Aircraft encounters with volcanic clouds over Micronesia, Oceania, 2002-03

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Volcanic clouds pose a severe hazard to aviation; however, the extent of the threat, particularly for older clouds, is still undefined. This study examines three aircraft encounters with apparently 'old' volcanic clouds over Micronesia, northeast of Papua New Guinea, in November 2002 and March 2003. Satellite image analysis was performed using standard techniques, but no ash was detected in the area on the occasions of the encounters. Backward and forward trajectories and dispersion forecasts were produced using the emergency response models HYSPLIT and CANERM to provisionally identify the source of the volcanic clouds in each case. For the 8 March 2003 encounter, the volcanic cloud most likely originated from Rabaul volcano, in New Britain, Papua New Guinea, and was lofted from low altitudes to aircraft cruising levels during extensive convection in the area. For the two encounters on 23/24 November 2002, one of which caused significant but not life-threatening damage to the aircraft involved, the volcanic materials almost certainly did not come from a local source, but were advected over a great distance. The probable source was the explosive 3/5 November 2002 eruption of El Reventador, Ecuador, South America, approximately 14000 km east of the encounters. Using AIRS satellite data, we were able to track ash from this eruption along the forecast path towards the encounter locations for seven days before it became too difficult to track. This eruption cloud is probably the oldest and furthest travelled to have been known to cause damage to an aircraft. These cases highlight the gap between our remote sensing and modelling capabilities and the expectations of the aviation industry. Further work is required to better define the nature of the ash threat and the standard of warning service that we aim to provide, and to improve our capacity to provide the service.

Introduction

The International Airways Volcano Watch (ICAO 2006) is a global warning system designed to protect aircraft from volcanic ash. Volcanic Ash Advisory Centres in Anchorage, Buenos Aires, Darwin, London, Montreal, Tokyo, Toulouse, Washington and Wellington provide ash cloud detection and disper-

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sion information to Meteorological Watch Offices for SIGMET preparation*. Volcanic ash can cause engine failure, windscreen abrasion and damage to other aircraft surfaces, and the associated substances in volcanic clouds (e.g. sulphur dioxide, sulphuric acid) will also damage aircraft or pose health risks to passengers. There have been dozens of life-threatening and less severe encounters documented (Casadevall 1994; Casadevall et al. 1996; Hanstrum and Watson 1983; Simpson et al. 2002; Tupper et al. 2004). However, one point of uncertainty has been the concentration of ash necessary to cause significant damage to an aircraft. In general, the more severe the encounter, the better the information available, but often the damage information is insufficient for detailed investigation of incidents.

The encounter of a NASA DC-8 with a 35 hour-old eruption cloud from Hekla, Iceland, in February 2000 (Grindle and Burcham 2002, 2003) has sharply focused attention on this area. The NASA DC-8 flew for seven minutes in cloud that had up to 0.8 ppm SO_2, and nearly 30,000 particles cm^{-3} aerosols. Unfortunately, although the SO_2 concentration was just within the normally detectable range (0.3-1.4 ppm), the crew did not recognise the volcanic cloud and continued through; had the cloud been noticed by the crew, no doubt avoidance procedures would have been performed.

Grindle and Burcham (2002, 2003) concluded from their analysis that, although the volcanic cloud could only be deduced from the research instruments on board the aircraft, significant damage had been done to the engines, and engine life had been reduced as a result. Although this analysis is not universally accepted, if the result can be generalised, pilots flying in volcanically active areas may have experienced many unnoticed volcanic ash encounters, and may be flying aircraft with undetected engine damage.

Standard operating procedures for most aircraft require that engines that are suspected to have encountered ash be thoroughly inspected for damage using a borescope, an optical tool used for inspecting inaccessible areas, before continuing operations. After the eruption of Miyakejima, Japan in 2000, two aircraft required replacement of engines, while another that had also encountered ash close to the volcano was returned to service with no repairs necessary (Tupper et al. 2004). Even where there is no damage, the time that an aircraft is out of service while being inspected creates a significant cost for the airlines (of the order of hundreds of thousands of Australian dollars for a three-day inspection), and it would be useful to clarify what kind of encounters require inspections. Similarly, although many airlines emphasise complete avoidance of ash in their flight planning strategies (Cantor 1998), in practical terms such avoidance can be very costly. During the eruptions of Manam in Papua New Guinea in 2004/05, one airline reported diversion costs of ~AUD60 000 per day for a period of many months, simply caused by precautionary route closures (Tupper et al. 2006).

There is therefore an urgent need to examine cases of aircraft encounters with diffuse volcanic clouds, to help clarify the risk to aviation, the avoidance required, and whether the current operation of the International Airways Volcano Watch is sufficient for the aviation industry.

