaged and had to be replaced, forward visibility was lost on the windscreen except for a small area under the windshield wiper. The leading edges and tail were abraded, and the radome, air data probes damaged. The cost was at least US $ 5 million.

iii) At 1235 UTC, a Boeing 747 encountered strong sulphuric smells and 'sparking' on the windshield, strongly indicative of an ash encounter. The aircraft had diverted from Airway B586 to Airway 337 in an attempt to avoid the ash, and was partially successful since satellite imagery suggests less ash in that area. The aircraft was removed from service and inspected for three days, but no ash or damage was found. Nevertheless, the cost to this airline of diversions and inspections exceeded US $2 million.

iv) At 2010 UTC, another 747 reported sulphuric smells. There was no evidence of ash in this encounter, although the aircraft was apparently not removed from service for a detailed inspection. This aircraft had diverted a considerable distance eastward from Airway 337, after receiving the report of the 1235 UTC encounter.

Other aircraft movements

The movement of other aircraft around the eruption cloud are incompletely known. A DC-10 transited the same airspace at almost the same time as the first two confirmed encounters, but made no report. Given the extent of the eruption clouds and their proximity to Narita and Haneda airports, it seems likely that other aircraft encountered ash.

Four Japan Airlines flights observed the eruption during the evening (from 0830 UTC to 0924 UTC), and successfully avoided the ash clouds, as did later night flights. It appears that the action taken was generally to fly to the northwest of the eruption, the only area unpolluted at cruising levels. This avoidance action appears quite contrary to the Air Traffic Control advice to the aircraft in encounter ii), and reflects the fact that the Japan Airlines flights were operating with superior information and were not reliant on the official warnings.

Performance of International Airways Volcano Watch

Fig. 2 summarises the time and stated cloud height of advisories and warnings. The eruption was exceptionally well observed by the Japan Meteorological Agency and by pilots, reports were made extremely quickly, and the speed of issue of warnings was probably the fastest of any major event in the history of the International Airways Volcano Watch. The time from eruption, to the issue of a volcanic ash advisory, then to the domestic 'Area Meteorological Advisory' (ARMAD) and then the international SIGMET, the official meteorological warning for the eruption, was still twenty-three minutes in total, reflecting a long chain of communication. However, the first SIGMET was still issued over an hour before the two most serious aircraft encounters.

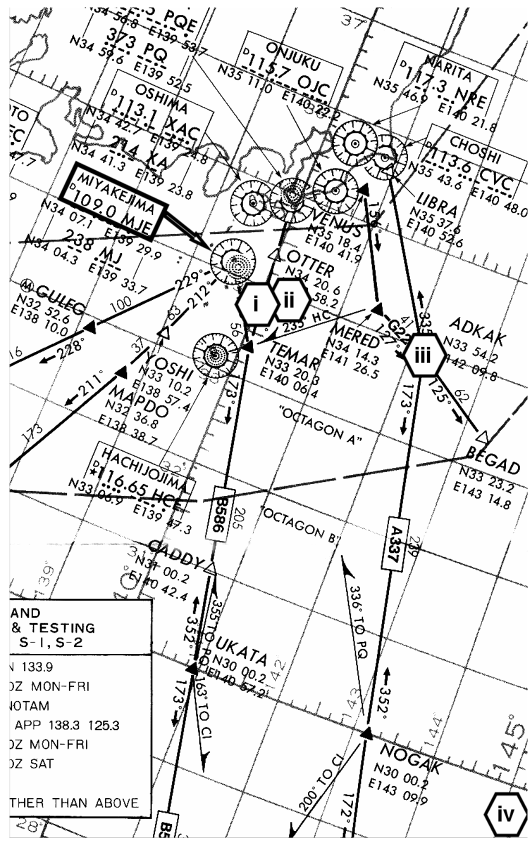

Figure 1 - Detail of air routes around Miyakejima. Hexagons labelled i-iv denote positions of reported aircraft encounters. The areas of restricted airspace are labelled 'Octagon A' and 'Octagon B'

A number of major problems can be identified. Firstly, the observation received by Tokyo VAAC at 0812 UTC of an eruption with tops ***greater than*** FL190 (5.8 km) was translated into tops ***to*** FL190 in the official NOTAM and SIGMETs (Fig 2, 'a'). The entire avoidance procedure during the critical first phase of the eruption was based on the incorrect assumption of a low-level eruption.

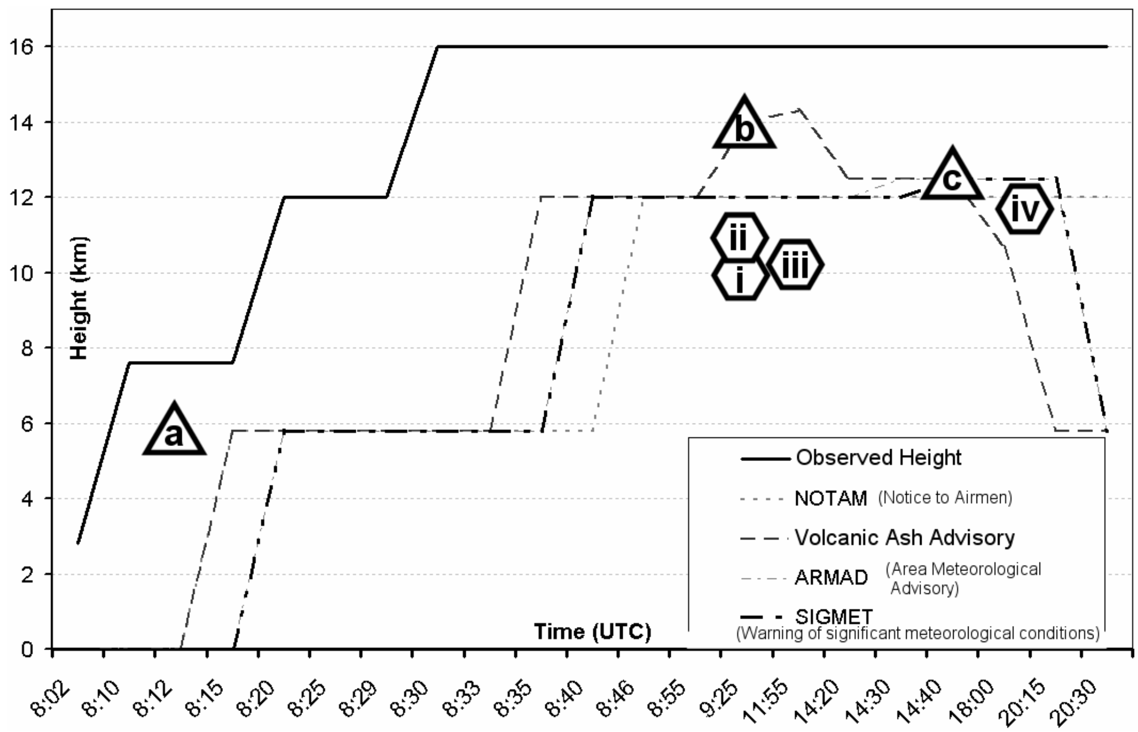

Figure 2 - Height of eruption reflected in observations, advisory and warning products. Lettered triangles show the time of key events described in the text, and hexagons show the time and height of confirmed aircraft encounters.

Even though these warnings were superseded around 0835 UTC, the misinformation continued to propagate through the warning system, as the initial information was passed on. This kind of height confusion is actually quite common: a useful guideline may be to assume that eruption clouds above 5 km extend to the tropopause until evidence is given to the contrary (Tupper and Kinoshita, 2003).

Secondly, the cloud dispersion at cruising levels was not well understood. The Tokyo VAAC was unable to prepare and issue a full dispersion forecast for the eruption until 0925 UTC ('b' in Fig.2), i.e. about the time of the encounters. The SIGMETs, the official warning product, never included a dispersion forecast and stated only that the ash was going to the southeast or east-southeast. The wind field in the area and likely dispersion of the plume was well known, with an upper air observation station just to the south, and an observation of eruption height over 45,000 ft (13.7 km) and spot wind observation of northwest winds at 50 knots (92 km/h) reported to Air Traffic Control by JAL at 0830 UTC. Despite this controllers apparently failed to grasp the extent of the cloud and were directing aircraft into the ash an hour after the JAL report and high-level SIGMET.

During the event, staff at Tokyo VAAC became concerned these issues, and took the initiative of distributing extra graphics showing a 'close-up' view of the eruption cloud.

