NAME modelling of aircraft encounters with volcanic ash plumes from historic eruptions

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Abstract

Prolonged disruption to aviation during the April - May 2010 eruption of Eyjafjallajökull, Iceland resulted in pressure to predict ash concentrations within the volcanic cloud for the purpose of considering allowing aircraft to fly in regions where ash concentrations were below an acceptable limit. Over the past few decades there have been a number of incidents where aircraft have flown into volcanic ash clouds resulting in damage to the aircraft and, in the most serious cases, loss of power to all engines. Understanding the volcanic ash concentrations these aircraft encountered provides important input to determining a safe concentration limit.

In this technical note we study six historic volcanic eruptions associated with aircraft encounters, namely Galunggung 1982, Soputan 1985, Redoubt 1989, Pinatubo 1991, Hekla 2000 and Manam 2006. Atmospheric dispersion modelling of these incidents is conducted using NAME (Numerical Atmospheric-dispersion Modelling Environment) to estimate ash concentrations. Uncertainties in the eruption source detail (start time, stop time and eruption height) and in the aircraft encounter location and flight path are found to be major limitations in some cases. In addition, errors in the driving meteorological data (which is often coarse in resolution for historic studies) and the lack of plume dynamics (for example, representation of umbrella clouds) in dispersion models results in further uncertainties in the predicted ash concentrations.

In most of the case studies, the dispersion modelling shows the presence of ash at the aircraft encounter location. Maximum ash concentrations in the vicinity of the aircraft are predicted to be at least $4000\ \mu g m^{-3}$ although confidence in the estimated concentrations is low with uncertainties of orders of magnitude shown to be possible.

1 Introduction

The 2010 volcanic eruption of Eyjafjallajökull, Iceland highlighted the disruption that can occur to air travel when large quantities of volcanic ash are emitted into the atmosphere near major flight paths. To combat the threat to aviation of volcanic ash, the accepted guidance prior to the 2010 eruption of Eyjafjallajökull was that ash should be completely avoided by aircraft [17]. This guidance was used as the basis of the International Civil Aviation Organization's volcanic ash contingency plan for the European region [18].

As the 2010 Eyjafjallajökull eruption continued over a prolonged period and much of aviation into and out of Europe was brought to a standstill, pressure mounted from the airlines to allow aircraft to fly within regions of the volcanic plume with low levels of ash. By the end of the incident, aircraft were allowed to fly in the predicted plume within regions of low ash concentration provided the airlines then conducted enhanced checks and maintenance schedules. The decision to permit such operations was taken by the UK Civil Aviation Authority (CAA) after discussion with aircraft engine manufacturers, European transport ministers, Eurocontrol and input from various scientific experts including those from the Met Office, UK. One piece of information relevant to this decision was an estimate of the ash concentrations which caused damage to aircraft during historic encounters with volcanic plumes.

Over the past 30 years there have been a number of cases in which aircraft have encountered volcanic ash plumes resulting in varying degrees of damage to the aircraft and, in the most serious cases, loss of power to all engines [11]. The range of damage that may occur to aircraft flying through a volcanic eruption cloud depends on the concentration of volcanic ash in the cloud, the length of time the aircraft actually spends in the cloud, and the actions taken by the pilots to get out of the cloud [9]. Fortunately, to date there has been no loss of life, but these historic events highlight the serious nature of the problem.

In this technical note we study six historic volcanic eruptions between 1982 and 2006 that were associated with aircraft encounters with ash clouds. Atmospheric dispersion modelling results and the predicted ash concentrations encountered in each incident are presented. A number of difficulties, resulting in (often significant) uncertainties in the predicted ash concentrations, are identified and discussed

2 Modelling strategy

The Numerical Atmospheric-dispersion Modelling Environment (NAME) [20] is the UK Met Office's atmospheric dispersion model and the operational model of the London Volcanic Ash Advisory Centre (VAAC). It was initially developed following the Chernobyl accident but now has a wide range of uses including emergency response work to predict the transport and spread of airborne diseases and other hazardous substances (e.g. chemical, biological and nuclear), volcanic ash modelling, dust modelling, air quality forecasting, and determination of pollutant source strengths and locations [4, 22, 30, 46]. The NAME model has been validated against observations and other atmospheric dispersion models in a number of studies [8, 33, 48].

NAME is a Lagrangian model in which large numbers of model 'particles' are released into the model atmosphere. Each 'particle' represents a certain mass of the released material which is reduced over time by wet and dry deposition processes. The transport and dispersion of material is governed by the input meteorological data. For volcanic ash modelling, a particle size distribution, based on measurements of volcanic ash presented in Hobbs et al. [13] and including the 1989 - 1990 eruption of Redoubt discussed in Section 3.3, is adopted (table 1). It is assumed that volcanic ash particles with diameters larger than 100 μm fall out near to the source and are of minimal interest away from the proximity of the volcano. Sedimentation of volcanic ash particles due to gravitational settling is included within NAME, with the sedimentation rate determined as a function of the particle size.

Diameter (μm)	Cumulative mass fraction
0.1	0
0.3	0.001
1.0	0.006
3.0	0.056
10.0	0.256
30.0	0.956
100.0	1.0

Table 1: The particle size distribution for volcanic ash used by NAME

There is no treatment of the dynamics of the rising volcanic plume in the simulations presented here. Instead a uniform mass release profile from the volcano summit to the observed / estimated plume top is used. The volcano ash release rate is determined by

$$M = 88.2H^{1/0.225}, \qquad (1)$$

where M is the mass release rate in kg s^{-1} and H is the height of the plume top above the volcano summit in kilometres. Equation (1) was used during the 2010 Eyjafjallajökull eruption and was determined by fitting a continuous curve to the VAFTAD table [22] and calibrating using Mastin et al. [24] (see [47] for details). The estimated mass release rate determined using equation (1) compares well with that given by Mastin et al. [24], obtained from plume height and mass eruption rate information from a number of well studied volcanic eruptions (see figure 1). Between 90% and 99.9% of the emitted mass is thought to fall out close to source due to organised downdrafts and gravitational settling of large tephra grain sizes and of aggregations of smaller grain sizes. There are, however, significant uncertainties in the mass release rate (Mastin et al. [24]) and in the fall out rate.

Hourly averaged volcanic ash concentrations are generated on a horizontal output grid with a

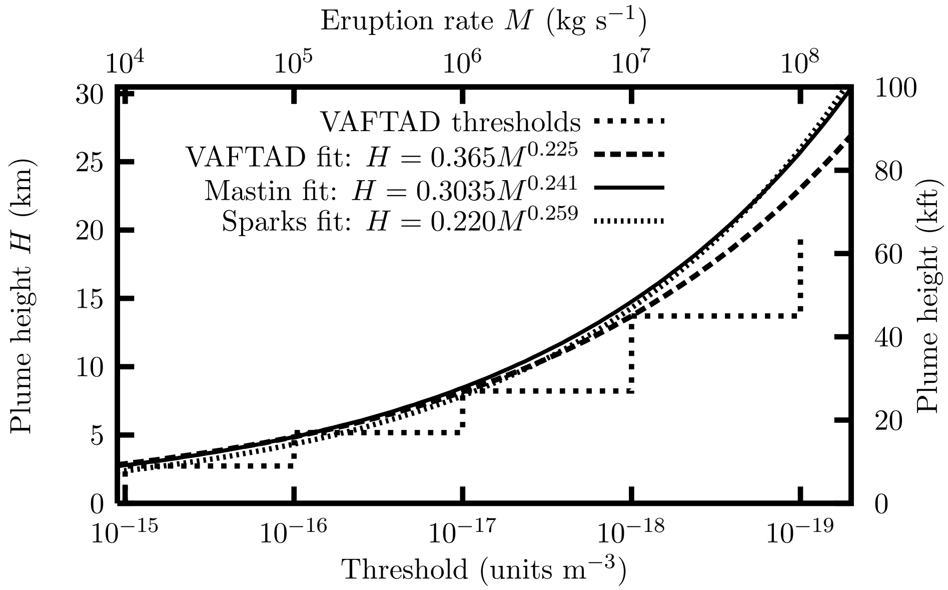


Figure 1: A comparison of estimates of eruption rate M as a function of the plume rise height H above the vent. The estimates made by Sparks et al. [42] (see their section 5.2) and by Mastin et al. [24] are shown, together with the estimates obtained using the calibrated VAFTAD thresholds (for a vent height of 5,000 feet) and using a power fit to the calibrated thresholds. For the VAFTAD thresholds, the lower axis shows the VAFTAD 'visual ash' threshold for a 1 unit release while the upper axis shows the eruption rate.

resolution of 0.1°× 0.1° and over three vertical layers: FL000 - FL200, FL200 - FL350 and FL350 - FL550, where FL are flight levels which are approximately equivalent to hundreds of feet. The horizontal and temporal resolution is relatively high compared with that often used in operational set-ups when model run-time is key. The higher temporal and horizontal spatial resolution gives a better representation of ash concentrations at locations near to the volcano or when the release duration is short-lived; situations which are both of relevance to the aircraft encounters investigated here. To account for unresolved peak concentrations within the thick layers used, a conversion factor (a peak-to-mean ratio) is used to convert the NAME predicted mean volcanic ash concentrations into predicted peak concentrations. In reality, this conversion factor and the factor accounting for near-source fall out have been found to roughly cancel out [47]. Hence, using the total eruption mass release rate, M, and neglecting these factors (or taking their product to be unity) leads to a reasonable estimation of peak concentrations although this is a significant source of uncertainty in predicted concentrations. For aircraft encounters which occurred close enough to source that only a fraction of the near-source fall out had occurred, one might expect these assumptions to under-predict ash concentrations. Also the unresolved concentration peaks may have different properties from those considered in Webster et al. [47], both due to the higher model resolution and due to the fact that often our interest here is in the regions closer to the volcano. These two causes are likely to lead to effects that have opposite sign but that are not easily estimated, giving another source of uncertainty in our results.

For volcanic ash modelling, NAME is usually driven by numerical weather prediction (NWP) data from the Met Office's Unified Model (MetUM) [3]. Over the years, the resolution of the MetUM has increased and accuracy has improved, due to advances in both science and computing. Currently the global MetUM has a horizontal resolution of approximately 25 km in mid-latitudes. For historic events, however, the availability of meteorological data, and the lower resolution of the NWP models used at the time, limits the modelling. For the most recent of the historic cases studied, namely Manam and Hekla (table 2, below), the Met Office's global MetUM data are available at horizontal resolutions of approximately 40 km and 60 km, respectively. For the earlier historic cases, the meterological data used are the ERA-Interim and ERA-40 NWP reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) with horizontal resolutions of approximately 85 km and 125 km, respectively. All meteorological data sources used for these historic case studies have a temporal resolution of 3 hours.

Throughout this technical note, altitudes are given above sea level (asl) unless otherwise stated.