In this study, three aircraft encounters with 'old' volcanic clouds are discussed. Our analysis is frustratingly limited by a lack of concrete information in some areas. Nevertheless, we are able to suggest the likely sources of the clouds, identify some deficiencies with our current warning system, and suggest further ways to further improve the warning system.

Trajectory modelling and satellite analysis

We produced dispersion forecasts and 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 with GASP input meteorology (Seaman et al. 1995) and at NOAA (Draxler and Rolph 2003), and we also produced trajectories using the Canadian Meteorological Center trajectory model (CMC 2006b), hereafter 'CMC trajectory model'. Table 1 summarises the model configurations used in these analyses. It is difficult to give an idea of the typical uncertainty associated with dispersion and trajectory calculations, as in operations we see a very wide variation – on some occasions, the model analysed winds appear to be completely contrary to observed cloud movement and manually analysed winds. For the cases shown here, we have compared the trajectory and dispersion results with apparent cloud drift, analysed charts, and each other, and found no obvious problems in the analysis.

Operational satellite analysis techniques in the western Pacific are described in Tupper et al. (2004). For diffuse ash, the standard analysis technique is the 11-12 μm split-window or 'reverse' absorption technique

*A longer description of the International Airways Volcano Watch, some of the references cited here, a gallery of eruption images, and relevant links are available on the Darwin Volcanic Ash Advisory Centre website maintained by the Australian Bureau of Meteorology, at http://www.bom.gov.au/info/vaac.

(Prata 1989a, 1989b) which relies on a greater absorption of infrared radiation by ash-dominant clouds then by ice-dominant clouds at 11 μm. In the tropics, the technique can be less effective due to the higher level of background water vapour (Potts 1993), or the incorporation of large volumes of water into the cloud (Rose et al. 1995). However it is still generally effective for moderate to large eruptions, as long as the eruptions themselves are not obscured by cirrus from deep tropical convection (Tupper et al. 2004). For the cases described here, we analysed Geostationary Meteorological Satellite (GMS-5) Visible and Infrared Spin-Scan Radiometer data (VISSR), US National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data, and NASA Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) data according to the methods described in Tupper et al. (2004), filtering out cold temperature false alarms (Potts and Ebert 1996) and 'speckle' type noise in the reverse absorption imagery, and also using single channel infrared and visible imagery.

For the November 2002 case, we performed further analysis using non real-time Atmospheric InfraRed Sounder (AIRS) data. AIRS is an echelle grating spectrometer operating at wavelengths between 3.74 to 15.4 μm and is in polar orbit on board NASA's earth-observing Aqua platform. AIRS has 2378 spectral channels, a nominal (nadir) pixel size of 15x15 km and acquires images over a swath width of 1650 km. The retrieval schemes used to derive total column SO_2 and ash (silicate) mass loadings are described by Prata and Bernardo (2006) and Prata and Grant (2001), respectively. Sulphur dioxide is determined from the very strong SO_2 absorption feature located at 7.3 μm. AIRS channels near this wavelength region respond to upper-level (heights > 3 km) SO_2, provided water vapour loadings are small. The retrieval scheme accounts for atmospheric water vapour effects, but 'in-cloud' water vapour, water droplets and ice particles cause SO_2 retrieval errors. The ash retrieval scheme assumes spherical silicate particles, a modified-Γ particle size distribution, and uses a radiative transfer model that assumes isotropic radiation and neglects scattering, absorption and transmission of radiation above the ash cloud layer. Mass loadings are calculated on a pixel-by-pixel basis by integrating the retrieved particle sizes and assuming the ash is composed of silicate of density 2600 kg m^{-3}. The SO_2 retrievals have an accuracy of about 6 Dobson Units, while the mass loading retrievals, which require many more assumptions, may have errors of up to 50 per cent. The comparatively large AIRS pixel size (~225 km^2 compared to MODIS, ~1.2 km^2) results in low sensitivity at low concentrations or for small areas of ash. The low sensitivity is partially compensated by the high spectral resolution of AIRS. Generally speaking AIRS is unable to track ash clouds beyond a few days, unless the eruption is particularly large. For SO_2, AIRS has been able to track gas clouds for two weeks or more.