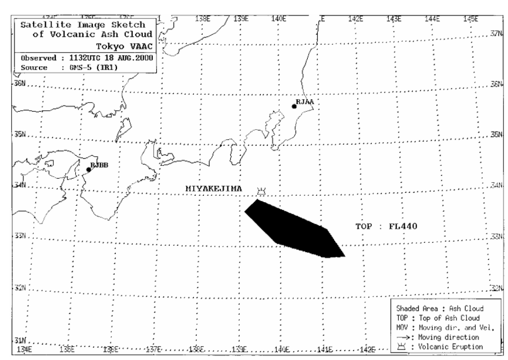

Figure 3 - Supplementary nephanalysis issued during the event by Tokyo VAAC.

Thirdly, as in many other volcanic ash events, the procedures for warning cessation at the stage where ash becomes difficult to detect were not defined. Encounter iv) occurred after the high level ash had become impossible to detect on satellite imagery and as Tokyo VAAC staff were beginning to concentrate on the lower level eruption clouds (Fig. 2, 'c').

Fourthly, it appears that, where local operators such as Japan Airlines were in direct receipt of graphical warnings, followed their own contingency plans, and were well aware of the situation at Miyakejima, foreign operators were not as well informed. All operators should receive the official warnings, and an arrangement exists where Japan Airlines redistributes graphical advices to other airlines. However it is evident from the written reports of airlines that suffered damage that justifiably or otherwise, they felt badly informed. As a consequence, the Tokyo VAAC was pressured with phone calls from several airlines, as well as the media, frustrating the VAAC's efforts to get information into the official warning system, and also frustrating the foreign operators who struggled with language issues.

Finally, despite the seriousness of the encounters and some direct complaints by airline operators, we have been unable to find any evidence of an investigation by the government agencies concerned. We assume that, because no post-analysis is explicitly mandated in the arrangements of the International Airways Volcano Watch, and no agreement was in existence between the responsible agencies in Japan that required an investigation in a situation where aircraft have been damaged but no fatalities have occurred, no process existed to trigger such an investigation.

<u>Discussion</u>

None of the issues identified above are uniquely Japanese. For example, in the Australian region, Qantas functions as a conduit for volcanic information to other international airlines in the same way that Japan Airlines does in Japan, and it is likely that any sudden eruption in Australian airspace would show that some airlines are far better informed than others.

Formally, Volcanic Ash Advisory Centres exist to advise Meteorological Watch Offices about the dispersion of volcanic ash cloud. However, airline dispatchers, who make critical decisions about their aircraft, are often desperate for information during crises and will use whatever resources are available to make their decisions. Personal relationships are also highly emphasised in meteorological / aviation relationships the world over; information flows much more freely where offices perceive a good working relationship.

A major challenge for the International Airways Volcano Watch is to ensure that enough information is distributed over *official* warning channels to allow all operators to avoid the ash cloud. Current initiatives, such as globally consistent volcanic ash graphics, universal SIGMET and NOTAM implementation, and better training, could substantially improve the information distribution. In turn, this will reduce the pressure on VAACs to provide telephone service to aviation operators.

There are substantial issues of workload. For example, the SIGMET 2 for this event was:

RJTG SIGMET 2 VALID 180845/181445 RJAA – TOLYO FIR VA MIYAKEJIMA (34.1N 139.5E) OBS at 0829 OVER MIYAKEJIMA VA TOPS MORE THAN FL400 DRIFTING TO E-SE BY B747 INTSF

This SIGMET, while informative, contains no explicit dispersion forecast. In today's coding, an appropriate SIGMET for that time may have been:

RJTG SIGMET 2 VALID 180845/181445 RJAA- TOKYO FIR VA ERUPTION MIYAKEJIMA LOC N31 E139 VA CLD OBS AT 0830Z SE OF MIYAKEJIMA SFC/FL460 N3415 E13925 - N3410 E13950 - N3345 E13955 - N3350 E13930 - N3415 E13925 MOV SE 40KT INTSF FCST 1445Z VA CLD APRX N3430 E13915 - N3420 E14105 - N3035 E14330 - N3155 E13850 - N3430 E13915 OTLK 012045Z VA CLD APRX N3435 E13905 - N3035 E13830 - N2855 E14505 - N3415 E14220 - N3435 E13905 020130Z VA CLD APRX N3440 E13905 - N2955 E13830 - N2730 E14700 - N3410 E14305 - N3440 E13905

Even this SIGMET is a simplification, as it treats all the ash as one layer in a situation where the wind changed markedly with height. Text SIGMETs will be necessary for some time yet, until graphical products are universal. When composing and then decoding SIGMETs such as those above, which are derived from even more complex Volcanic Ash Advisories, some delay is inevitable unless the whole process can be simplified and/or automated.

The deamnds of the media are unlikely to be reduced by informative warnings. It is difficult to keep operational contact numbers confidential, and every centre should have a firm policy for handling media enquiries during an event. Since there is virtually no public benefit in feeding extra information to the media during an event, responding these calls should be given a low priority at most.

Large volcanic eruptions in any particular area are relatively infrequent. The mistakes made in the VAAC, Meteorological Watch Office, airline offices and Air Traffic Control centres are likely to recur for future eruptions in other regions unless regular training is performed. Similarly, the sensitivities associated with any damage from a volcanic event are such that, unless a clear protocol is already in place for post-analysis, it is possible that no effective investigation would be performed.

A final point of interest is that no damage was found to the aircraft involved with encounter (iii), despite three days of inspections. When compared to the Hekla 2000 incident (Grindle and Burcham, 2003), this suggests that further research is necessary to determine the danger threshold of ash clouds.

Following the Miyakejima eruptions, the Tokyo VAAC has had substantial experience with other eruptions. Volcanic SIGMETs, previously restricted to heights around 5 km, are now issued for all altitudes. Numerous case studies have been conducted for training purposes, a VAAC web site has been created, and the Japan Meteorological Agency provides a representative to the ICAO International Airways Volcano Watch Operations Group, which is shaping the future warning system.

Conclusions

The eruption of Miyakejima provides us with a remarkable example of a major eruption of a monitored volcano, in airspace serviced by highly sophisticated aviation and meteorological services. The eruption therefore gives us an insight into the issues that are likely to be prominent over the rest of the world once the basic technological challenges of monitoring are sorted out.

In this case, despite rapid observation of the eruption and a relatively rapid issue of warnings, two aircraft were seriously damaged, and at least two others encountered the cloud. To address these challenges, we suggest:

1) Further development of the International Airways Volcano Watch to ensure that information before and during an eruption is adequate for international aviation operators.
2) Regular training and drills to ensure operational readiness.
3) The development of internationally agreed post-analysis procedures for improvement of the International Airways Volcano Watch.

Acknowledgements

We gratefully acknowledge the help of the airlines who anonymously provided information about their encounters with the Miyakejima eruption clouds, Dr. A. Terada of Hokkaido University for providing a video of the eruption, and Prof. K. Kinoshita of Kagoshima University for much related discussion and materials. We also acknowledge the operational efforts of the staff on duty during the eruption, which was the first major eruption in Japanese airspace since the creation of the Tokyo VAAC.

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VOLCANIC ASH CLOUDS POSE A REAL THREAT TO AIRCRAFT SAFETY

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1. ABSTRACT

Volcanic ash clouds pose a real threat to aircraft safety. More than 100 jet aircraft have encountered volcanic ash clouds in the past 25 years often resulting in damage to the aircraft. The ash is abrasive and capable of causing serious damage to aircraft engines, control surfaces, windshields, and landing lights. The ash can clog the pitot-static systems, which determine airspeed and altitude, and can damage sensors that deliver electronic data to automated systems used to fly the aircraft. Seven of these encounters caused in-flight loss of jet engine power.

The ash cloud, transported by atmospheric winds, can drift over great distances causing disruption to air traffic and is a potential hazard to aircraft hundreds of miles from its source.

The hazard is compounded by the fact that volcanic ash clouds are not detectable by the present generation of radar instrumentation carried aboard aircraft. Complete avoidance of volcanic ash clouds is the only procedure that guarantees flight safety.

Addressing the threat of volcanic ash to aircraft safety has brought together Governments, University Scientists, Pilots, Dispatchers, Meteorologists, Air Traffic Controllers, and many representatives of the aviation industry to work collaboratively to reduce the hazards caused by volcanic ash. The First International Symposium and recently the Second International Conference on Volcanic Ash, Aviation Safety, The International Civil Aviation Organization, (I.C.A.O.), The World Meteorological Organization (W.M.O.), The Airline Pilots Association (A.L.P.A.), The Airline Dispatchers Federation (A.D.F.), and many others identified the need for specialized air carrier operations, procedures, communications, routings, and training are essential in maintaining a high level of flight safety.