3 Case studies

Six historic volcanic eruptions associated with aircraft encounters have been studied (table 2, figure 2). These include the well-known all engine flame-out incidents that occurred following the 1982 Mount Galunggung and the 1989 Mount Redoubt eruptions. Each incident is described in turn and NAME modelling of the ash concentrations encountered is presented. Further information on the incidents can be found in Guffanti et al. [11].

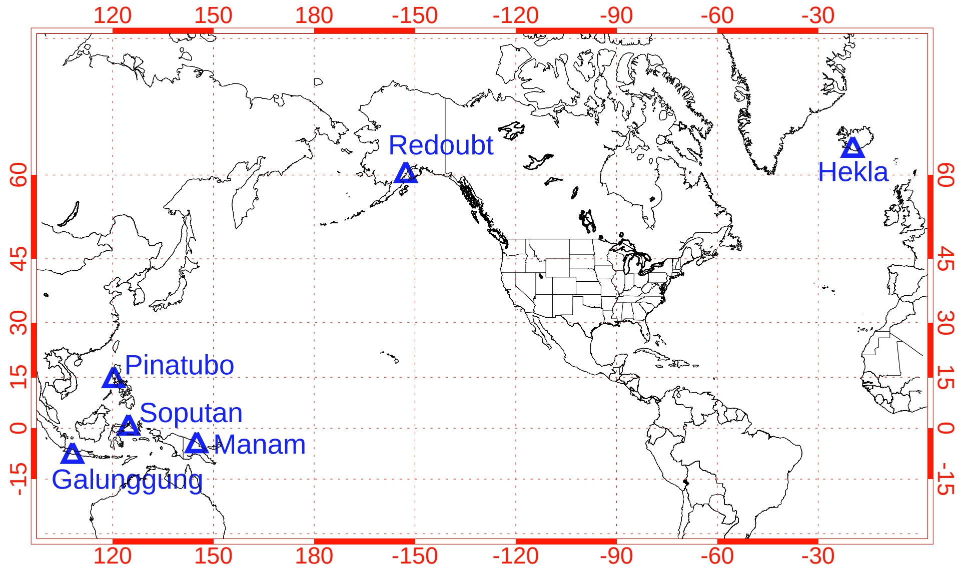


Figure 2: The location of the six volcanoes associated with the aircraft encounters studied

Volcano	Eruption date	Effects of aircraft encounters	NWP analysis met data
Galunggung, Indonesia	June 1982	747:- In-flight loss of power to all 4 engines, heavy abrasion to leading edges and windows.	ERA-40
Soputan, Indonesia	May 1985	747:- In-flight observations of St Elmo's fire and dust in cabin. Subsequently found to have damage to all 4 engines	ERA-40
Redoubt, Alaska	December 1989	747:- In-flight loss of power to all 4 engines. Damage to aircraft estimated at $80 million.	ERA-Interim
Pinatubo, Philippines	June 1991	At least 20 aircraft encounters causing damage to engines, windows, probes, lights and aircraft edges. In-flight failure of engine(s) in two encounters.	ERA-Interim
Hekla, Iceland	February 2000	DC-8:- Damage to all 4 engines.	MetUM 60 km / ERA-Interim
Manam, Papua New Guinea	July 2006	Gulfstream II:- Twin-engine failure	MetUM 40 km / ERA-Interim

Table 2: Volcanic eruptions associated with the studied aircraft encounters

3.1 Galunggung, June 1982

British Airways flight 009 travelling from Kuala Lumpur to Perth, Australia on 24th June 1982 encountered volcanic ash from Mount Galunggung, Indonesia at 13:40 UTC at an altitude of 37,000 feet ($\sim$11.3 km), resulting in loss of power to all four engines and abrasion to its windshield and wing surfaces. St Elmo's fire was observed on the windshield and a thick dust and sulphurous odour filled the cabin. The Boeing 747, with 247 passengers on board, descended unpowered for about 14 minutes until the engines were restarted progressively at an altitude of about 13,000 feet ($\sim$4 km) [19]. The aircraft made a safe emergency landing at Jakarta but the event was a major milestone in the recognition of the threat of volcanic ash to aviation and in the creation of the VAACs.

Mount Galunggung ($7^\circ\ 15'\ 00''$ S, $108^\circ\ 03'\ 30''$ E) is a stratovolcano on the west side of the island of Java in Indonesia. The volcano has a summit elevation of 7,113 feet ($\sim$2.2 km) (present day). Intermittent explosions of Mount Galunggung began on 5th April 1982 [36]. In total, more than 30 large explosive eruptions occurred between April 1982 and January 1983, with ash clouds rising to altitudes in excess of 10 km on some occasions. Indonesian newspapers reported that people a few kilometres from the crater heard thundering sounds and saw a glow over the volcano before the 24th - 27th June explosions began. Residents of Tasikmalaya (17 km east-southeast of the volcano) saw incandescent tephra ejection at 19:00 LT (local time), 19:10 LT, and 19:30 LT (12:00 UTC, 12:10 UTC and 12:30 UTC) on 24th June 1982 [36]. Images from the Japanese geostationary meteorological satellite (GMS) and the NOAA 7 polar orbiter satellite showed that the eruption cloud moved west then curved towards the south with its distal end reaching a point roughly 850 km south of Galunggung [36].

Detailed information regarding the eruption on 24th June 1982 has been difficult to find. Galunggung has, in recent history, erupted to heights of 24 km. The most explosive phase of the 1982 - 1983 eruptions occurred from mid May to October 1982 producing ash clouds to a height of 20 km [34]. The Smithsonian Institution [37] reports that the April 1982 - January 1983 eruption had a volcanic explosivity index (VEI) of 4 which equates to an eruption column height between 10 and 25 km [25]. Hanstrum and Watson [12] estimated the volcanic ash cloud height from cloud top temperatures and concluded that the cloud height was in excess of 12 km on 24th / 25th June 1982. They add that this is supported by the altitude that the British Airways aircraft encountered volcanic ash ($\sim$11.5 km) and that the size of the particles ingested by the aircraft engines suggests that the height of the cloud may have been considerably higher. No further details or references are given, however.

Information on the start and stop times of the eruptive phase beginning on 24th June 1982 is inconsistent and limited. According to Hanstrum and Watson [12], information from Indonesia indicated that the eruptions occurred at about 15:00 UTC but this is inconsistent with the reported time of the aircraft encounter with the volcanic ash plume (13:40 UTC). However, they also report that the aircraft encounter occurred at approximately 15:00 UTC which is approximately an hour later than reported elsewhere. Satellite imagery at 18:00 UTC from the Japanese geostationary meteorological satellite GMS-2 (fig. 2 in [12]) shows the volcanic ash plume from Mount Galunggung and suggests that the volcano was still erupting at this time. The ash plume is not, however, visible on satellite imagery at 12:00 UTC although residents report seeing emissions of ash at 12:00 UTC, 12:10 UTC and 12:30 UTC [36].

The precise location (latitude and longitude) of the aircraft encounter with the volcanic ash plume has not been found in the literature. A flight path taking the aircraft south-southeast down through Sumatra and across the western edge of Java is shown in Hanstrum and Watson (fig. 1 in [12]). Encounter locations reported in the literature are 130 miles southeast of Jakarta (Rolls Royce, private communication), 150 km west-southwest of Galunggung [36], 330 km south of Jakarta [19] and 230 km south of Jakarta [12]. The distances between the reported locations is relatively large compared to the distance from the volcano. Figure 3, subsequently provided by Rolls Royce, shows the aircraft's reported location at the start of the incident plotted using data from the black box recorder. The aircraft's location in figure 3 is approximately 107.5° E, 8.0° S and is taken here to be accurate. The aircraft's altitude is consistently reported to have been 37,000 feet ($\sim$11.3 km).

A continuous eruption was modelled in NAME from 12:00 UTC until 18:00 UTC on 24th June 1982. The emission rate was determined using equation (1) for three different eruption heights of 12 km, 15 km and 20 km (table 3). ECMWF ERA-40 met data have been used. These meteorological data are relatively coarse with a horizontal resolution of approximately 125 km and hence may not accurately capture the detail of the local winds. The large uncertainties in the eruption height, start time and duration mean that extreme caution needs to be taken in drawing conclusions

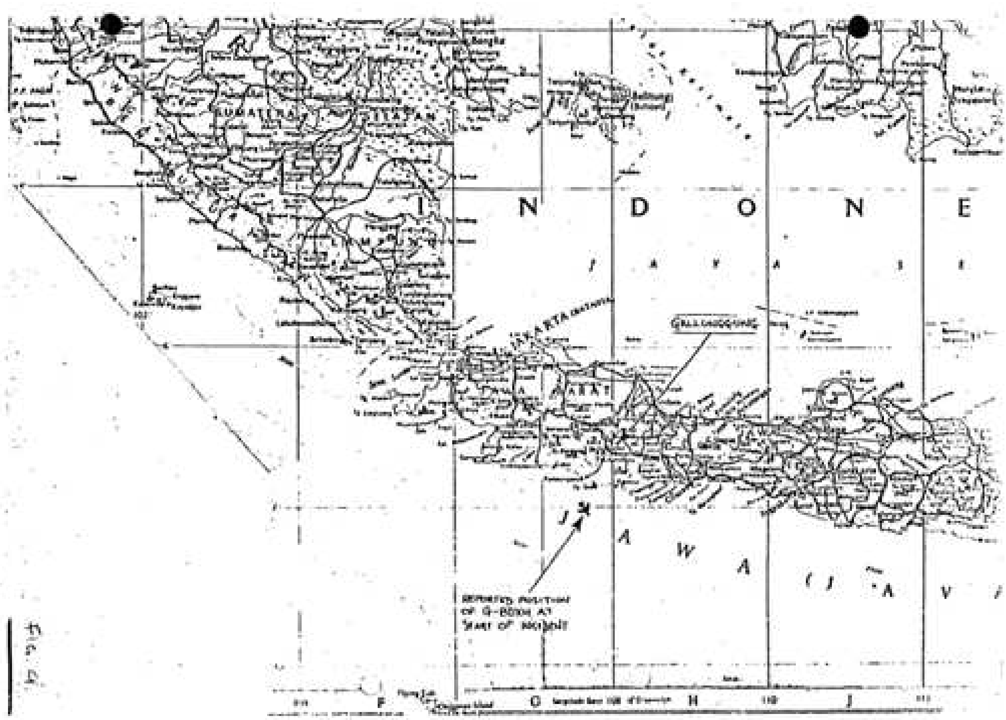


Figure 3: Galunggung:- The aircraft's reported location at the start of the incident using data from the black box recorder (Rolls Royce, private communication)

regarding actual concentrations encountered by the aircraft.