Aircraft encounter on 8 March 2003

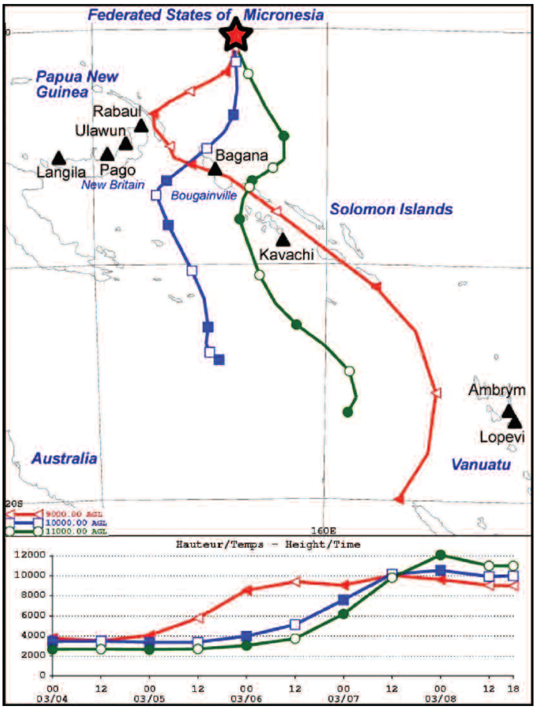
At 1745 UTC 8 March 2003, an aircraft reported volcanic ash at FL330 (approximately 10 km altitude) to the Oakland, USA, air traffic control centre. The position was given as within 60 nautical miles (111 km) of the equator at 156°E, at the border of the Port Moresby (Papua New Guinea) and Oakland Oceanic 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 2006). 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.

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. 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 an incident noticeable to the passengers (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. Clues to volcanic ash encounters can include St Elmo's Fire, the smell of sulphur, glazing of windshields, a glow in the engine intakes, instrumental malfunction, communication problems, 'dust' in the cabin and engine failure.

Figure 1 shows back-trajectories from the CMC trajectory model from the position of the assumed encounter (denoted by a red star), with the most active volcanoes in the area at the time indicated (Smithsonian Institution 2004). Of these volcanoes, explosive eruptions were most likely from Rabaul, Ulawun, Langila, Ambrym and Lopevi. We can be reasonably certain that there were no major eruptions

Fig. 1 CMC backward trajectories for 8 March 2003 encounter, for endpoints at 9, 10 and 11 km at 1800 UTC on 8 March 2003, beginning 4 March 0000 UTC. Volcanoes with known or assumed activity during the period are indicated, and the red star indicates the approximate location of the encounter. The red, blue and green lines represent ending heights of 9, 10 and 11 km respectively.



from any of these volcanoes, although Langila, Ambrym and Lopevi were not constantly monitored through this period. The only explosions actually observed were from the 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, although cloud reports from the ground are frequently limited by night or the plume going into the cloud base (e.g. Tupper et al. 2006).

Ensemble HYPSLIT back-trajectories (Draxler 2003) were performed with TLAPS and FNL data (Table 1, Fig. 2). 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.

The trajectories in Figs 1 and 2 all show relatively strong model vertical motion on 7 March 2003, at about the time that the trajectory members are passing New Britain. Figure 3 gives the vertical velocity field for a NOAA FNL-based back-trajectory, and takes a parcel from low levels to aircraft cruising levels within hours. It appears that the analyses have captured

Table 1 Model characteristics during post-analysis (2003/04). Note: tabulated resolution is the grid spacing of input analyses, not necessarily the native resolution of the model analyses.

Model	*Input meteorology*		
	Model/data used	*Horizontal resolution*	*Vertical resolution*
HYSPLIT 4.7 (Australia)	Global Assimilation and Prognosis (GASP) (Seaman et al., 1995)	2.5 deg.	19 levels
	Tropical Limited Area Prediction System (TLAPS) (Davidson and Puri, 1992)	0.375 deg.	29 levels
HYSPLIT 4.7 (USA)	FNL (final) archive model analysis data (NOAA, 2006b), NCEP/NCAR Reanalysis meteorology (http://www.arl.noaa.gov/ss/transport/archives.html	0.9 deg. (near equator), 2.5 deg.	13 levels, 17 levels
CMC trajectory (Canada)	Canadian Meteorological Centre Global Data Assimilation and Forecasts System archives (CMC 2006a)	0.9 deg.	28 levels

Fig. 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). Note: time-scale at bottom is in opposite direction to Fig. 1.