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2. INTRODUCTION

The first notable encounter was the British Airways 747 near Galunggung, Indonesia, in 1982. It showed that, in such encounters, we might expect a loss of engine power, problems with airspeed indications, and extensive abrasion damage, including a loss of windshield transparency. The encounter placed the flight in great danger, and it required heroic and persistent efforts by the crew to restart the engines and bring the flight to a safe conclusion (Tootell, 1985).

During the eruption of Redoubt Volcano in Alaska on 15 December 1989, a new B747-400 on a flight from Amsterdam to Anchorage flew into the plume and lost power from all four engines. The crew was able to restart the engines and land the aircraft safely. The initial estimate of damage to the aircraft was $80 million, including the replacement of all four engines (Brantley, 1990).

3. WARNING-SYSTEM

To ensure aviation safety, it is necessary that reports of eruptions be processed without delay into warnings to Pilots, Air Traffic Control Centers, and Air Carrier Operations Centers. Volcanoes are a threat to air safety from the moment that they erupt. A warning system should be capable of a 5-minute response time once an eruption has been detected. The Mount St. Helens ash took approximately 5 minutes to reach aircraft-cruising altitudes (Rosenbaum and Waitt, 1981) at a rate of climb of approximately 5,000 ft per minute. A modern jet aircraft is traveling over 500 mph and advancing 6-8 miles per minute.

Winds play the dominant role in the distribution of volcanic ash. The agency for subsequent ash-location advisories should be the meteorological office. The computerized model of winds over the eruption site can be used, in conjunction with the dispersion models, to predict ash trajectories, as an aid to flight path planning for avoiding airborne volcanic ash, such as, the NOAA Air Resources Laboratory Volcanic Ash Forecast Transport And Dispersion (V.A.F.T.A.D.) model (Heffter and Stunder, 1998).

4. VOLCANIC ASH ADVISORY CENTERS

The Volcanic Ash Advisory Centers (V.A.A.C.s) were established in September 1995 in Darwin at a meeting of the I.C.A.O. At this meeting it was decided that in an effort to ensure that volcanic cloud hazards were addressed there must be an interface between Volcano Observatories, Meteorological agencies, Air Traffic Control Centers, and Air Carrier Operations. In order to meet their goal they decided the world should be divided into different regions differentiated by their volcanic activity and volcano observatories. The designated V.A.A.C. would be in charge of keeping track of the activity by analyzing satellite imagery in their designated region.

The V.A.A.C.s operate advanced science-based tools for detecting, identifying, tracking and projecting the movement of airborne volcanic ash. Because many of the world's active volcanoes are located in uninhabited regions, the rapid detection and location of volcanic eruptions are often problematic (Chen, 1998).

The Volcanic Ash Advisory Statement (V.A.A.S.) is issued by the V.A.A.C.s. The V.A.A.C.s must provide the required advisory information to the various M.W.O.s for a timely issuance of the SIGMETS.

The nine V.A.A.C.s are the contacts meteorologists can utilize for many of the details regarding a volcanic eruption. They are Anchorage, Buenos Aires, Darwin, London, Montreal, Tokyo, Toulouse, Washington, and Wellington.

The I.C.A.O. International Airways Volcano Watch publication of Operational Procedures and List of Operational Contact Points Between Vulcanological Agencies, Meteorological Watch Offices and Area Control Centers provides areas of responsibilities on a global scale, the phone numbers, fax numbers, e-mail addresses, and electronic addresses.

5. STATUS OF ACTIVITY OF VOLCANO

A color code for the "Level of Alert" indicates the status of activity of the volcano. A group representing many agencies, meeting in Anchorage, Alaska shortly after the Redoubt Eruption in 1989 developed this. It was determined this would be a simple method by which all could immediately understand the current condition of the volcano.

RED	Volcanic eruption in progress. Ash plume/cloud reported above FL250.
ORANGE	Volcanic eruption in progress but ash plume/cloud not reaching FL250.
YELLOW	Volcano known to be active from time to time and volcanic activity has recently increased significantly, volcano not currently considered dangerous but caution should be exercised.
GREEN	Volcanic activity considered to have ceased and volcano reverted to its normal state.

6. SIGMETS, NOTAMS, AND ASHTAMS

The operational requirements for the issuance of SIGMETS and NOTAMS have been part of the relevant Annexes for a number of years. The requirements for ASTAMS were included in Annex 15 - Aeronautical Information Services in November 1997. The SIGMET and NOTAM are excellent sources of information for the Pilot, Dispatcher, Air Traffic Control Facility, and Meteorologist.

7. AIR CARRIER OPERATIONS

Pilots are the last link in the chain of safety actions to avoid or mitigate encounters with volcanic ash. In order for pilots to be effective, it is necessary that the rest of the system meet the needs of the pilots. Pilots view the sky in terms of routes, fixes, and (or) coordinates. The Air Traffic Controller and Dispatcher are best equipped to provide this information to the Pilots in aviation language.

Approximately 600 of the 1,500 potentially active volcanoes are classified as active (Foreman, 1991). Volcanoes are not generally marked on aeronautical route charts. The Dispatcher or Air Traffic Controller will provide a statement of where an eruption is occurring expressed in aeronautical terminology, a bearing and distance from a navigational fix, or a latitude and longitude. Statements of distance will be expressed in nautical miles, rate of movement in knots, and plume heights in flight levels. References to time should always be in Universal Coordinated Time.

8. PLUME AVOIDANCE

Before operating in a region of known potential volcanic activity Pilots and Dispatchers (Jointly Responsible for Flight Safety by Federal Air Regulations under 121) should check Significant Meteorological Information Reports (SIGMETs), Notices to Airmen (NOTAMs), ATC directives, and Pilot Reports (PIREPs) for that region. To aid in identifying regions that are potentially active at a particular time United Airlines has developed procedures that provide flight safety (Hinds and Salinas, 1998). Since volcanic eruptions can seriously impact operational routes and destinations the United Airlines Weather Center has been designated as the initial point of contact in the Operational Control Center (O.C.C.) to gather pertinent data and information and issue a United Airlines Volcano Advisory (UVA). The Meteorologists will research sources such as, but not limited to, VAAC's, SIGMETS, NOTAMS, PIREPS, Volcano Observatories, ATC, VAFTAD's, Local Station Managers, and Civil Emergency Agencies. The Air Carrier issues a text and graphic Alert noting the volcanic eruption. This advisory will appear on documents that are sent to the Pilots and Dispatchers. The United Volcano Advisory UVA will be updated continuously during the event and will only expire after no activity is evident and VAAC concurs.
The advisory will contain the following:

- Advisory Number
- Valid Time (UTC)
- Volcano Name and Location
- Summit Height
- Winds at Summit
- Height of Eruption in Flight Levels
- Winds at Flight Levels
- Estimate Ash Coverage lat./long.
- Comments (Plain Language)

This information will be provided in both text and graphical form that is much easier to use and are more compelling in terms of amending flight plans for the purpose of avoidance. The standard graphic product will utilize the internationally recognized symbol to represent a volcanic eruption in progress on the graphical display.

9. MITIGATION FOLLOWING AN INADVERTENT ENCOUNTER

Emphasis must be placed on the avoidance of volcanic ash. Avoid flight at night in areas of known volcanic activity or in instrument meteorological conditions (IMC), when volcanic ash may not be visible. Plan the flight to remain well clear of reported activity. If possible, stay upwind of volcanic ash. But, if ash penetration occurs, crews should know what to do. Criteria for recognizing that one's airplane is in a volcanic ash plume and suggested procedures for escaping from a plume, are covered in the paper Recommended Flight-Crew Procedures if Volcanic Ash is Encountered (Campbell, 1991).

10. RECOGNITION

Volcanic ash may be difficult to detect at night or during flight through clouds; however, flight crews have observed the following conditions:

- At night, heavy static discharges (St. Elmo's fire) around the windshield, accompanied by a bright white glow in the engine inlets.
- At night, landing lights cast sharp, distinct shadows in volcanic clouds (unlike the fuzzy, indistinct shadows that are cast against weather clouds).
- Volcanic ash and dust appearing in the cockpit and cabin.
- An acrid odor or the smell of sulfur.
- Multiple engine malfunctions, such as surge, increasing exhaust-gas temperature, torching from tailpipe, and flameouts.
- Decrease in indicated airspeed.