Start time (UTC)	Stop time (UTC)	Height (km asl)	Emission rate (kg hr^{-1})
12:00 24/06/1982	18:00 24/06/1982	12	8.194×10^9
12:00 24/06/1982	18:00 24/06/1982	15	2.676×10^{10}
12:00 24/06/1982	18:00 24/06/1982	20	1.155×10^{11}

Table 3: Assumed eruption parameters for NAME modelling of the eruption of Galunggung in June 1982

Figure 4 shows the hourly-averaged peak volcanic ash concentrations predicted by NAME from 13:00 UTC to 14:00 UTC on 24th June 1982 between altitudes of FL350 and FL550, assuming an eruption height of 12 km. The aircraft encounter location taken from the black box recorder is shown to be within the predicted ash plume. The predicted peak ash concentration at the encounter location is approximately $900\,\mu g\,m^{-3}$ for an eruption height of 12 km. Significantly higher ash concentrations are predicted by NAME in the nearby vicinity. Comparing the flight path in Hanstrum and Watson [12], which has a NW to SE orientation, with the NAME predicted ash plume (figure 4) suggests that the aircraft may have flown through higher concentrations of ash prior to reaching the reported location. Taking this into account and allowing for small positional errors in the encounter location and in the ash plume (due to possible errors in the coarse NWP winds), the NAME modelling, for an eruption height of 12 km, predicts that the aircraft may have encountered ash concentrations up to $45,000\,\mu g\,m^{-3}$.

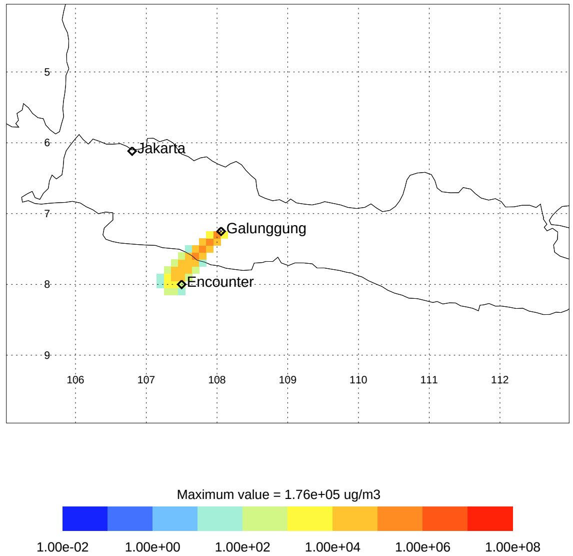
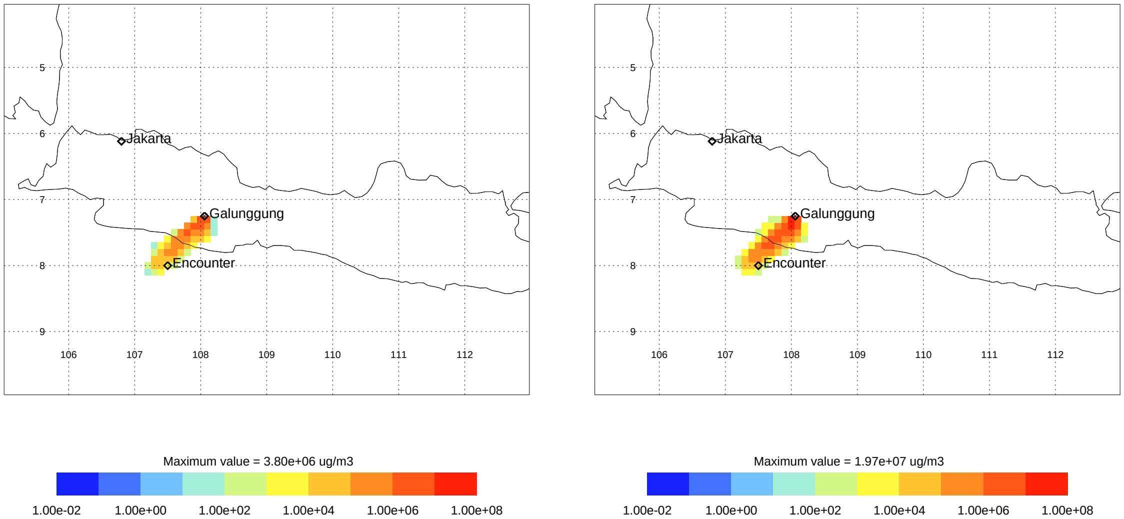


Figure 4: Galunggung:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL350 to FL550 between 13:00 UTC and 14:00 UTC on 24/06/1982, assuming an eruption height of 12 km

Figure 5 shows the hourly averaged NAME predicted peak volcanic ash concentrations for the same time on 24th June 1982 between altitudes of FL350 and FL550, for higher eruption heights of 15 km and 20 km. As the eruption height increases, the predicted ash concentrations within the plume increase. For an eruption height of 15 km, the predicted ash concentration at the aircraft encounter location is approximately $5,000\ \mu g\ m^{-3}$ with maximum nearby concentrations up to $250,000\ \mu g\ m^{-3}$. Predicted ash concentrations increase further for an eruption height of 20 km to approximately $20,000\ \mu g\ m^{-3}$ at the encounter location and maximum values of the order of $750,000\ \mu g\ m^{-3}$ nearby. Hence it can be seen that the uncertainty in the eruption height results in significant uncertainty in the predicted ash concentrations.

3.2 Soputan, May 1985

At 00:58 LT on 20th May 1985 (16:58 UTC on 19th May 1985), a Qantas Airways Boeing 747 en route from Hong Kong to Sydney, Australia, with 267 passengers and 16 crew members on board, encountered an ash cloud from Soputan volcano approximately 36 km south-southeast of the volcano (approximately 0° 50′ N, 124° 54′ E) at FL370 (∼11.3 km). An orange glow discharged from the nose of the aircraft and orange sparks passed over the windshield [38]. Engine inlets were illuminated by a white light. A light haze that smelled like burnt dust filled the cabin, and ash accumulated on flat surfaces. These effects continued for 7-8 minutes, while the aircraft remained on course at a speed of 0.85 times the speed of sound, for a distance of roughly 120 - 135 km. The aircraft continued to Sydney and landed uneventfully, 4 hours after exiting the ash cloud. Because of damage caused by the ash cloud, it was necessary to replace all four of the aircraft's engines,



(a) 15 km eruption height

(b) 20 km eruption height

Figure 5: Galunggung:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL350 to FL550 between 13:00 UTC and 14:00 UTC on 24/06/1982, for eruption heights of 15 km and 20 km.

other navigational components, and more than a dozen windows.

The Smithsonian Institution [38] reports the aircraft's location as 0.50° N and 124.54° E (equating to a distance of approximately 80 km from the volcano). The report by the aircraft crew (figure 6) provided by Rolls Royce clearly states the aircraft's location as 0° 50′ N, 124° 54′ E (just 36 km from the volcano). It is assumed, here, that the minutes have incorrectly been taken to be hundredths of a degree in the report by the Smithsonian Institution [38] and the location reported by the aircraft crew is taken to be correct.

Soputan (1° 06′ 30″ N, 124° 44′ 00″ E) is one of Sulawesi's most active volcanoes. The Indonesian volcano has a summit elevation of 5,853 feet (∼1.8 km) (present day). An ash eruption from Soputan's main crater occurred from 18:15 LT (10:15 UTC) on 19th May 1985 until 01:30 LT on 20th May 1985 (17:30 UTC on 19th May 1985) [38]. Ground based observations suggest the eruption column rose to an altitude of 4 km. The TOMS instrument on the NIMBUS 7 polar orbiting satellite detected an area of SO_2 and aerosol enhancement southeast of Soputan during its pass at 12:00 LT (04:00 UTC) on 20 May 1985 (figure 7). The area of SO_2 enhancement extended from about 124.5° E to 126.0° E near the equator and from about 125.0° E to 127.0° E at 1.5° S with the maximum at about 1.0° S, 126.0° E [38]. Tupper and Wunderman [45] cite a maximum eruption height determined from satellite observations of 12 km above mean sea level (amsl).

There is a discrepancy between the maximum reported daily eruption height from ground observations (4 km) and satellite observations (12 km) [45]. Given that the aircraft was reported to have been flying at FL370 ($>$11 km) when it encountered the Soputan volcanic ash cloud, it is difficult to see how this would have been possible with a maximum eruption height of 4 km. Hence an eruption height of 12 km was modelled (table 4). The size of the discrepancy between the ground based and

4.0 <u>Crew Report and Area of Incident</u>

4.1 <u>Captain's Report</u>

On the 19 May, 1985 while cruising at FL370 on HKG-SYD sector between BONDA and AMBON on airway A61D 00° 50.0'N - 124°59.0'E at 1700 Zulu the aircraft experienced heavy St. Elmo's fire and cabin filled with dust from air conditioning outlets. The deposits were accompanied by a light acrid smell rather like "burning" dust, these conditions lasted for approximately 4 to 5 minutes and left a residue of dust (volcanic?) throughout the aircraft. A small sample was collected by the crew for analysis. Darwin was advised of this condition on HF at the time.

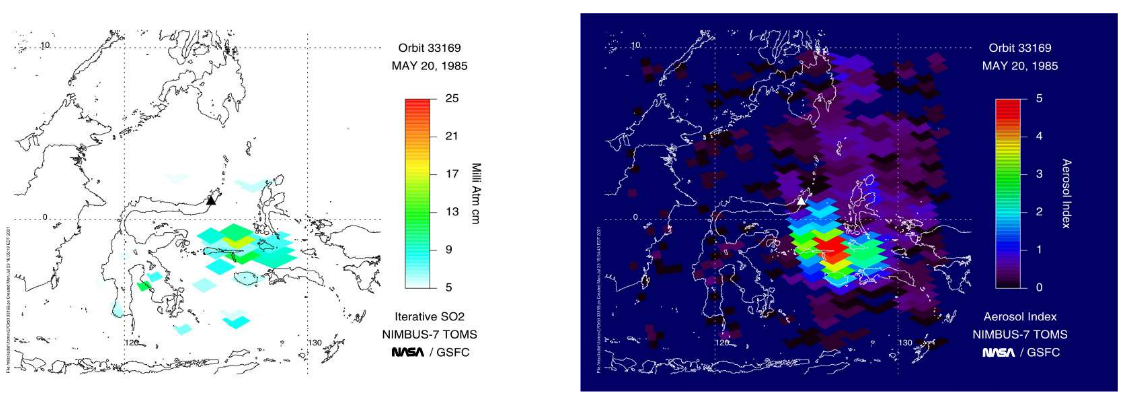
4.2 <u>Flight Engineer Report</u>

At 1658Z position 00°.50.0'N, 124°54'E, FL370 aircraft experienced huge St. Elmo's fire. Orange sparks passing over windscreens with occasional orange glow discharging from nose section. Engine inlets illuminated by a white light.