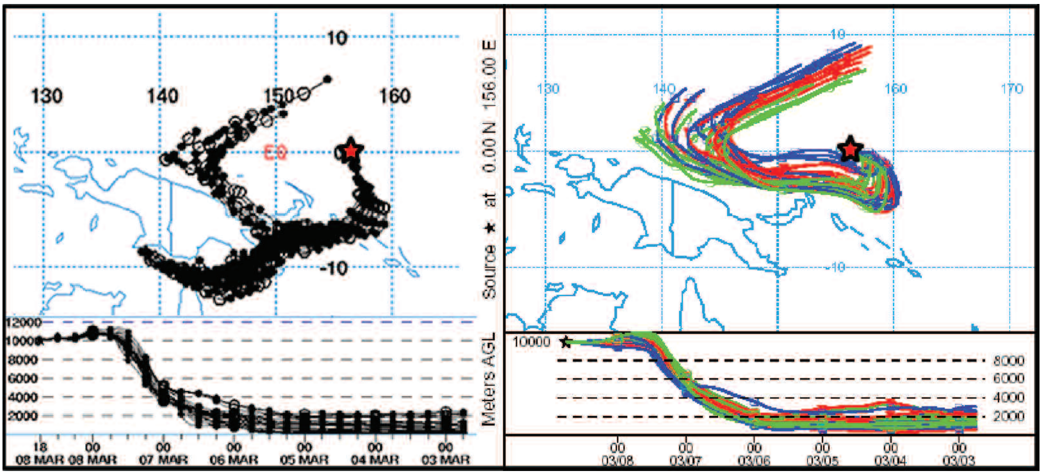
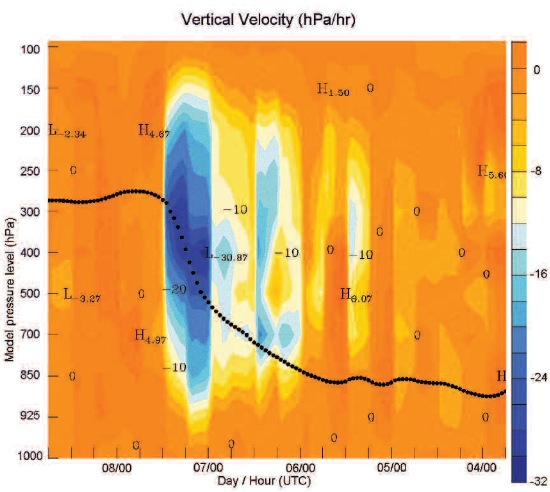


Fig. 3 FNL vertical velocity for NOAA-HYSPLIT back trajectory starting at 8 March 2003 encounter position. Black dots show the trajectory height, in terms of atmospheric pressure, at hourly intervals.

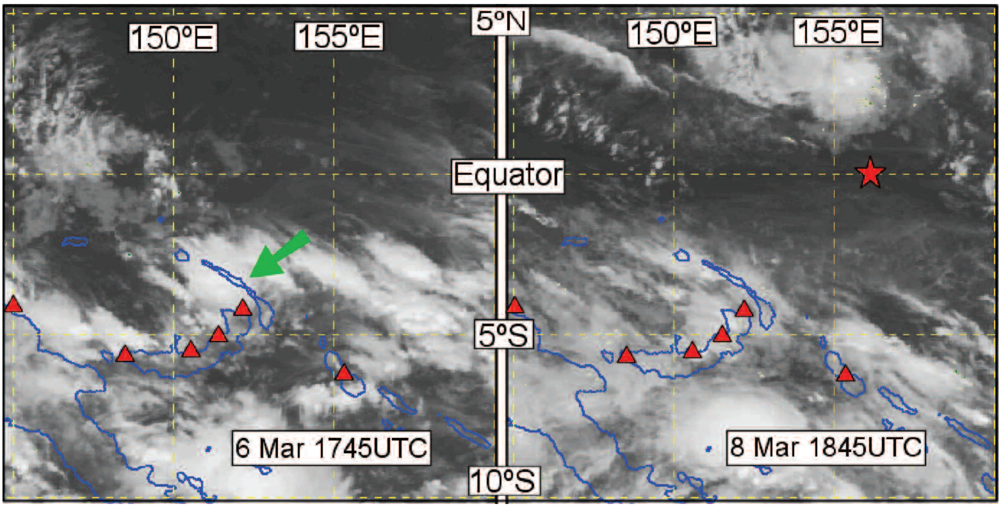


monsoonal convection associated with large-scale ascent, which could have resulted in passive transport to high altitudes. Another possibility is that ash has been quickly lifted in thunderstorm convection; this is not explicitly captured by the models, but is already known to be able to transport ash above cruising altitudes (Tupper et al. 2005).

Combined infrared/reverse-absorption satellite images are shown in Fig. 4; detected volcanic ash would show in green or red shades (Tupper et al. 2004). No ash can be seen, suggesting that any ash was either very diffuse or masked by ice. Consistent with the back-trajectories and model vertical motions, the image on the left, at 1745 UTC 6 March 2003, does show a deep layer cloud mass with embedded convection near Rabaul (green arrow), associated with the convergence north of a strong monsoon trough and Coral Sea low near 15°S (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 (Fig. 4, right image), at the time of the aircraft encounter (red star), shows another period of deep cloudiness beginning near New Britain, while skies near the equator were relatively clear of cloud.

In summary, 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 three days of dispersion, enhanced for a period of at least 12 to 24 hours by moisture deposition and fallout within the precipitating cloud mass. Further analysis of this case is limited by the lack of a detailed written report from the aircraft involved.