11. ENCOUNTER PROCEDURES

If volcanic ash is encountered, accomplish the following (Campbell, 1991):

- Immediately reduce thrust to idle.
- Auto throttles off (if engaged).
- Exit volcanic cloud as quickly as possible. Volcanic ash may extend for several hundred miles. The shortest distance/time out of the ash may require an immediate, descending 180-degree turn.
- Engine and wing anti-ice on. All air conditioning packs on. Turn on engine and wing anti-ice.
- Start the auxiliary power unit (APU), if available.
- Oxygen mask on and 100 percent, if required.
- Ignition on.
- Monitor EGT.
- Close outflow valves.
- Do not pull fire switches.
- Leave fuel boost pump switches "on" and open cross feed valves.
- Do not use fuel heat.
- Engine restart may be required. Successful engine start may not be possible until airspeed and altitude are within the air start envelope.
- Monitor airspeed and pitch attitude.
- Land at the nearest suitable airport.

12. SPECIAL AIR REPORT OF VOLCANIC ACTIVITY

Pilot observations of volcanic activity are of use to others. The Volcanic Ash Working group has produced a special air report of Volcanic Activity Form (VAR), which is carried by United Airlines pilots and most other Air Carrier pilots. The form is a guide. The form should be delivered to the local meteorological office on arrival. This form provides a detailed and useful tool for others in accurate reporting. The ICAO standard for the contents include:

- Aircraft identification
- Position
- Time
- Flight level or altitude
- Volcanic activity observed
- Air temperature
- Winds
- Supplementary information

13. CONCLUSIONS

There are 1,500 known volcanoes worldwide, and about 600 of these volcanoes are considered active. An average of 55-60 volcanoes erupt each year, and about 8-10 of these eruptions produce ash clouds that reach flight altitudes. Volcanic Ash can reach aircraft cruise altitudes in 5 minutes and considering jet aircraft are traveling at 5-8 miles per minutes a 5-minute communications warning system is imperative.

Pilot and Dispatcher training is a priority. Both must understand that volcanic ash is not like sand or dust, and they must know how to recognize inadvertent entry into an ash cloud. The Boeing Company in cooperation with the Air Line Pilots Association and the U.S. Geological Survey has developed a Volcanic Ash Training Video. In addition Pilots, Dispatchers, and Air Traffic Controllers must be aware of any potential volcanic activity affecting their area of operation. Should an inadvertent penetration of a volcanic ash cloud be made, flight crews must be aware of potential problems and be prepared to deal with the arising flight conditions.

Prompt communication among Volcano Observers, Meteorologists, Air Traffic Controllers, Flight Dispatchers, and Pilots regarding location of drifting ash clouds will maintain a high level of flight safety.

The detection and tracking of ash-cloud movement using remote-sensing techniques and atmospheric transport models continue to provide the graphical data required in long-range flight planning. Enhanced monitoring of the

Earth's active volcanoes, especially in the remote regions of the world, such as the new communication links with the Russians for warning and information about Kamchatkan volcanoes (Miller and Kirianov, 1993), now provides prompt notification of an eruption.

Location of a volcano has been simplified by using the Global Planning Chart showing the position of known active volcanoes relative to air routes and air navigation aids. (U.S.G.S. Casadevall and Thompson, 1994).

Avoidance requires the coordinated efforts of a broad group of technical specialists. The goal of these efforts is to avoid an area or airspace that has been contaminated by volcanic ash. Avoidance of Volcanic Ash Clouds is the only procedure that guarantees flight safety

14. Acknowledgments

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AIR NIUGINI AND THE VOLCANIC ASH THREAT

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ABSTRACT

Air Niugini is the national airline of Papua New Guinea, operating international services to Asia, Australia and the South West Pacific as well as domestic ports in the New Guinea Islands region. The airline operates a small fleet of turboprop and jet aircraft in an area notable for its high number of active volcanoes, some situated near major centre’s and airport's, many situated directly beneath major international air route's. Air Niugini's experience with volcanic activity and airborne ash has resulted in a heightened state of awareness of the phenomena and we have developed in house methods for maintaining crew awareness of the threat as well as standard operating procedures designed to better enable crews to manage ash encounters. Papua New Guinea's unusual reliance on air transport for commerce and communication mean's that the airline is continually seeking out those solutions best suited for our operating environment in order to maintain services in an area prone to volcanic activity.

INTRODUCTION

Papua New Guinea is an island chain stretching from Indonesia in the west to the Solomon Island's in the east, a distance of approximately nine hundred nautical miles. Most of the population lives on the main island but significant population centres exist on the outlying islands of New Britain, New Ireland, Manus and Bougainville. Air Niugini as the national carrier is tasked with servicing these communities as well as providing international connection's to neighbouring states. Many of the major population centres happen to be situated near active or dormant volcanoes, which are concentrated in a line reaching from the north coast of the main island across to New Britain and the island of Bougainville.

ENCOUNTERS

Air Niugini crews fly in the vicinity of active volcanoes on a daily basis, but as yet we have been fortunate when it comes to actual ash encounters. The most significant encounters have involved Fokker F28 aircraft operating close to erupting volcanoes at Rabaul (Tavurvur) in 1994 and Manus Island in 1996. In the first case, an F28 on the ground at Rabaul Airport was effectively scrambled in the midst of a volcanic eruption only a few kilometre’s from the airfield. In the second example, an aircraft enroute between the towns of Wewak and Madang reported passing close by Manus Island as it erupted. Other airborne encounters have been limited to observations only from a safe distance. Operational procedures from ash contaminated runways exist but given the lack of suitable ground equipment at many outport's for clearing ash and towing aircraft to clear areas for engine operations, company policy is to simply cease operation's to affected ports until the ash contamination has been cleared. Apart from Rabaul Airport, such ash deposits have been light coverings only.

DAMAGE

Air Niugini has had no significant report of damage to its aircraft resulting from in flight ash encounters. Aircraft suspected to have flown in the vicinity of ash are removed from service while they are inspected and cleaned, and because of our restrictive operating procedure's, we find our aircraft serviceability and engine overhaul cycles are comparable to industry standards for our fleet type and type of operations. While our aircraft have fared well, the same cannot be said of some of the airstrips we operate into. Rabaul Airport was effectively destroyed by the 1994 eruption, along with much of the town, and while Air Niugini was fortunate enough to manage to extract its aircraft during the eruption, several companies lost both fixed and rotary wing aircraft to heavy ash falls.

SOCIO-ECONOMIC CONSEQUENCES

In regard to passenger services, the islands of New Guinea, New Britain, New Ireland and Bougainville are serviced almost exclusively by air. Sea transportation is relatively slow and infrequent and the country has no railway network. The mountainous terrain, up to 14000 feet or more in places, has limited road access to the coastal areas and one rough road into the Highlands region of the main island. Any major disruption to the countries regular air services has an immediate and severe impact on the communities involved, and it should be noted that apart from small numbers of commuter size aircraft, Air Niugini holds a virtual monopoly on regular public transport. Tourism is a major source of foreign income, as is small scale high value seafood and agricultural produce. The presence of volcanic ash near major centres invariably causes major disruptions to these industries with flow on effect's that run into weeks if not month's. When airstrips are closed due to volcanic activity, communities are reduced to travelling long distances to alternate airfields where the only service available is usually a small commuter aircraft of nine to nineteen seats capacity.

Air Niugini's guidelines for operating in regions prone to volcanic activity are simple and effective, but result in frequent schedule delay's and cancelled flights. One example is the Rabaul area, where night operations are banned even though facilities exist for full night time operations. Aircraft do not overnight at this port due to the possibility of ash damage from the nearby volcano and flight in Instrument Meteorological Conditions (IMC) is not permitted. In the wet season, between November and April, flight's operating into Rabaul/Tokua frequently divert to Kavieng if there is cloud cover over Simpson harbour. If the flight is an early evening one, the designated alternate is Port Moresby, a seventy minute flight. Air Niugini and the communities it serve's are adversely affected by even the risk of volcanic ash due to the difficulty of establishing whether or not ash is actually present in area's of high risk.

CONCLUSIONS

Air Niugini has to date successfully managed to minimise the risk of exposure to volcanic ash through the use of a restrictive set of standard operating procedures. The negative consequence of this has been the disruption of services to communities almost wholly reliant on our scheduled services for commerce and communication's. We believe the best way of improving our schedule maintenance while maintaining our record for ash avoidance would be the adoption of volcanic ash detection technology suited to our particular needs. Ground based ash detection at certain airfields coupled with appropriate procedures would allow crews to make more informed decisions, thereby enabling the airline to better service the community while ensuring aircraft are protected from exposure to airborne ash.