Aircraft cabin filled with a mild haze, smelling like burnt dust (not unlike white smoke smell in EP trainer). Engine ignition and nacelle anti-ice were put on and pack valves returned to full flow. Engine parameters normal throughout occurrence which lasted approximately 7 to 8 minutes.

Cabin crew reported haze in cabin, dust (soot) on galley bench tops, some dust collected for analysis. Incident report raised by

Figure 6: The crew report from the aircraft which encountered the volcanic ash plume from Soputan (Rolls Royce, private communication)



(a) SO_2 (b) Aerosol index

Figure 7: Soputan:- SO_2 and aerosol index at 04:00 UTC on 20th May 1985 detected by the TOMS instrument on the NIMBUS 7 polar orbiting satellite (obtained from the TOMS Volcanic Emissions Group, UMBC/NASA GSFC (`http://so2.gsfc.nasa.gov/`), 19th May 1985 data not available)

satellite based observations may be an indication that the eruption height varied during the eruption. It may, however, be due to limitations in ground based observations in situations of significant cloud cover. As details of any variation with time are not known, a fixed eruption height of 12 km was used. The meteorological data used are ECMWF ERA-40 data with a horizontal resolution of approximately 125 km.

Start time (UTC)	Stop time (UTC)	Height (km asl)	Emission rate (kg hr^{-1})
10:15 19/05/1985	17:30 19/05/1985	12	9.715 $\times$ 10^{9}

Table 4: Assumed eruption parameters for NAME modelling of the eruption of Soputan in May 1985

NAME modelling of the incident places the aircraft just outside of the volcanic ash plume at the time, height and location of the reported encounter (figure 8). The maximum predicted concentration within the centre of the plume, at a similar distance from the volcano as the reported encounter location, is approximately $200,000\ \mu g\ m^{-3}$. The captain's report states that the aircraft was cruising between way points BONDA (2° 00′ 00″ N, 124° 51′ 12″ E) and AMBON (3° 36′ 53″ S, 128° 11′ 09″ E) on airway A61D. The straight line in figure 8 gives an approximate flight path between the two way points. Based on this approximate flight path and the reported encounter location, it is possible that the aircraft may have flown further into the plume.

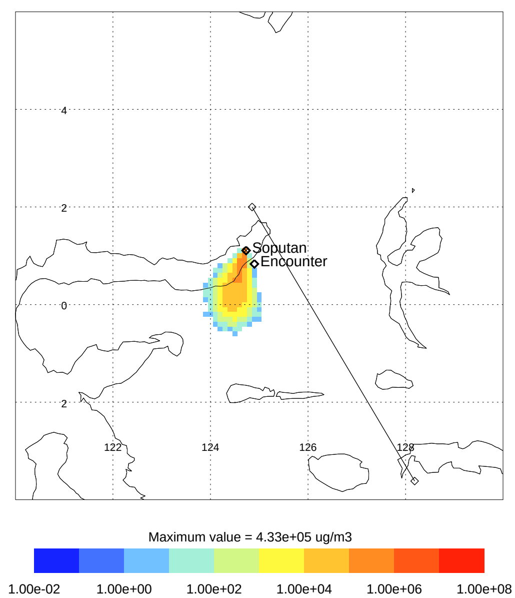


Figure 8: Soputan:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL350 to FL550 between 16:00 UTC and 17:00 UTC on 19/05/1985

Figure 9 shows the vertically integrated ash plume predicted by NAME corresponding to the time of the satellite imagery presented in figure 7. The predicted plume does not agree well with the satellite observations. The ERA-40 winds are in different directions at different altitudes: winds at lower levels are southerlies, upper level winds are north-easterlies and in between, winds are westerlies. Upper level material is predicted to have been transported in a southwesterly direction whereas the satellite observations show that the plume was transported southeastwards from the volcano. This suggests that there may well be errors in the meteorological wind data used, with winds, in reality, having a stronger eastwards component. The meteorological data available and used in this study (ECMWF ERA-40) are coarse in resolution, with a horizontal resolution of approximately 125 km. Given the errors in the predicted plume, it is likely that the reported encounter location was further in the plume, and hence in higher ash concentrations, than is suggested in figure 8.

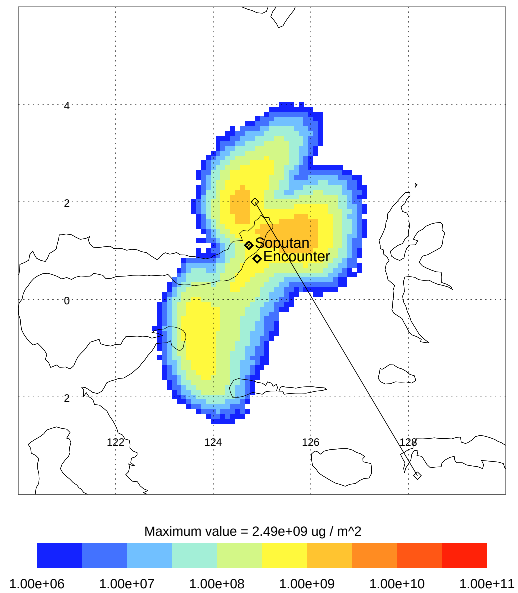


Figure 9: Soputan:- Hourly-averaged vertically integrated ash plume predicted by NAME from 03:00 UTC to 04:00 UTC on 20/05/1985

3.3 Redoubt, December 1989

At 11:46 LT (20:46 UTC) on 15th December 1989, KLM flight 867 (a Boeing 747 aircraft) en route from Amsterdam to Anchorage entered the ash cloud from Mount Redoubt at an altitude of 25,000 feet (∼7.6 km) near Talkeetna, about 150 km north of Anchorage [1, 13, 39]. The crew were aware of reports of ash in the vicinity and had altered their flight path in order to try to avoid the ash cloud (figure 10 below, taken from Casadevall [1]). Just before the encounter the crew observed thin layers of white clouds below them [1]. On descending into this apparently normal layer of clouds, the environment quickly changed from white to black, visibility was greatly reduced and smoke entered the cockpit. The crew increased engine power to climb out of the ash cloud, but all four engines stalled shortly afterwards and the aircraft descended for around 8 minutes to an altitude of approximately 13,300 feet (∼4 km). All four engines were successfully restarted and the aircraft landed safely at Anchorage. The nearly new 747 aircraft was badly damaged during the incident with the total cost of repair estimated to be between $50 million and $80 million. Five other jet aircraft in the Anchorage area encountered the ash clouds from Mount Redoubt between December 1989 and February 1990. Damage to these aircraft included abrasion of leading edges and windshields, which were, in some cases, replaced. In addition there were two further encounters with ash from Mount Redoubt over west Texas on 17th December 1989. In these two cases, the ash had travelled over 5,000 km and was between 35 and 55 hours old [1].

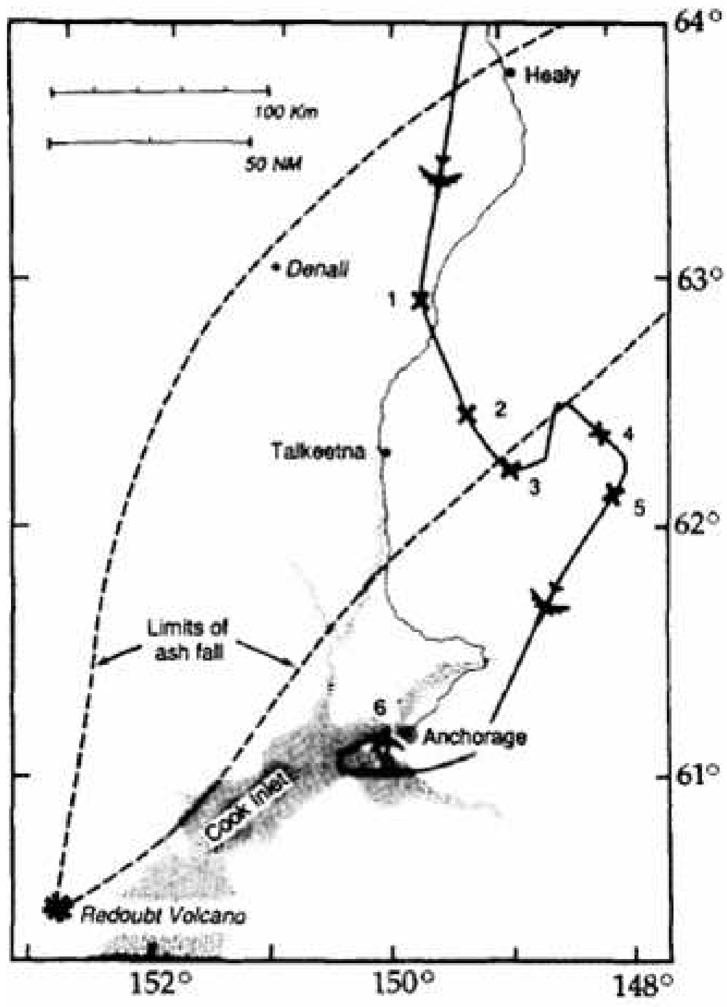


Figure 10: The flight path of the KLM flight which encountered the ash cloud from Mount Redoubt (taken from Casadevall [1])

Redoubt (60° 29′ 07″ N, 150° 44′ 31″ W) is a stratovolcano in southwestern Alaska with a present day summit elevation of 10,197 feet (∼3.1 km). A series of strong eruptions on 14th and 15th December 1989 resulted in ash clouds reaching altitudes of 12 km with reports of ash layers in the atmosphere as far as south Texas (some 5,000 km from the volcano). The eruption time profile used in the NAME modelling of the KLM flight 867 encounter is based on reports of the eruption height and duration [39] and is given in table 5. ECMWF ERA-Interim meteorological data with a horizontal resolution of approximately 85 km were used.

Figure 11 shows the hourly-averaged volcanic ash plume predicted by NAME between 20:00

Start time (UTC)	Stop time (UTC)	Height (km asl)	Emission rate (kg hr^{-1})
19:13 14/12/1989	22:00 14/12/1989	10.5	2.318 $\times$ 10^9
10:40 15/12/1989	11:40 15/12/1989	6.5	7.310 $\times$ 10^7
12:38 15/12/1989	13:38 15/12/1989	6.5	7.310 $\times$ 10^7
19:17 15/12/1989	20:00 15/12/1989	12	5.264 $\times$ 10^9

Table 5: Assumed eruption parameters for NAME modelling of the eruption of Mount Redoubt in December 1989

UTC and 21:00 UTC on 15th December 1989 and from FL200 to FL350. The marked flight path and location points are taken from Casadevall [1]. At "Loc1" the aircraft turned towards the south-east to try to avoid the ash cloud and started to descend. At "Loc2" the aircraft encountered the ash plume at FL250. Evasive action was taken, increasing engine power to climb out of the ash plume, but, after just a minute and a half, all four engines stalled at "Loc3" and FL279. The sequence of events agrees well with the NAME modelling of the incident. "Loc2" is within the NAME predicted ash plume with estimated concentrations at "Loc2" approximately $4,000\ \mu g\ m^{-3}$. Predicted concentrations between "Loc2" and "Loc3" increase to a maximum value of about $55,000\ \mu g\ m^{-3}$ at "Loc3". Maximum concentrations in the nearby vicinity of "Loc2" and "Loc3", allowing for some uncertainty in the route, are approximately $70,000\ \mu g\ m^{-3}$. These predicted ash concentrations are considerably lower than the $2\ g\ m^{-3}$ estimated by Przedpelski and Casadevall [29] on the basis of the nozzle-deposit buildup in comparison to that measured during engine tests conducted by Dunn and Wade [6].