Fig. 4 **Convective activity near Rabaul on 6 March 2003 (left), and cloud distribution at time of 8 March 2003 encounter (right). The location of the encounter is marked with a red star. GMS-5 'reverse' absorption / IR1 imagery (see text).**



Aircraft encounters, 23/24 November 2002

Three written pilot reports were received for the November events, shown here with our comments in italics, and Fig. 5 shows the location of the encounters together with some back-trajectories from the encounter locations.

Encounter 1

1. IDENTIFIER - *(removed for confidentiality)*
2. POSITION - 80NM *(~150 km)* NORTH W/P DOHRT-AWY B452 *(DOHRT is at 0N, 156.83E)*
3. TIME - 23.1728Z *(23 November 1728 UTC)*
4. FLT LEVEL - FL330 *(about 10 km)*
5. VOLC ACTIVITY OBSERVED AT - NOT REPORTED *(no eruption observed)*
6. AIR TEMP - M35C
7. SPOT WIND - 150/10 *(a southeasterly wind at 10 knots, or ~5 m s^{-1})*
8. SUPP INFO - VOLCANIC ASH REPORTED AS FLYING IN CB CLOUD ACI RQST ANY REPORTS THAT U MAY HAVE RCVD. *(We've encountered volcanic ash while flying in a cumulonimbus top, please tell us what's going on.)*

In post-flight briefing, the aircraft crew reported intense St Elmo's Fire, and light white 'smoke' (ash) with 'burn smells' (most probably indicating the presence of SO_2 together with the ash). 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 at least 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, on the south side of the Rabaul Caldera)*
VOLCANO NAME – TAVURVUR *(the active volcanic cone at Rabaul)*
DIRECTION OF ASH DRIFT - VERY HEAVY ASH FRM VOLCANO GOING STRAIGHT INTO CLOUD (BASE 3000 FT) *(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 *(no eruption observed)*
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

In discussion, the pilot in charge of this flight acknowledged that the signs were not agreed by all flight crew. However they could discern a different 'haze' below them for about 20 minutes before the sulphurous smell was noticed for 2 to 3 minutes. Looking down-sun the haze was evident, and looking up-sun there was a 'corona' around the sun. These additional data emphasise the importance of obtaining complete information at the time of a report. At cruising speed, a cloud observed for 20 to 25 minutes corresponds to an approximate cloud width of (assuming a circular cloud) at least 300 to 375 km, with the smell noticed over an area of at least 30 to 45 km across.

Analysis of GMS-5/VISSR, EOS/MODIS and NOAA/AVHRR data (not shown) did not identify any ash in the area. Back trajectories (Fig. 5, inset) suggest that the cloud at the position of Encounter 2 was near approximately 2°N 157°E at the time of Encounter 1 (that is, within 50 km of Encounter 1), and at altitude of 10 km. It is therefore almost certain 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° elevation), which would have made 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 in itself was not a mandatory reporting element for aircraft at that time.

One possible source of this ash cloud was the entrainment of volcanic ash into deep convection, as discussed for the March encounter. The report from Tokua airport is a strong indication of this phenomenon. However, this event occurred after the first encounter, and some distance away. Moreover, manual and NWP 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. Satellite analysis of the area clearly shows that higher-level clouds were moving from east to west, consistent with the numerical analyses. The active volcanoes in the vicinity of the encounters were the same as those shown in Fig. 1, but short term back-trajectories (not shown) indicate little to no 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. For example, in 1989 an eruption cloud from the Mt Redoubt, Alaska, eruption caused loss of power to an aircraft engine over Texas, 5400 km away (Casadevall 1994), and in 1991 ash from Cerro Hudson in southern Chile circled the Southern Ocean to cause non-damaging aircraft encounters over Australia (Barton et al. 1992).

Fig. 5 **20-day back trajectories for Encounter 1 in November 2002, using HYSPLIT/GASP, ending 0000 UTC 24 November 2002 (top), and for Encounter 2, ending 1200 UTC (bottom). The positions of encounters 1 and 2 on 23/24 November are marked with red stars. The red, blue and green lines are for trajectories ending at 10, 11 and 12 km above ground level respectively. Solid markers are at six hourly intervals, and hollow markers at 24 hour intervals.**