REDUCING ENCOUNTERS OF AIRCRAFT WITH VOLCANIC-ASH CLOUDS

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Introduction

The volcanic-ash hazard to aviation is not a rare possibility on a worldwide scale, given that many major air routes traverse the world's most volcanically active regions (Casadevall et al., 1999; Ewert and Newhall, this volume). Miller and Casadevall (2000) estimate that volcanic ash can be expected to be in air routes at altitudes greater than 9 km (30,000 ft) for roughly 20 days per year worldwide. Numerous instances of aircraft flying into volcanic ash clouds have demonstrated the life-threatening and costly damages that can be sustained. Upon impact with aircraft traveling at speeds of several kilometers per minute, airborne ash particles abrade forward-facing surfaces, including windscreens, fuselage surfaces, and compressor fan blades in turbine engines. Moreover, the melting temperature of the glassy silicate rock material that comprises ash is lower than the operating temperatures of modern jet turbine engines; consequently, ash particles ingested into such engines can melt in hot sections and then accumulate as re-solidified deposits in cooler parts of the engine. The overall result of an encounter of an aircraft with an ash cloud can be immediately degraded engine performance (including flame out and loss of thrust power), loss of visibility, and failure of critical navigational and operational instruments (Dunn and Wade, 1994).

Systematic collection of information about ash/aircraft encounters is important to substantiate the nature and extent of the risk to aviation and to improve the multi-faceted mitigation strategy of ash avoidance. To that end, the U. S. Geological Survey (USGS) and Smithsonian Institution, in collaboration with the Darwin Volcanic Ash Advisory Center, are compiling a summary of reported encounters in the form of a database that includes information about the source volcanoes that produced the ash clouds and conditions during the encounters. This paper presents a preliminary analysis of information about encounters from 1973 through 2003. The bulk of the encounter data is published in the Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds by the International Civil Aviation Organization (ICAO, 2001). An updated summary of encounters will be provided to ICAO for publication in a future update of the 2001 Manual.

Overview of Known Encounters

Appendix I of the Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds (ICAO, 2001) identifies 83 ash/aircraft encounters from 1935 to 1993 and provides information about the source volcanoes, eruption dates, aircraft types, and severity of the encounters; preliminary mention of another ~17 encounters from 1994 to 2000 is given in an accompanying table. An additional 9 encounters are known through 2003 that are not included in the Manual. The most recent reported incident occurred in July 2003 in the Caribbean region (see Beerley, this volume).

From 1973 through 2003, 105 encounters of aircraft with airborne volcanic ash have been documented (Figure 1); this is a minimum value because encounter incidents are not consistently reported. The highest annual encounter rate (25 incidents) occurred in 1991, mostly due to the eruption of Mt. Pinatubo in the Philippines. Since 1991, 26 encounters are documented through 2003, an average of two per year, again a minimum value.

The encounter database does not include information about aircraft caught on the ground at airports affected by ash; a separate database is being compiled for airport disruptions resulting from volcanic activity (see Guffanti et al., this volume).

Aircraft have been damaged by ash clouds from eruptions ranging from small, recurring episodes (e.g., at Soufriere Hills Volcano, Montserrat, 1996) to very large, singular events (e.g., at Pinatubo, 1991). Thirty source volcanoes have produced ash clouds encountered by aircraft (Table 1). (For a few encounters, the source volcanoes are not known.) Six volcanoes are associated with highest number of encounters ($\geq$5): Pinatubo in the Philippines, Sakura-jima in Japan, Galunggung in Indonesia, and St. Helens, Augustine, and Redoubt in the United States.

To quantify the effects of reported encounters on aircraft, a severity index for ash encounters (Table 2) has been formulated (ICAO, 2001). The criteria for each class in the severity index are based on the actual types of damage or conditions reported. Severity of encounters ranges from minor Class 0 incidents (acrid odor in cabin, electrostatic discharge on windshield) to very grave Class 4 and 5 incidents (engine failure). Fortunately, no Class 5 encounters (those resulting in crashes) have occurred.

In the database, most encounters (roughly 75%) are Class 0-2. Accurately documenting the extent of Class 0 encounters is problematical. Some likely occur that not publicly reported because no significant damage is involved. Smelling sulfur does not necessarily indicate the presence of damaging ash, given that separation of the gas and ash components of volcanic clouds is known to occur (Bluth et al., 1994; Guffanti et al., in press). Moreover, the human nose very sensitive to sulfur dioxide (R. Wunderman, written communication, 2004) and may sense it at levels that are undetectable by remote-sensing methods.

A significant percentage (~25%) of encounters comprises serious Class 3-4 incidents. Eight Class 4 encounters involving temporary engine failure occurred from 1980-1991 (Table 3). These encounters occurred 240 to 960 km (150 to 600 miles) from the source volcanoes (St. Helens, Galunggung, Redoubt, Pinatubo, Unzen). The encounters lasted from 2 to 13 minutes at altitudes ranging between 4.6-11.3 km (15,000-37,000 ft) above sea level.

Some recent documented encounters in August 2000 did not involve engine failure, but were nevertheless very dangerous. A Boeing 737-800 nearing Japan's Narita Airport flew into an ash cloud produced during an eruption about an hour earlier at Mijake-jima volcano, located about 100 miles from the airport. The engines continued to function, but the flight management computer and electronic engine controls failed. Handicapped further by severe loss of visibility due to abrasion of all but a small part of the windscreen, the crew managed a safe landing. Shortly thereafter, a 747 had a similar experience. Three additional aircraft also are thought to have encountered the Miyake-jima cloud. Costs to the aviation industry, including replacement of engines, exceeded US $12 million (see Tupper et al., this volume).

ICAO recommends that information on ash clouds and encounters be documented by having pilots complete the Volcanic Activity Report (VAR) when appropriate. The VAR can be found in Annex 3 and ICAO Doc 4444. Pilots and Air Traffic Services should complete these reports and forward them to appropriate services and agencies for operational use and historical record-keeping by the USGS and Smithsonian. In addition, encounter information can be sent to any of the authors of this paper or by email to gvn@volcano.si.edu. Such information does not need to be received by the USGS and Smithsonian in an operational, real-time mode. Furthermore, information identifying the airlines or aircraft operators involved in encounters will not be included in the USGS/Smithsonian database.

Discussion

Under the auspices of ICAO's International Airways Volcano Watch, operational procedures for ash avoidance have been formulated. Avoidance requires that dispatchers, pilots, and air-traffic controllers quickly learn of explosive eruptions and the locations of ash clouds. Accordingly, mitigation involves elements of: (a) real-time volcano monitoring and rapid eruption reporting, (b) detecting ash clouds in a timely manner, (c) forecasting expected cloud dispersion, (d) ensuring communication among the diverse parties responding to the hazard, and (e) not least, educating key operational personnel such as volcanologists, meteorologists, pilots, dispatchers, and air-traffic controllers about the hazard and how to respond to it (Guffanti and Miller, 2002). Arguably, implementation of these mitigation elements has reduced the likelihood of aircraft encounters with ash clouds. Fewer encounters have been reported since 1991 (Figure 1), while at the same time the amount of air traffic in volcanic regions grew (and the level of eruptive activity remained more-or-less constant).

But encounters do continue to occur for a variety of reasons. Unexpected eruptions occur at unmonitored volcanoes, and timely eruption reporting by volcanological agencies to the aviation sector sometimes is overlooked. Inherent limitations exist in remote-sensing methods of detecting ash clouds, including the time it takes to receive and analyze processed satellite data at ground facilities. Models for forecasting cloud dispersion also have significant limitations, such as incomplete input parameters describing the initial eruption plume and sparse wind-field data. Breakdowns occur in the multi-step process of information dissemination. Training and hazard awareness may be inadequate, especially as new personnel enter into critical positions.

Only as the above problems are identified and rectified can encounters be minimized or, ideally, eliminated altogether. Perversely, effective mitigation can give the erroneous perception that the hazard has been eliminated, leading to dangerous complacency. As our ability to prevent encounters improves to the point that even fewer incidents occur, we must not mistakenly conclude that no threat exists, but rather call for continued vigilance and support of proven, broad-based mitigation efforts.

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Tupper, A., Kamada, Y., Todo, N., Miller, E., this volume, Aircraft encounters from the 18th August 2000 eruption of Miyakejima, Japan.

Figure 1. Frequency of reported encounters of aircraft with volcanic ash, 1973-2003.