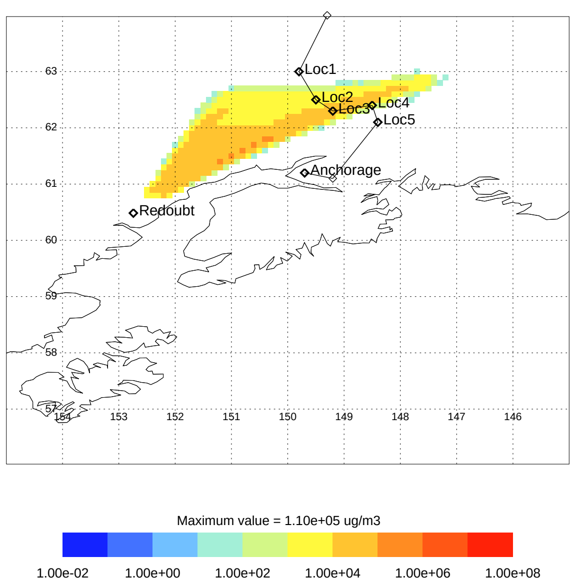


Figure 11: Redoubt:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL200 to FL350 between 20:00 UTC and 21:00 UTC on 15/12/1989

3.4 Pinatubo, June 1991

Mount Pinatubo ($15^\circ\,08'$ N, $120^\circ\,21'$ E) in the Philippines is a stratovolcano which was relatively unknown before 1991. Prior to its eruption in 1991, it had a summit elevation of 5,724 feet ($\sim$1.7 km). In June 1991, after more than two months of increasing seismicity, deformation, and emission of small plumes, a series of strong explosions occurred that culminated in one of the largest eruptions of the 20th Century. The climactic phase on the 15th and 16th June sent ash to altitudes in excess of 30 km, generated voluminous pyroclastic flows, and left a small caldera ($\sim$2.5 km wide) in the former summit region. Ten days later, the aerosol cloud formed a nearly continuous band that stretched 11,000 km from Indonesia, westwards across the Indian Ocean, to Central Africa.

The eruption times and heights used in modelling the sequence of eruptions (table 6) have been taken from Hoblitt et al. [14], Holasek et al. [15] and Wolfe and Hoblitt [49]. The first major eruption began at 08:51 LT (00:51 UTC) on 12th June, generating a column of ash and steam that rose to an altitude of at least 19 km. Following this major eruption there were three more vertical eruptions and then a sequence of 13 explosive eruptions (representing a change in activity to pyroclastic surge formation) before the onset of the climactic eruption at 13:42 LT (05:42 UTC) on 15th June. Assumed eruption durations, before the start of the climactic phase, are generally based on length of recorded seismic tremor so may not fully represent the eruption duration. The climactic phase lasted approximately 21 hours, during which time the maximum eruption height declined from $\sim$40 km to $\sim$13 km. To aid modelling, this phase has been divided into 8 time periods with similar eruption heights (table 6). A comparison of the modelled eruption height time profile during the climactic phase to the actual hourly eruption heights derived from satellite data by Holasek et al. [15] is shown in figure 12. NAME simulations using a more detailed time-series of eruption heights show that the simplifications made by dividing the climactic phase into 8 time periods do not unduly affect model predictions.

The climactic phase eruption produced a giant umbrella cloud in the middle to lower stratosphere. The umbrella cloud is an intrusive gravity current which is formed by the spreading of well-mixed material in a stratified environment at the level of neutral buoyancy. Satellite imagery showed the umbrella cloud covered a large area exceeding 230,000 km^2 and eventually reached over 1,100 km in diameter. The top of the umbrella cloud was at an altitude of at least 35 km and the cloud was roughly 10 - 15 km thick [35]. With an average expansion rate of 20 m s^{-1}, significant upwind spread was observed (the umbrella cloud was seen to intrude more than 200 km upwind) and, at times, the dominant motion of the plume was governed by gravitational spreading. Satellite imagery of the spread of the umbrella cloud during the climactic phase of the eruption is shown in figure 14c, taken from Holasek et al. [15]. No information has been found on umbrella cloud formation during the earlier eruptive phases.

Modelling of the 1991 Pinatubo eruption is difficult for additional reasons. Firstly, the size of the eruption is off the scale of the VAFTAD table and hence we have assumed that the continuous fit

Start time (UTC)	Stop time (UTC)	Height (km asl)	Emission rate (kg hr^{-1})
00:00 10/06/1991	00:51 12/06/1991	3	8.713×10^5
00:51 12/06/1991	01:51 12/06/1991	19	9.981×10^{10}
14:52 12/06/1991	15:06 12/06/1991	24	3.093×10^{11}
00:41 13/06/1991	00:46 13/06/1991	24	3.093×10^{11}
05:09 14/06/1991	05:11 14/06/1991	21	1.625×10^{11}
06:00 14/06/1991	06:11 14/06/1991	15	3.091×10^{10}
07:16 14/06/1991	07:21 14/06/1991	18	7.655×10^{10}
10:53 14/06/1991	10:58 14/06/1991	24	3.093×10^{11}
15:20 14/06/1991	15:38 14/06/1991	21	1.625×10^{11}
17:15 14/06/1991	17:38 14/06/1991	15	3.091×10^{10}
21:55 14/06/1991	22:00 14/06/1991	12	9.881×10^9
00:10 15/06/1991	00:15 15/06/1991	12	9.881×10^9
02:27 15/06/1991	02:41 15/06/1991	15	3.091×10^{10}
03:17 15/06/1991	03:30 15/06/1991	14	2.181×10^{10}
03:58 15/06/1991	04:07 15/06/1991	8	1.098×10^9
04:22 15/06/1991	04:32 15/06/1991	8	1.098×10^9
04:52 15/06/1991	04:56 15/06/1991	8	1.098×10^9
05:13 15/06/1991	05:28 15/06/1991	8	1.098×10^9
05:42 15/06/1991	08:41 15/06/1991	38.5	2.876×10^{12}
08:41 15/06/1991	11:41 15/06/1991	33.8	1.565×10^{12}
11:41 15/06/1991	14:41 15/06/1991	28	6.447×10^{11}
14:41 15/06/1991	17:41 15/06/1991	24.5	3.414×10^{11}
17:41 15/06/1991	20:41 15/06/1991	18.8	9.477×10^{10}
20:41 15/06/1991	23:41 15/06/1991	14.7	2.792×10^{10}
23:41 15/06/1991	01:41 16/06/1991	13.5	1.813×10^{10}
01:41 16/06/1991	02:41 16/06/1991	15	3.091×10^{10}

Table 6: Assumed eruption parameters for NAME modelling of the eruptions of Pinatubo in June 1991

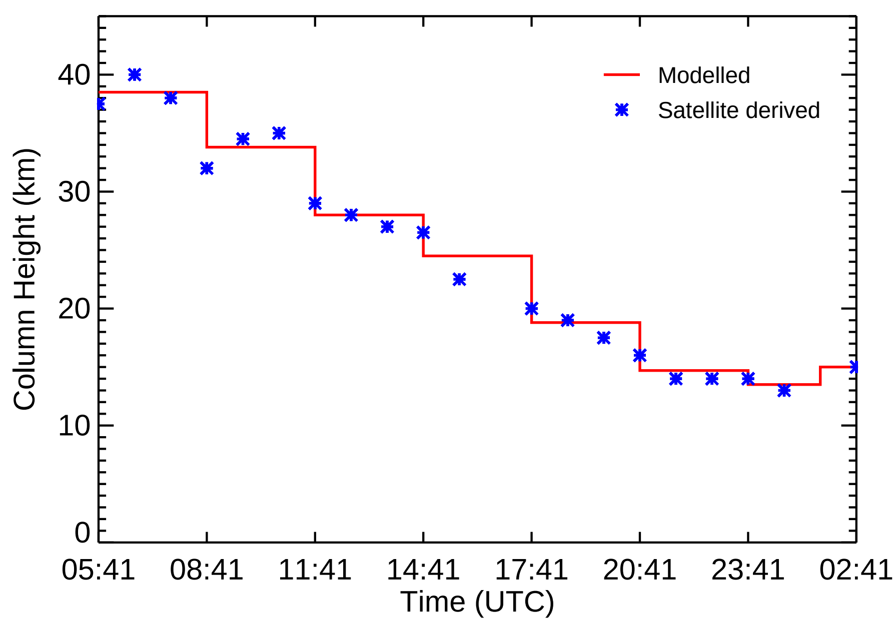
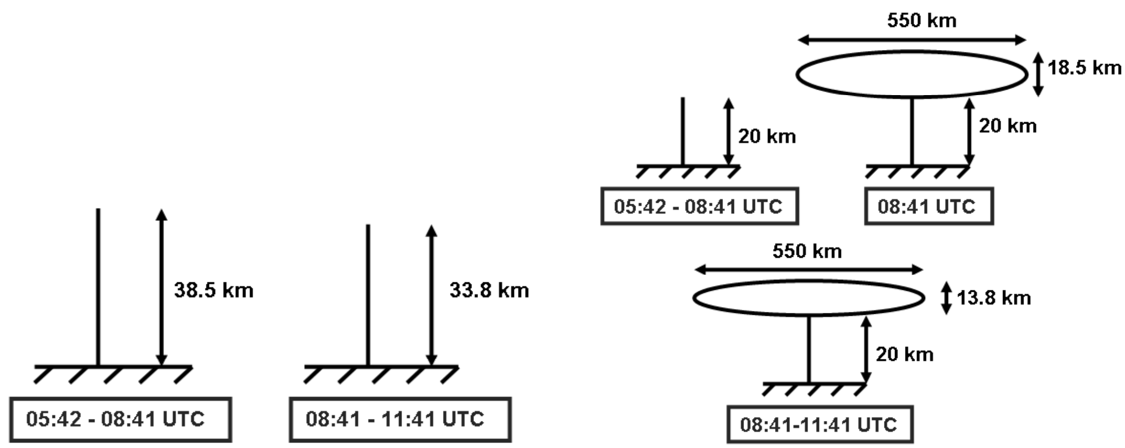


Figure 12: Comparison of the modelled and satellite derived eruption heights (Pinatubo, 15th - 16th June 1991)

to the VAFTAD table can be extrapolated to the range of eruption heights seen during the climactic phase. Mass emission rates for eruption heights between 35 km and 40 km obtained using the continuous fit to the VAFTAD table (1.8 - 3.4 $\times$ 10^{12} kg hr^{-1}) are slightly higher than those obtained using the equation given by Mastin et al. [24] (1.0 - 1.9 $\times$ 10^{12} kg hr^{-1}) but agree within a factor of two. In addition, no attempt was made initially to explicitly represent the umbrella cloud and this dynamic feature will not be well represented by the dispersion in the model alone. Simple attempts to represent the spread of the umbrella cloud were made in subsequent modelling exercises and are described further below. Fero et al. [7] state that the majority of the Pinatubo ash cloud was below the maximum eruption column height and below the level of neutral buoyancy. They suggest that this could either be due to the majority of ash being injected at altitudes much lower than the maximum eruption column height or due to some other mechanism, such as significant subsidence of the horizontally intruding component of the umbrella region, leading to a concentration of ash at this lower level. The modelling strategy used here generally assumes a uniform vertical distribution of ash which is unlikely to be accurate. Furthermore, the size of the Pinatubo eruption, transporting material to altitudes around 40 km, questions the validity of the modelling assumption that volcanic ash particles larger than 100 μm fall out near to the source.