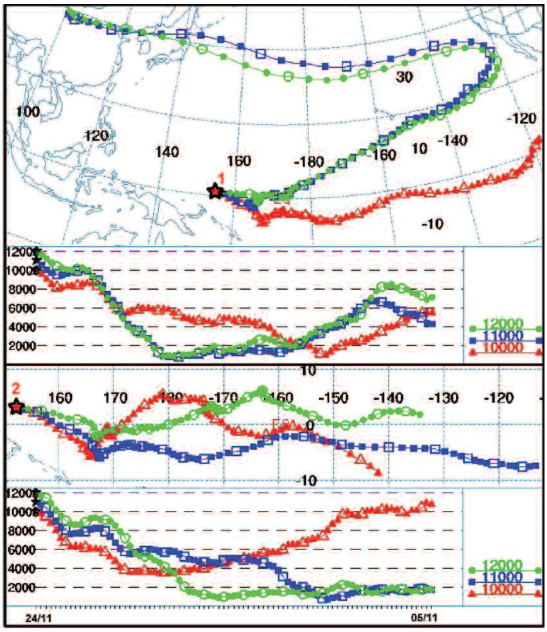


Figure 5 shows an extended 20-day backward trajectory from the position of Encounter 1, using HYSPLIT-4 with GASP analysis data. This and other back-trajectories performed (not shown) initially came from the east, giving a high degree of confidence to the diagnosis of a remote eruption source. At a greater distance from the encounters, there is significant divergence in both position and altitude. Many trajectories meander along the equator (for example, the 10 km (red) trajectory in Fig. 5, and all the trajectories in the inset), 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 and ash being emitted at low levels.

However, by far the biggest eruption globally in November 2002 was the sudden explosion of El Reventador in Ecuador, South America, on 3 to 5 November. The eruption column was at least 17 km high, with approximately 53 kilotonnes of sulphur dioxide released, and an unknown quantity of ash (Smithsonian Institution 2004). El Reventador is almost exactly east of the encounters (albeit 13,950 km east). Since the clouds associated with the encounters twenty days later came from the east, El Reventator is an obvious potential source of the ash clouds.

Real-time Washington VAAC advisories tracked the Reventador cloud as far west as 90°W using GOES data, before it became too indistinct on operational imagery to follow (NOAA 2006a).

During the November 2002 eruptions of Reventador, AIRS was able to image both SO_2 and ash clouds. There were 62 AIRS granules* processed to derive ash mass loadings and SO_2 total column for the period 4-25 November covering the geographic region from 30ºW to 140ºE (in the westward direction) and 10ºS to 10ºN. We were only able to identify ash and SO_2 clouds in a coherent manner in data from 4 to 10 November. Figures 6 and 7 show the cumulative SO_2 and ash mass loadings respectively, derived from 20 AIRS granules for the period 4 to 10 November 2002. The bulk of the SO_2-rich clouds spread eastwards at upper tropospheric or lower stratospheric altitudes, crossing Brazil and entering the Atlantic before the AIRS retrievals were unable to unambiguously identify the SO_2 cloud. The lower-level (tropospheric) ash-rich clouds mainly travelled westwards, towards the Galapagos and further into the Pacific Ocean. By 11 November the ash was too dispersed to be clearly identified in AIRS data, or reached a concentration that is below the sensitivity of AIRS. The AIRS data indicate that the bulk of the ash-rich cloud travelled westwards and in an opposite direction to the bulk of the SO_2-rich cloud.

To test the hypothesis that the westward-travelling Reventador ash may have caused our encounters, we performed 26-day ensemble trajectories and dispersion model runs from the eruption location. Figure 8 shows a sample of the results of runs from the eruption location. The ensemble trajectory runs are consistent, except for a group of trajectories in the US output that quickly went into the southern hemisphere mid-latitudes and circled the Southern Ocean. Particles from the given starting altitude follow the observed path of ash indicated by Fig. 7, and the majority of trajectories then continue directly westwards to Papua New Guinea and Indonesia at various altitudes. Two different presentations of the dispersion concentrations are shown; for 10 km above msl only (Fig. 8, panel C), and for all heights (panel D). In both runs shown here, the major portion of the westward-moving cloud has approached the area of the encounters at the time of the encounters; the Australian output has the cloud over the region already, and the US output had slower transport with the cloud not yet in the area. Given the uncertainties that we would expect to be associated with very long dispersion runs, these results would appear to support the idea that the ash was from Reventador.

*An AIRS granule consists of 90 pixels by 135 lines by 2378 channels.

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; on the other hand the report from March 2003 was vague and impossible to clarify. Issues relating to pilot reporting are discussed in Simpson et al. (2002) and Tupper et al. (2006). In response to these concerns, measures leading to the improvement of pilot reports, and the documentation of all aircraft encounters with volcanic clouds, are being taken by the International Civil Aviation Organisation's International Airways Volcano Watch Operations Group.