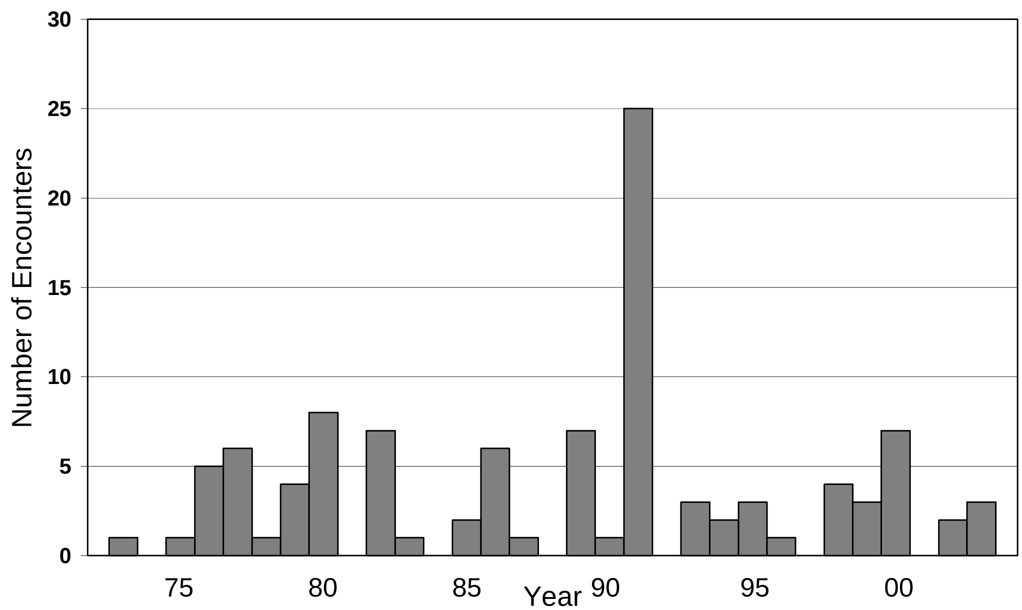

Table 1. List of volcanoes that produced ash clouds encountered by aircraft, 1973-2003. Volcanoes are organized by country, eruption year in parentheses.

Chile: Hudson (1991)

Colombia: Nevado del Ruiz (1985)

Dem. Rep. of Congo: Nyamuragira (1991)

Ecuador: Guagua Pinchincha (1999), Tungurahua (1999)

Guatemala: Fuego (1998), Pacaya (1987, 1993, 1998)

Iceland: Hekla (2000)

Indonesia: Colo (1983), Galunggung (1982), Langila (1997), Soputan (1985)

Italy: Etna (1989, 2000)

Japan: Asama (1973), Izu-Oshima (1986), Miyakejima (2000), Sakurajima (1975, 1977, 1978, 1979, 1982, 1986, 1991, 1994), Unzen (1991), Usu (1997)

Mexico: El Chichon (1982), Popocatepetl (1998)

Philippines: Pinatubo (1991, 1993)

Papua New Guinea: Manam (1993), Rabaul (1995)

Russia: Kliuchevskoi (1994)

United Kingdom: Soufriere Hills (1996, 2003)

United States: Anatahan (2003), Augustine (1976, 1986), Redoubt (1989, 1990), St. Helens (1980)

Table 2. Severity Index for Ash Encounters, from ICAO (2001, Appendix I, p. I-6).

Class	Criteria
0	Acrid odor (e. g. sulfur gas) noted in cabin Electrostatic discharge (St. Elmo's fire) on windshield, nose, engine cowls No notable damage to exterior or interior
1	Light dust in cabin; no oxygen used Exhaust gas temperature (EGT) fluctuations with return to normal values
2	Heavy cabin dust; "dark as night" in cabin Contamination of air handling and air conditioning systems requiring use of oxygen Some abrasion damage to exterior surface of aircraft, engine inlet, & compressor fan blades Frosting or breaking of windows due to impact of ash Minor plugging of pitot-static system; insufficient to affect instrument readings Deposition of ash in engine
3	Vibration of engines owing to mismatch; surging Plugging of pitot-static system to give erroneous instrument readings Contamination of engine oil hydraulic system fluids Damage to electrical system Engine damage
4	Temporary engine failure requiring in-flight restart of engine
5	Engine failure or other damage leading to crash

Table 3. Summary of Class 4 encounters, modified from ICAO (2001)

Encounter Date	Source Volcano	Encounter Altitude	Encounter Duration
25 May 1980	Mt. St.Helens, USA	15,000-16,000 ft	~4 minutes
24 June 1982	Galunggung, Indonesia	37,000 ft	13 minutes
24 June 1982	Galunggung, Indonesia	33,000-35,000 ft	unknown
13 July 1982	Galunggung, Indonesia	33,000 ft	unknown
15 December 1989	Redoubt, USA	25,000 ft	~8 minutes
17 June 1991	Pinatubo, Philippines	37,000 ft	2 minutes
17 June 1991	Pinatubo, Philippines	unknown	unknown
27 June 1991	Unzen, Japan	37,000 ft	unknown

AIRCRAFT ENCOUNTERS WITH VOLCANIC CLOUDS OVER MICRONESIA, OCEANIA, 2002/03

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Abstract

Three aircraft encounters with volcanic clouds were reported over the Micronesia area, northeast of Papua New Guinea; two in November 2002 and one in March 2003. Satellite analysis was performed using standard techniques, but no detectable ash was found in the area. Back and forward trajectories were then performed, to attempt to identify the source of the volcanic clouds. For the March 2003 encounter, the volcanic cloud most likely derived from Rabaul, Papua New Guinea, and was probably lofted from low altitudes to aircraft cruising levels during extensive convection in the area. The two aircraft in November 2002 appear to have encountered parts of a cloud approximately 350 km (190 nautical miles) across, and about 12 hours apart. One aircraft, an Airbus 340, reported intense St Elmo's Fire, and light white 'smoke' with 'burn smells'. Three pitot probes were replaced because of ash inside, some light abrasion was found on the engine air inlets but no damage on the windscreen or the nose, and no internal engine damage was reported. The second aircraft observed the ash cloud and smelt a slight odour but found no damage. In this case, the volcanic cloud almost certainly did not come from a local source, but was advected over a great distance. The most likely source of the cloud is the eruption of Reventador (Ecuador) twenty days earlier, but trajectory analysis is inconclusive.

Introduction

It is important that every aircraft encounter with volcanic clouds be investigated, even when the damage is relatively minor, and the available information is incomplete. Here, we discuss three such encounters over or near Micronesia, north and northeast of Papua New Guinea.

For these events, we produced forward and backward trajectories for the events described using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1998), implemented at the Australian Bureau of Meteorology and at NOAA (Draxler and Rolph, 2003), and the Canadian Meteorological Centre trajectory model (CMC, 2004), hereafter 'CMC trajectory model'. We also conducted reverse absorption and visible analysis using GMS, GOES and MODIS data.

Aircraft encounter on 8 March, 2003

On 8 March, 2003, at 1745 UTC an aircraft reported volcanic ash at FL330 (approximately 10 km altitude) to the Oakland, U.S.A., air traffic control centre. The position was given as within 60 nautical miles (111 km) of the equator at 156E, at the border of the Port Moresby (Papua New Guinea) and Oakland Oceanic Flight Information Regions. The information was passed on by telephone to the Guam Weather Forecast Office, which then issued a SIGMET for volcanic ash cloud.

The report was passed to Washington Volcanic Ash Advisory Centre (VAAC), who immediately contacted the Darwin VAAC, as the report originated within Darwin's area of responsibility (ICAO, 2004). Washington and Darwin meteorologists discussed the satellite analyses (no ash detected, no known major eruption, no obscuring factors such as cloud in the area), and both VAACs issued advisories to alert Meteorological Watch Offices in the area to the situation. The SIGMET issued from Guam was not found in Darwin VAAC communications traffic, indicating either an addressing problem or a problem in the message handling within the Australian Bureau of Meteorology.

No hard copy of the report was received in Guam, nor was any further information logged at Oakland (Frank Wells (NOAA), Steven Albersheim (US FAA), personal communications). Enquiries to various airlines have also proved fruitless; accordingly, we have no knowledge of damage caused or of any characteristics of the ash encounter, which is somewhat frustrating. Our analysis here is based on the assumption that the information received was correct, if sketchy.

Under this assumption, we surmise that the encounter did not cause severe on-board systems failure (from the lack of media reports), and that, as the encounter occurred on a moonless night, that visible or other sensible indications of volcanic ash were close to the aircraft in order to be observed by the crew.