A further complicating factor in modelling the Pinatubo eruption is the presence of typhoon Yunya. A track of the storm is shown in Oswalt et al. (fig. 7 in [26]). By about 20:00 LT (12:00 UTC) on 14th June, the leading edge of typhoon Yunya had reached the area and strong storms began moving over the volcano at about 05:00 LT on 15th June (21:00 UTC on 14th June). The typhoon centre passed within 75 km of Mount Pinatubo at approximately 11:00 LT (03:00 UTC) on 15th June and twenty-four hours later it had weakened leaving light-moderate showers which persisted through the 16th. Typhoon Yunya was a small (or midget) storm which induced a southward bias in the middle to upper tropospheric winds [26]. We do not expect the meteorological data used in this study (ERA-Interim with a horizontal resolution of approximately 85 km and a temporal resolution of 3 hours) to accurately capture the small-scale typhoon.

NAME is not currently designed to model the spread of an umbrella cloud as a gravity current. However, for the climactic phase of the 1991 Pinatubo eruption, evidence suggests that to accurately represent the transport of volcanic ash, the formation, transport and spread of the umbrella cloud needs to be taken into account. Simplified representations of the umbrella cloud were therefore included in some NAME simulations. Holasek et al. [15] state that analysis of the spreading umbrella plume suggests that the plume spread horizontally as a gravitational intrusion over the first 4 - 5 hours before being advected by the ambient winds. According to satellite data, the umbrella cloud at 08:41 UTC on 15th June 1991 had a diameter of approximately 550 km [15]. To represent the umbrella cloud in a basic way, we introduce an instantaneous ellipsoid source of this size between altitudes of 20 km and 38.5 km at 08:41 UTC (figure 13). In this way we are not attempting to model the initial stages of the umbrella cloud formation from 05:42 UTC to 08:41 UTC. The mass of volcanic ash released within this umbrella cloud region is chosen to be equivalent to that which would have been emitted above 20 km over this period with a uniform source in the vertical (table 6) but distributed over a wider horizontal area. The distribution of mass within the ellipsoid umbrella cloud region is spatially uniform and hence the vertical distribution of mass is no longer uniform but peaks at the mid-height of the ellipsoid. From 08:41 UTC, up until the time that the eruption height falls below 20 km (17:41 UTC), a continuous release over an umbrella cloud region is modelled between 20 km and the plume height (table 6 and figure 13). We assume that the umbrella cloud is transported by the mean and turbulent winds and subject to sedimentation. That is to say, we assume that the radial velocities from the gravity current are now small enough, in comparison to the mean winds, that they can be ignored. Clearly this is a much simplified representation of a complex feature and cannot be expected to be accurate. Nonetheless, it is hoped that this approach will give some guidance on the influence of the umbrella cloud.

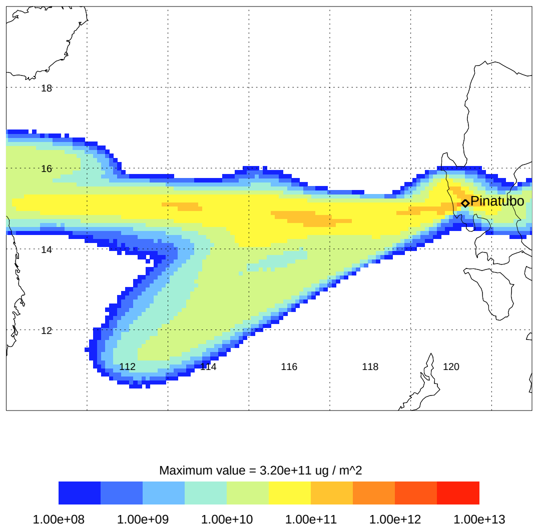


(a) No umbrella cloud

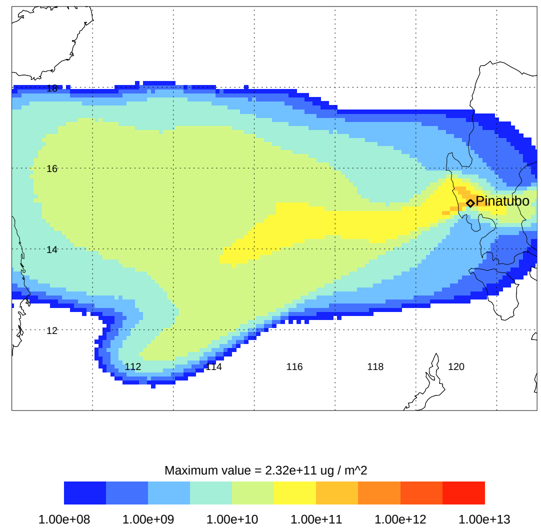
(b) With umbrella cloud

Figure 13: Schematic representation of the NAME source term between 05:42 UTC and 11:41 UTC on 15th June 1991

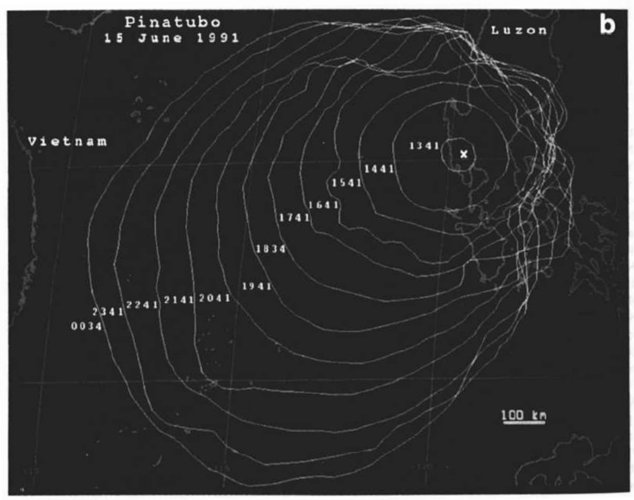
Figure 14 shows a comparison between the vertically-integrated NAME predicted plume, with and without the simple umbrella cloud representation, between 16:00 UTC and 17:00 UTC on 15th June 1991 and GMS (Geostationary Meteorological Satellite) thermal InfraRed satellite imagery taken from Holasek et al [15]. The predicted plume without representation of the umbrella cloud does not agree well with the satellite imagery: it is subject to much less horizontal spread and is, in the main, transported westwards by the mean forecast wind. The simple umbrella cloud representation spreads the plume over a wider area but the horizontal spread is still insufficient, suggesting the radial velocities cannot, in the main, be neglected even once the umbrella cloud has reached a horizontal extent of 550 km. Furthermore, the satellite imagery shows that the umbrella cloud was transported towards the southwest suggesting there may be errors in the NWP mean wind. We noted above that typhoon Yunya induced a southward bias in the normal middle to upper tropospheric winds which might be hard for the NWP model to represent. The results are consistent with this, with figure 14c showing a more southerly drift of the volcanic ash plume than is modelled here using coarse meteorological data. Nonetheless, inclusion, in the modelling, of an umbrella cloud spreads the ash cloud over a much more appropriate area.



(a) Volcanic ash plume predicted by NAME between 16:00 UTC and 17:00 UTC on 15/06/1991 without the umbrella cloud representation



(b) Volcanic ash plume predicted by NAME between 16:00 UTC and 17:00 UTC on 15/06/1991 including a simple umbrella cloud representation



(c) Composite of satellite images from 05:41 UTC to 16:34 UTC on 15/06/1991 (taken from Holasek et al. [15]). Times given are local time equivalent to UTC + 8 hours.

Figure 14: Comparison of vertically-integrated and hourly-averaged volcanic ash plume as predicted by NAME with GMS thermal IR satellite imagery showing the movement of the plume.

Sixteen damaging in-flight encounters between jet aircraft and the Pinatubo ash clouds were reported between 12th and 18th June 1991 [2, 11]. Table 7 describes the encounters modelled in this study (incident numbers and aircraft type are taken from Casadevall et al. [2]). The most serious encounter was incident 91-16 when power was lost to two engines. Following the encounters, a total of 10 engines were replaced, including all 4 engines on the 747 involved in encounter 91-01. Further details of the encounters are provided in Casadevall et al. [2].

Incident number	Date	Time (UTC)	Height (FL)	Latitude (N)	Longitude (E)	Aircraft type
91-01	12/06/1991	04:20	370	14° 00′	119° 30′	747-300
91-03	12/06/1991	16:30	330	11° 10′	112° 10′	DC-10
91-11	15/06/1991	17:30	290	15° 15′	110° 30′	DC-10
91-04	15/06/1991	17:40	290	13° 10′	110° 50′	747-400
91-12	15/06/1991	19:10	290	15° 15′	110° 30′	DC-10
91-16	17/06/1991	04:12	370	19° 30′	112° 40′	747-200B

Table 7: Modelled aircraft encounters with the Pinatubo ash plume

3.4.1 Incident 91-01

The aircraft involved in incident 91-01 reported a 3 minute encounter with volcanic ash at 04:20 UTC on 12th June 1991 at an altitude of 37,000 feet (∼11.3 km) approximately 170 km from Mount Pinatubo, 60 nautical miles from Lubang along air-route B460 (details of the air-route are unknown). All four engines were replaced following the incident. NAME modelling of the incident places the aircraft on the edge of the ash plume (figure 15). The predicted ash concentration at the reported aircraft location is approximately $400\ \mu g\ m^{-3}$. Predicted concentrations within the centre of the ash plume are, however, much higher with values up to $2,000,000\ \mu g\ m^{-3}$. Hence, depending on the flight path, the aircraft may have flown through considerably higher concentrations of ash than those predicted at the encounter location.