Satellite analysis was unable to identify volcanic clouds at the time of the encounters. This is not a new issue, but bears restating; remote sensing algorithms are not sufficiently reliable to detect and monitor volcanic ash to the extent required for aviation ash avoidance. The issue of transport of volcanic ash in convection or in broadscale uplift is difficult to deal with. Convection is not explicitly treated in these models, and entrainment and detrainment mass fluxes depend on the nature of the convection and subtle variations in the atmospheric profiles (Cohen 2000). However, in the right circumstances, convection can lift large quantities of aerosols into the upper troposphere or lower stratosphere (Fromm and Servranckx 2003; Fromm et al. 2006; Tupper et al. 2005). It is possible to detect the effect of sufficient concentrations of volcanic ash in convective clouds during the day because of their reduced particle effective radius (Tupper et al. 2005), but night-time detection will remain a problem. A possible solution is to issue a 'Notice to Airmen' (NOTAM) when circumstances favourable for uplift of ash in volcanic-Cb are identified (Tupper et al. 2006).

Fig. 6 Total column SO_2 retrieved from AIRS infrared spectra (~7.34 μm) for the period 4-10 November 2002.

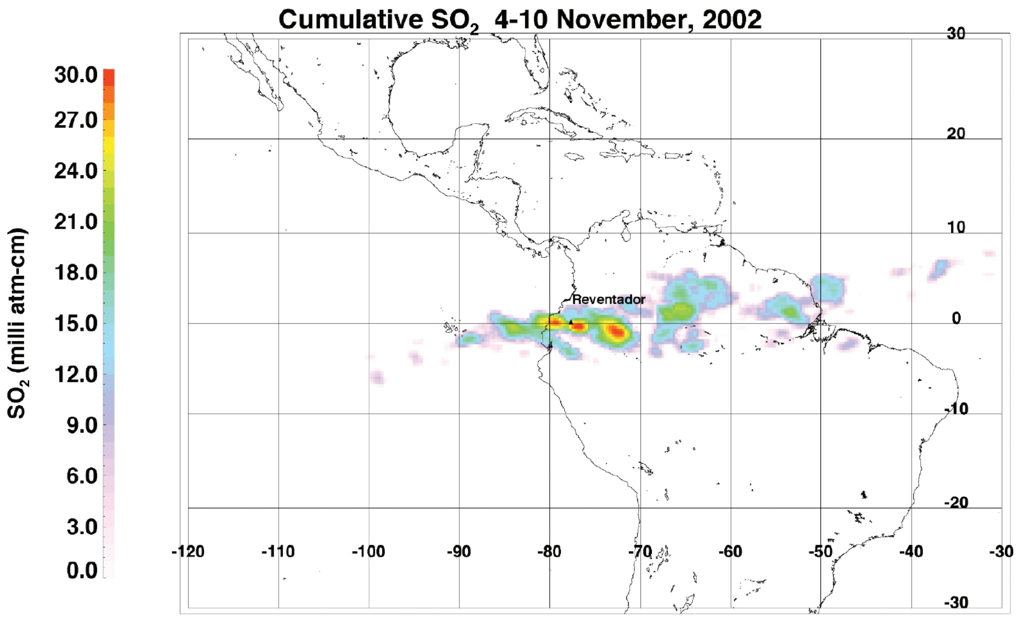


Fig. 7 Ash (silicate) mass loading (mgm^{-3}) derived from AIRS infrared spectra (~10-12 μm) for the period 4-10 November 2002.