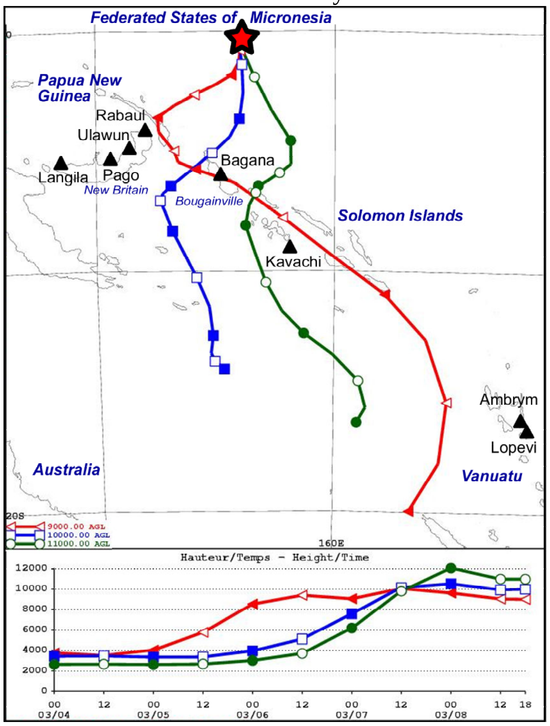

Figure 1-CMC backward trajectories for 8 March 2003 encounter, for endpoints at 9, 10 & 11 km at 18 UTC on 8 March 2003, beginning 4 March 00 UTC. Volcanoes with known or assumed activity during the period are indicated, and the star indicates the encounter location.

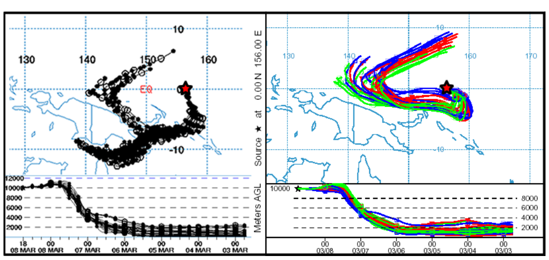

Figure 2 - 27-member ensemble HYSPLIT back-trajectories for 8 March 2003 encounter using (left) Bureau of Meteorology TLAPS analyses, and (right) NOAA FNL data. End-point separation 1 grid-point (horizontally), 0.01 grid point (vertically).

Figs. 1 & 2 show CMC trajectory model and HYSPLIT back-trajectories from the location of the encounter. Of the active volcanoes indicated in Fig. 1, explosive eruptions were most likely from Rabaul, Ulawun, Langila, Ambrym, and Lopevi. However, the only explosive activity actually observed (most of these volcanoes are not constantly monitored) was from Tavurvur cone at Rabaul, which fluctuated between 'white vapour' and 'convoluted pale grey ash clouds' rising a few hundred metres above the 223 m summit (Rabaul Volcano Observatory, 2003). This height is well below aircraft cruising levels, but the vertical motion shown in both figures suggests of the possibility of ash rising in convection or synoptic scale ascent.

The differences in the ensemble trajectories, and the differences between these trajectories and the CMC trajectory model, reflect the input analyses. In this case, TLAPS has probably captured the low-mid level monsoon trough slightly better because of the higher resolution. These ensemble trajectories suggest a more westward source than the CMC output, with many of the TLAPS ensemble members showing a source south of Papua New Guinea. This area is, however, not volcanically active: the most likely candidate volcanoes are in the New Britain region of Papua New Guinea, where the three models have all indicated a possible source region.

Satellite imagery at 1745 UTC on 6 March (not shown), indicates a deep layer cloud mass with embedded convection near Rabaul, associated with the convergence north of a strong monsoon trough and Coral Sea low near 15ºS (Darwin Regional Specialised Meteorological Centre, 2003). The cloud mass moved over a wide area, with cumulonimbus tops advecting slowly towards the northeast (and toward the position of the aircraft encounter) and dissipating. The situation two days later, at the time of the aircraft encounter, had another period of deep cloudiness beginning near New Britain, while skies near the encounter were relatively clear of cloud. This satellite analysis supports the strong vertical motion indicated by the model analyses.

The location of the suspected encounter is consistent with ash from eruptions at Rabaul, New Britain, several days earlier, transported in the vertical by enhanced ascent associated with an active monsoonal cloud mass. We presume that the concentration of ash at this time would have been quite low, given the effects of over 3 days of dispersion, enhanced for a period of at least 12-24 hours by moisture deposition and fallout within the precipitating cloud mass.

Aircraft encounters, 23/24 November, 2002

Fig.3 shows the locations of the two encounters discussed here. Three pilot reports were received, shown here with our comments in italics.

Encounter 1:

1. IDENTIFIER - *(removed for confidentiality)*
2. POSITION - 80NM NORTH W/P DOHRT-AWY B452 *(DOHRT is at 0N, 156.83E)*
3. TIME - 23.1728Z
4. FLT LEVEL - FL330 *(about 10 km)*
5. VOLC ACTIVITY OBSERVED AT - NOT REPORTED
6. AIR TEMP - M35C
7. SPOT WIND - 150/10

SUPP INFO - VOLCANIC ASH REPORTED AS FLYING IN CB *(cumulonimbus)* CLOUD
ACI RQST ANY REPORTS THAT U MAY HAVE RCVD.

In post-flight briefing, the aircraft crew reported intense St Elmo's Fire, and light white 'smoke' with 'burn smells'. These symptoms are characteristic of moderate severity ash encounters. The report was not transmitted during the flight because the crew were unable to establish contact with either Port Moresby or Oakland; radio interference is another characteristic of volcanic ash encounters. The aircraft, an Airbus 340, had three Pitot probes replaced because of ash inside, some light abrasion on the engine air inlets but no damage on the windscreen or the nose. The encounter lasted about one minute at cruising speed (≈900 km/h), suggesting an area of distinct ash cloud of the order of 15 km wide.

Eight hours later, a report was received from an aircraft on the ground at Rabaul:
LOCAL DATE - 24NOV2002
TIME (UTC) - 240330Z
A/C POSITION - ON THE GROUND TOKUA (AYTK) *(Tokua airport)*
A/C - P2-ANI
FLT NO. - PX204
VOLCANO NAME – TAVURVUR *(note: a cone at Rabaul)*
DIRECTION OF ASH DRIFT - VERY HEAVY ASH FRM VOLCANO GOING STRAIGHT INTO CLOUD (BASE 3000FT) *(about 900 metres)*
WIND - LIGHT NORTH WESTERLY

Four hours after this, a second encounter report was made:

Encounter 2:

1. IDENTIFIER - *(removed for confidentiality)*
2. POSITION - 0320N 15210E
3. TIME - 24.0717Z
4. FLT LEVEL - FL360 *(about 11 km)*
5. VOLC ACTIVITY OBSERVED AT - NOT REPORTED
6. AIR TEMP - NOT REPORTED
7. SPOT WIND - NOT REPORTED
8. SUPP INFO - PLAIN LANGUAGE QUOTE NOT CONCLUSIVE BUT POSS SLIGHT HAZE AND A LITTLE SMELL AT FL360 UNQUOTE

Additional information was also obtained from this airline: 'The pilot in charge of that flight acknowledges that the signs were inconclusive and not agreed by all flight crew. The time and location were his recollection of actual event. He added that looking down-sun the haze was evident, and looking up-sun there was a "corona" around the sun. They flew into clearer air without these signs a bit later.' Further inquiries elaborated on the phrase 'a bit later': 'they could discern a different "haze" below them for about 20 minutes before the sulphurous smell was noticed. That lasted for "2-3 minutes, less than 5 anyway"'. These additional data emphasise the importance of obtaining complete information at the time of a report. At cruising speed, a cloud observed for 20-25 minutes corresponds to an approximate cloud width of 300 – 375 km, with the area where the smell of sulphur was noticed about 30-45 km across.

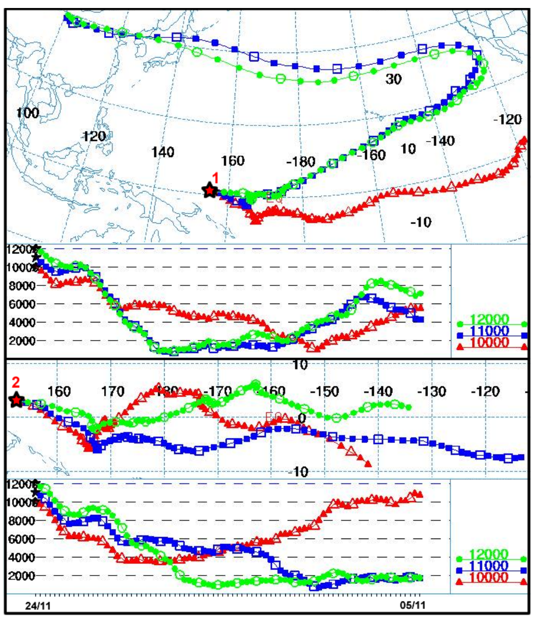

Figure 3 - 20-day back trajectories for Encounter 1 in November 2002, using HYSPLIT/GASP, ending 00 UTC 24 November 2002 (top), and for Encounter 2, ending 12 UTC (bottom). The positions of encounters 1 & 2 on 23/24 November are marked with stars.