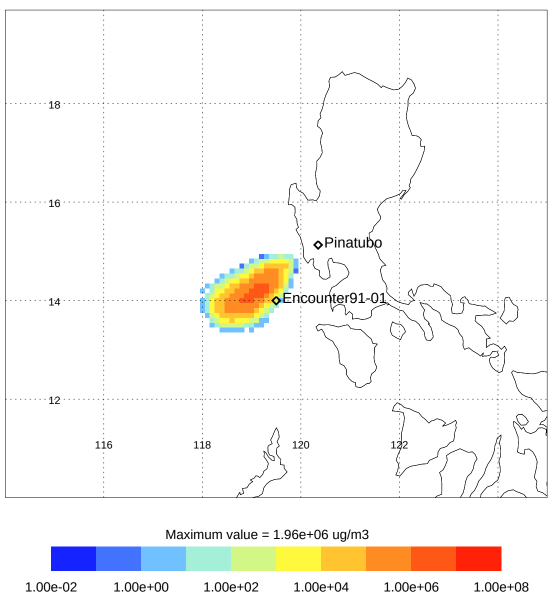
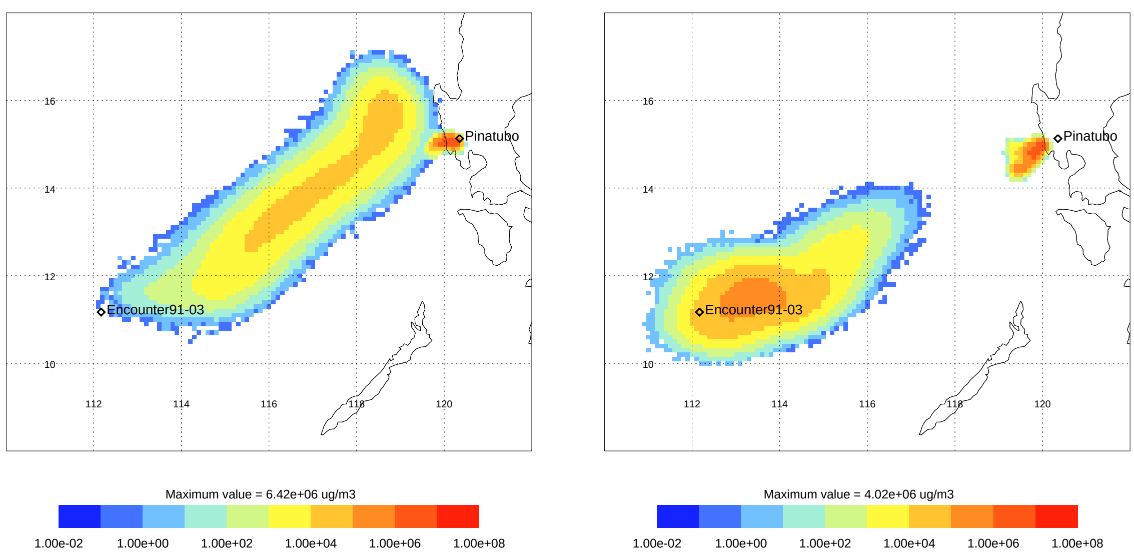


Figure 15: Pinatubo, incident 91-01:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL350 to FL550 between 04:00 UTC and 05:00 UTC on 12/06/1991

3.4.2 Incident 91-03

Incident 91-03 occurred at 16:30 UTC on 12th June 1991 at an altitude of 33,000 feet (∼10 km) approximately 1,000 km from Pinatubo, between way points ADPIM and LAVEN (locations of the way points are unknown) and involved an aircraft travelling from Kuala Lumpur to Tokyo. For 20 minutes, discharge phenomena on the windshield were observed. Ground inspection, however, revealed no damage. NAME modelling (figure 16a) predicts that ash concentrations at the aircraft location were zero at the time of the encounter. Small amounts of ash from the first major eruption (at 00:51 UTC on 12th June 1991) are predicted to have reached the nearby vicinity and hence NAME predicts that the aircraft may have flown through very low concentrations (less than $1\ \mu g\ m^{-3}$). At higher levels in the atmosphere (FL350-FL550) (figure 16b), there were significant amounts of ash at the encounter location (corresponding to predicted maximum concentrations of about $25,000\ \mu g\ m^{-3}$). Hence, if the aircraft had been ∼2,000 feet higher, the ash concentrations predicted by NAME would be significantly higher, although this strong sensitivity is due to the low vertical resolution of the NAME output / configuration used in this study. Mean winds at Pinatubo extracted from the numerical weather prediction (NWP) data are towards the southwest and show a substantial increase in wind speed from 3 m s^{-1} at 8 km agl (above ground level) to 11 m s^{-1} at 13 km agl. The higher ash concentrations predicted at levels above the aircraft are likely to be due to greater wind speeds resulting in faster transport of the ash plume. Any underprediction by the NWP model of the wind speed at the height of the aircraft will result, in this case, in an underprediction of the ash concentration encountered.



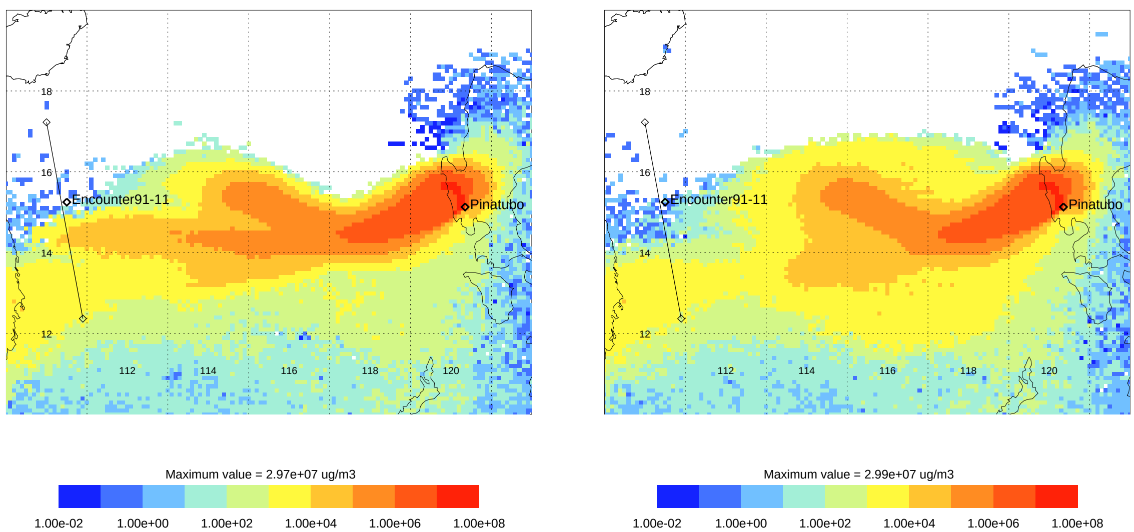
(a) FL200 to FL350

(b) FL350 to FL550

Figure 16: Pinatubo, incident 91-03:- Hourly-averaged concentrations of volcanic ash predicted by NAME between 16:00 UTC to 17:00 UTC on 12/06/1991

3.4.3 Incident 91-11

Incident 91-11 involved the same aircraft as incident 91-03 but occurred three days after the encounter described in Section 3.4.2. It occurred at 17:30 UTC on 15th June 1991 at an altitude of 29,000 feet (∼8.8 km) and at a location approximately 1,050 km from the volcano, between way points SUKAR (12.367° N, 110.898° E) and CAVOI (17.225° N, 110.0° E), 120 nautical miles from CAVOI. The aircraft was en route from Kuala Lumpur to Tokyo. Discharge phenomena were observed on the windshield for 25 minutes (equating to an estimated distance of 335 km assuming a mean average speed of 500 mph). A later ground inspection, however, revealed no damage to the aircraft. NAME modelling of the incident suggests that at the reported encounter location the aircraft was close to, but outside of, the Pinatubo ash plume (figure 17a). However, assuming the aircraft followed the flight path from SUKAR to CAVOI denoted by the black line in figure 17a (the exact path is unknown), the modelling predicts that the aircraft would have encountered significant ash concentrations in the minutes prior to reaching the reported encounter location.



(a) Without umbrella cloud representation

(b) With umbrella cloud representation

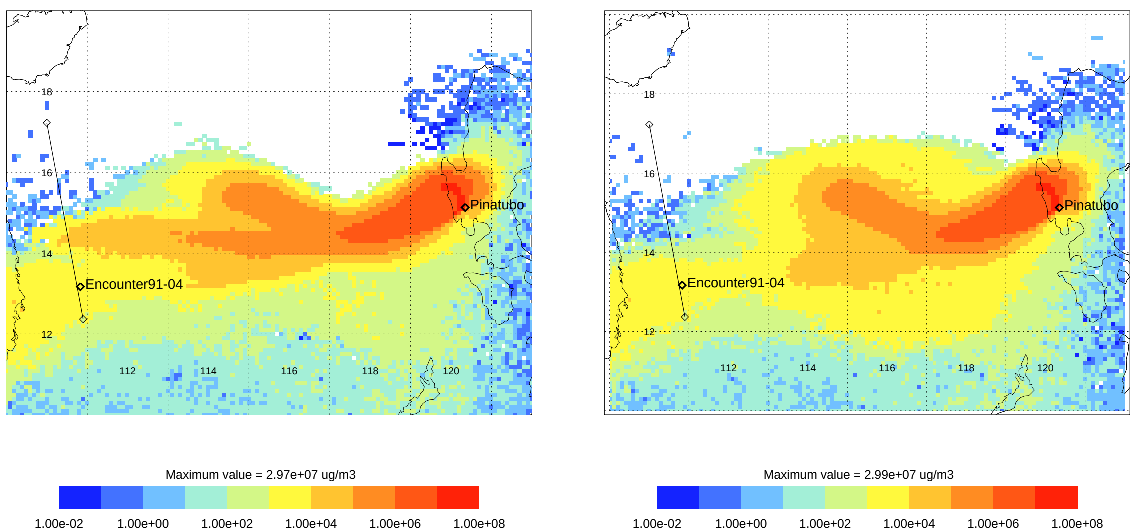
Figure 17: Pinatubo, incident 91-11:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL200 to FL350 between 17:00 UTC and 18:00 UTC on 15/06/1991. The black line denotes an approximate flight path between way points SUKAR and CAVOI.

Satellite observations in the hours leading up to this aircraft encounter clearly showed the presence of an umbrella cloud. Extrapolating figure 14c to the time of the aircraft encounter (17:30 UTC), one can see that the ash cloud may have reached the location in question. The literature suggests, however, that the umbrella cloud was much higher than the aircraft's reported altitude.