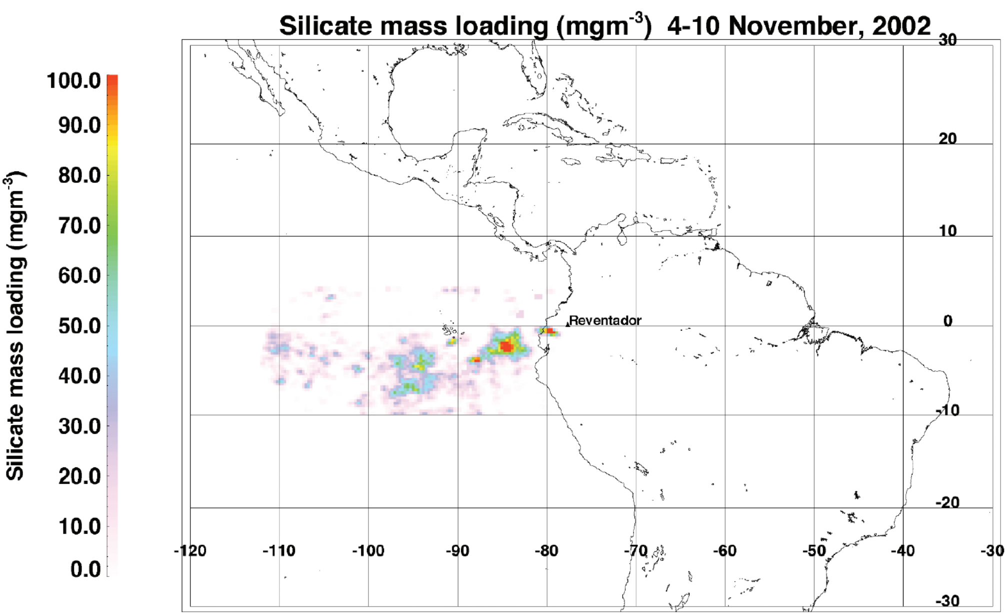
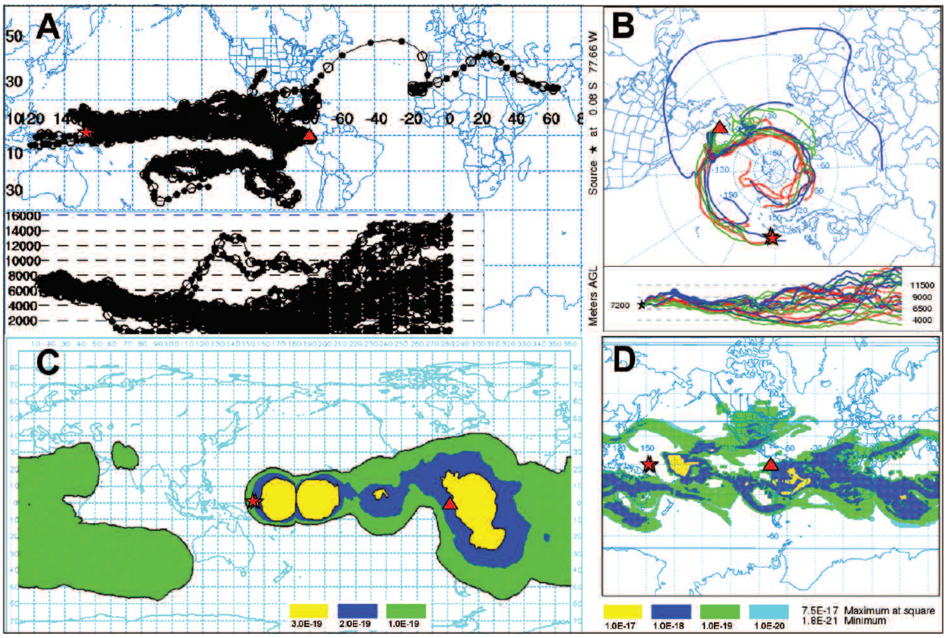


Fig. 8 **HYSPLIT forward trajectories and dispersion modelling for 3-4 November 2002 Reventador eruption, with location of volcano marked as a red triangle, and encounter locations for 23-24 November marked with overlapping red stars. The eruption length was assumed to be 8 hours, starting at 1400 UTC 3 November 2002, to a height of 18000 m with column base 3500 m. (a) 26-day ensemble trajectories from 1400 UTC 3 November starting at 7.2 km above ground level, using GASP input data, (b) as for (a) but with NCEP/NCAR reanalysis meteorology, (c) integrated concentrations for 10 km level, for 24 hours from 0000 UTC 24 November using GASP input data, and (d) integrated concentrations averaged between 0 and 16 km above msl for 24 hours from 1400 UTC 23 November, using NCEP/NCAR reanalysis meteorology.**



One issue raised in Servranckx and Chen (2004) is that there has been no defined criterion for the cloud density that we are attempting to warn for, beyond the vague term of a 'visual' ash cloud. There are a number of reasons for this. The main ones are: (a) lack of quantitative data defining the eruption parameters that are used as input to the volcanic ash dispersion and transport models; and (b) lack of quantitative 3D measurements of airborne volcanic ash from satellites or other instruments. The cases discussed here would, if borescope analysis on the engines had been performed and reported for each encounter, have contributed to our knowledge in this area. However, despite the lack of such an analysis, we can still draw some conclusions from the November 2002 encounters. In encounter 1, both ash and SO_2 were sensible to the pilots, and the aircraft suffered damage. In encounter 2, the smell and the haze were both marginal, but were still noticed. In both cases then, the cloud probably had higher particulate and SO_2 concentrations than the 2000 Hekla cloud, despite the probable greater age of the Micronesia cloud. We should examine the possibility of replacing a 'visual' ash cloud concept with a more quantitative definition using the unique measurements provided by the research aircraft that reported damage after an encounter with the Hekla cloud (Grindle and Burcham 2003). Actually implementing such a standard worldwide would of course be problematic.

Conclusions

The volcanic ash from a reported aircraft encounter on 8 March 2003 most likely came from low-level eruptions at Tavurvur, Rabaul, Papua New Guinea, after being advected to high levels during active convection or broadscale monsoonal uplift more than a day previously. The cloud responsible for the two aircraft encounters on 23/24 November 2002 probably originated from El Reventador in Ecuador 20 days earlier, which would represent the longest-travelled (~14 000 km) volcanic cloud known to have damaged aircraft; longer than the ~5400 km travelled by the 1989 Mt Redoubt cloud to where it caused engine failure over Texas (Casadevall 1994).

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