Analysis of GMS-5/VISSR, EOS/MODIS and NOAA/AVHRR data (not shown) did not indicate any ash in the area. Back trajectories (Fig.3) show that the cloud at the position of Encounter 2 was near approximately 2N 157E at the time of Encounter 1 (that is, within 50 km of Encounter 1), and at altitude of 10 km. It is therefore highly likely that the aircraft encountered parts of the same cloud. Because Encounter 1 occurred during the night, any haze or corona (suggesting ash or sulphate aerosols) would probably not be observed, and the cloud was probably only noticed when a less diffuse area affected the aircraft for a short period. At the time of Encounter 2, the sun was low in the sky (4 degrees elevation), which would make the haze more visible. Had the flight been slightly later, it is possible that no report would have been made at all, since the smell of sulphur was not a mandatory reporting element for aircraft (this is expected to change in the near future).

One possible source of this ash cloud was, the entrainment of volcanic ash into deep convection. The report from Tokua airport gives a strong indication of this phenomenon. However, this event occurred after the first encounter, and some distance away. Moreover, satellite, manual and model analysis prior to the encounters (not shown) all had light and variable winds at the surface and strong easterlies in the upper levels, suggesting that advection of ash from Rabaul to the encounter location was virtually impossible. The active volcanoes in the vicinity of the encounters were the same as those shown in Figure 1, but short-term back-trajectories (not shown) indicate little chance of ash from these volcanoes being responsible for the encounters.

If the ash did not derive from a local source, then it must have originated in a major eruption some distance away. This would be consistent with the sizeable width of the diffuse cloud. Encounters with ash at a great distance from the source have occurred before (Casadevall, 1994). Fig. 3 shows an extended 20-day backward trajectory from the position of Encounter 1, using HYSPLIT-4 with GASP analysis data. This and other back-trajectories performed (not shown) initially came from the east, giving a high degree of confidence to the diagnosis of a remote eruption source. At a greater distance from the encounters, there is significant divergence in both position and altitude. Many trajectories meander along the equator, while others go near Hawaii, North America, and Japan. One CMC back-trajectory (not shown) reached as far as Italy, where Mt Etna was in eruption with ash being emitted at low levels.

However, by far the biggest eruption globally in November 2002 was the eruption of El Reventador, in Ecuador, South America, on 3-5 November. The eruption column was at least 17 km high, with approximately 53 kilo-tonnes of sulphur dioxide released, and an unknown quantity of ash (Smithsonian Institution, 2004). El Reventador is almost exactly east of the encounters (albeit 13950 km east!). Since the tropospheric portion of the eruption cloud was observed to drift westwards in equatorial easterlies, and the clouds associated with the encounters twenty days later came from the east, El Reventator is a potential source of the ash clouds.

Twenty-day forward trajectories from the last observed position of the Reventador ash were performed to further investigate the possibility of Reventador being the source of ash for the Micronesia encounters. Fig. 4 shows the CMC trajectory result for this case; the ash initially heads westwards for several to many days, reaching as far eastwards as 160W, then tracks southwards in the Southern Hemisphere. HYSPLIT trajectories also show a number of possible tracks, including into the Northern Hemisphere. In general the speed of movement of the ash is a little too slow to reach Papua New Guinea in twenty days, although of course this is very sensitive to altitude in the models. Therefore, although the circumstances remain suggestive, we are not able to definitively verify Reventador as the source using either satellite techniques or trajectory forecasts. On the other hand, we are unable to suggest any other likely sources.

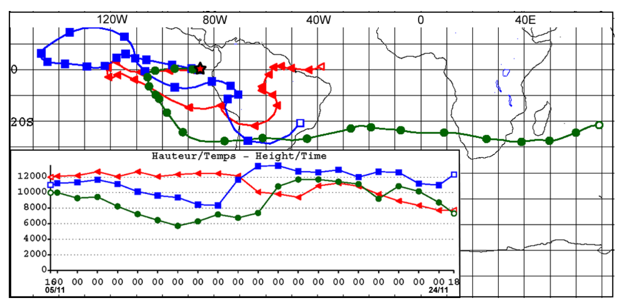

Figure 4 - 20-day CMC forward trajectories from the last known position of the Reventador eruption cloud, 5 November 2002.

Discussion

These cases show some of the more frustrating aspects of operational monitoring, detection and forecasting of volcanic ash for aviation:

- Pilot reporting is intermittent, sometimes not in real-time, and is often haphazard. The information obtained for November 2002 was remarkably good and reflects on the efficient operation of the airlines involved; on the other hand, the pilot report from March 2003 was vague and impossible to clarify.

- Volcanic eruption information in areas like the South Pacific is often difficult to obtain, due to resource and communication difficulties (Tupper and Kinoshita, 2003). Our analysis assumptions here have rested partly on the lack of major eruption reports from Bougainville, the Solomon Islands, and Vanuatu, all of which have inadequate volcanic monitoring.

- Satellite analysis was unable to identify volcanic clouds at the time of the encounters. This is not a new issue; satellite-based monitoring in the tropics is frequently problematic (Tupper *et al.*, 2004), increasing our reliance on ground-based reporting.

- For the March 2003 encounter, comparisons between trajectories based on different meteorological datasets show some significant divergence after 1-2 days. The trajectories suggest differences in the analyses of the three-dimensional wind field (e.g. strengths and/or positions of the monsoon trough, Coral Sea low, etc) and are an example of the increased uncertainty of trajectories in complex meteorological situations.

Conclusions

The volcanic ash from a reported aircraft encounter in March 2003, if reported correctly, most likely came from low level eruptions at Tavurvur, Rabaul, Papua New Guinea, after being advected to high levels during an active monsoon. In November 2002, an aircraft was significantly damaged by ash from an unknown source, and another aircraft flew through a part of the same cloud twelve hours later. The source of this cloud almost certainly was not local, and therefore originated from a major eruption elsewhere in the world. The most likely candidate source of the ash was El Reventador in Ecuador, but we are unable to prove this hypothesis to our satisfaction using either satellite or trajectory analysis. The volcanic clouds at the time of these encounters were not detectable by current satellite techniques.

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SULFUROUS ODORS: A SIGNAL OF ENTRY INTO AN ASH PLUME—BUT PERHAPS LESS RELIABLE FOR ESCAPE

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Although our understanding of odorous gases associated with volcanic ash plumes is incomplete, available reports indicate that during aircraft-ash encounters the pilots smelled sulfurous odors. Many people can smell the volcanic gases hydrogen sulfide (H_2S, "rotten egg") and sulfur dioxide (SO_2, "struck-match") at low concentrations—just a few parts per million (ppm). When subjects are exposed to sulfurous gases at slightly higher concentrations their smell receptors become saturated (undergoing 'olefactory fatigue'). Unless trained otherwise, pilots could arrive at the false sense that the gas is gone. Thus, pilots' sense of smell should reliably signal entry into (or proximity to) an ash plume; in contrast, once in a plume with significant regions above the saturation threshold, pilots' sense of smell could also mislead, providing a false sense of having emerged from the plume. Can such high concentrations occur? The few public records of aircraft-ash encounters suggest are inconclusive. Scientists have long known that large quantities of sulfurous gases escape during an eruption, but it is difficult to assess the gas concentrations of most ash plumes. Small droplets containing condensed sulfurous acids might also play a role. Thus, olefactory fatigue could plausibly present a very dangerous situation in the absence of other signs of entry into a plume (electrical discharges, clogged pitot tubes, etc.). Moreover, one could imagine the confusion induced by the perceived disappearance of the odor, as the aircraft penetrated into zones of higher or fluctuating H_2S concentrations. Pilots training might include brief exposure to low concentrations of sulfurous gases, with discussion of the strengths and limitations of the sense of smell, the range of observations that might confirm the presence of an ash cloud, and procedures leading to reliably escaping a plume. Scientists need to establish whether critical concentration thresholds are likely to be exceeded in eruptive plumes.