Figure 17b shows the NAME predicted hourly averaged volcanic ash concentrations between FL200 and FL350 from 17:00 UTC to 18:00 UTC on 15th June 1991 including the simplified umbrella cloud representation. Even taking into account the umbrella cloud, NAME still predicts that the reported aircraft encounter location was outside of the Pinatubo ash plume. As before, NAME predicts that the aircraft would have encountered higher concentrations of volcanic ash in the minutes prior to reaching the reported encounter location whilst on a flight path from SUKAR to CAVOI (denoted by the black line in figure 17b). There are, however, much larger uncertainties here, resulting in low confidence in the predicted ash concentrations, due to difficulties in modelling the umbrella cloud accurately.

3.4.4 Incident 91-04

Incident 91-04 occurred at 17:40 UTC on 15th June 1991 at an altitude of 29,000 feet ($\sim$8.8 km) approximately 1,150 km west of the volcano between way points SUKAR and CAVOI. Phenomena were observed on the windshield, in the cabin and on weather radar for a period of 6 to 8 minutes. A ground inspection revealed all four engines were damaged, as were the cockpit and cabin windows, some probes, lights and all leading edge areas. NAME modelling, without an umbrella cloud representation, predicts the reported aircraft location to be within significant ash concentrations (figure 18a). NAME predictions including a basic representation of the umbrella cloud (figure 18b) give similar results placing the aircraft encounter location within significant ash concentrations. Similar to incident 91-11, confidence in the predicted ash concentrations is low due to the influence of the umbrella cloud.



(a) Without umbrella cloud representation

(b) With umbrella cloud representation

Figure 18: Pinatubo, incident 91-04:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL200 to FL350 between 17:00 UTC and 18:00 UTC on 15/06/1991. The black line denotes an approximate flight path between way points SUKAR and CAVOI.

Incidents 91-04 and 91-11 occurred between the same way points and at similar times and altitudes. It is difficult to see how the dispersion modelling conducted here could explain why one aircraft sustained damaged whereas the other did not, unless their flight paths were substantially different. It is probably worth noting that the two encounters involved different types of aircraft;

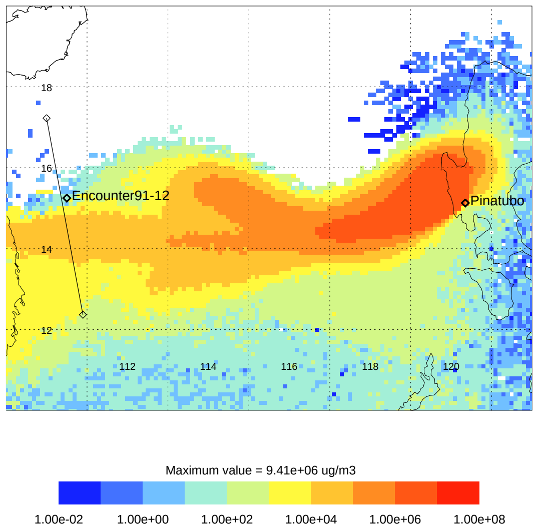
incident 91-11 involved a DC-10 whereas a 747-400 was involved in incident 91-04. The different aircraft, and therefore possibly different types of engines, might explain the apparent inconsistency. Alternatively, the difference in aircraft damage between the two incidents might also be explained by thin ash layers or a patchy nature of the ash plume (as was seen during the 2010 eruption of Eyjafjallajökull [23]) resulting in high localised ash concentrations.

3.4.5 Incident 91-12

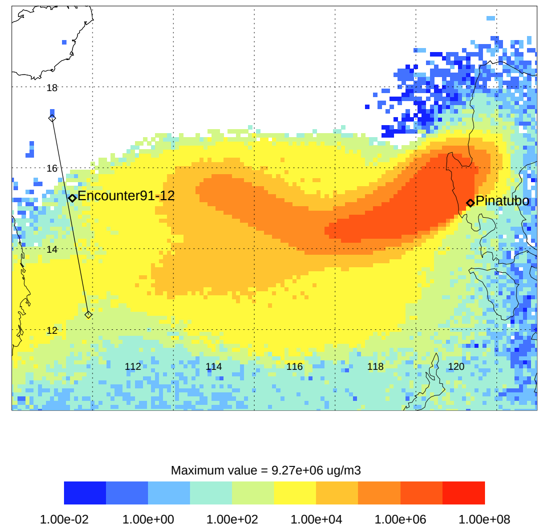
Incident 91-12 occurred at 19:10 UTC on 15th June 1991 at an altitude of 29,000 feet ($\sim$8.8 km) and at a location 1,050 km from Mount Pinatubo, between way points SUKAR and CAVOI, 120 nautical miles from CAVOI. The aircraft was en route from Singapore to Osaka and discharge phenomena were observed on the windshield for 30 minutes. A ground inspection later revealed no damage to the aircraft. NAME modelling, without an umbrella cloud representation, predicts the reported aircraft location to be within, but on the edges of, the Pinatubo ash plume (figure 19a). Over a 30 minute period, the aircraft could have travelled some 400 km (assuming a mean aircraft speed of 500 mph). Assuming the black line from SUKAR to CAVOI in figure 19a is the approximate flight path, the aircraft is predicted to have travelled through higher ash concentrations prior to reaching the reported encounter location. Given the later encounter time than for incidents 91-11 and 91-04 (both involving aircraft on the same flight path), it is possible that the umbrella cloud may have reached the location of incident 91-12 by this time. Figure 19b shows the hourly-averaged volcanic ash concentrations predicted by NAME between FL200 and FL350 from 19:00 UTC to 20:00 UTC on 15th June 1991 with a simple representation of the umbrella cloud. The umbrella cloud is predicted to just reach the encounter location and hence predicted concentrations are similar to those without the umbrella cloud representation. As discussed earlier, the modelled umbrella cloud is subject to insufficient horizontal spread. Hence significantly higher ash concentrations than predicted could be expected at the aircraft encounter location.

3.4.6 Incident 91-16

Incident 91-16 occurred at 04:12 UTC on 17th June 1991 at an altitude of 37,000 feet ($\sim$11.3 km), 930 km from Mount Pinatubo at a location 50 nautical miles east of way point IDOSI on route A901 (details of the way point and route are unknown). The aircraft was en route from Johannesburg to Taipei via Mauritius. One engine surged, and was shut down, and another lost power. Following the ash encounter, the aircraft descended to 29,000 feet ($\sim$8.8 km) and went on to land safely. NAME modelling, without an umbrella cloud representation, predicts that the ash cloud was not present at 37,000 feet ($\sim$11.3 km) at the time and location of the reported ash encounter (figure 20a). The ash cloud is, however, predicted to have been present, at this time and location, at lower levels in the atmosphere (figure 20b) with significant ash concentrations between FL200 and FL350. The NAME modelling suggests that the act of descending to 29,000 feet during the emergency, may



(a) Without umbrella cloud representation



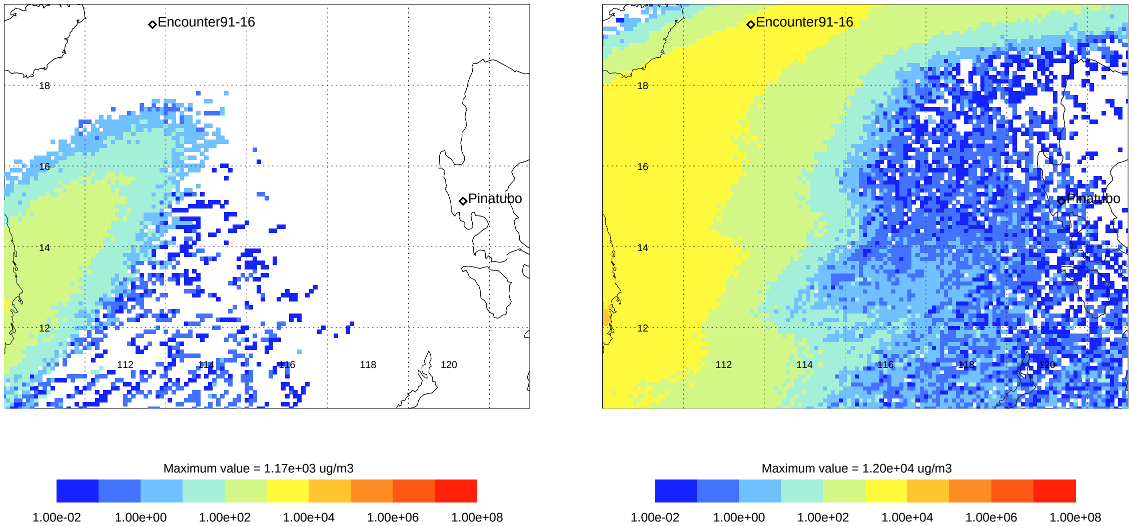
(b) With umbrella cloud representation

Figure 19: Pinatubo, incident 91-12:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL200 to FL350 between 19:00 UTC and 20:00 UTC on 15/06/1991. The black line denotes an approximate flight path between way points SUKAR and CAVOI.

have caused the aircraft to fly through higher concentrations of volcanic ash. The umbrella cloud is not predicted to have had any significant influence at the aircraft location. The TOMS instrument on the NIMBUS 7 polar orbiting satellite detected very little ash in the encounter region during its pass just after local noon (04:00 UTC) on 17th June 1991 (figure 21).

3.5 Hekla, February 2000

An instrumented NASA DC-8 research aircraft, in transit between Edwards Air Force Base, California and Kiruna, Sweden on 28th February 2000, inadvertently flew into an ash plume from Hekla, Iceland. The eruption of Hekla had occurred on 26th February 2000 and the aircraft encountered the ash plume at 05:08 UTC on 28th February 2000 at an altitude of 37,000 feet ($\sim$11.3 km). Information on the exact location of the encounter is not consistent between different reports in the literature (for example, Rose et al. [31] state 75.7° - 76.4° N latitude and 9.0° - 4.4° W longitude whereas Pieri et al. [28] state 76° N 00° W), but based on in-flight data (available from the SOLVE project website, `http://espoarchive.nasa.gov/archive/arcs/solve/data/dc8`) the encounter appears to have occurred within the region 75.7° - 76.5° N and 9.2° - 4.7° W. The on-board research instrumentation registered increased levels of aerosols and gases consistent with a volcanic plume. However, there was no change to cockpit instrument readings and no visible evidence of ash (e.g. abrasion to surfaces, odour, dust or St Elmo's fire). The encounter lasted approximately seven minutes, equating to a distance of about 50 nautical miles. The ash cloud was diffuse and Rose et al. [31] state that the volcanic cloud consisted of fine ash particles ranging in diameter from 0.5 to 20 μm. Initial investigations revealed no damage. The aircraft subsequently undertook six scientific



(a) FL350 to FL550

(b) FL200 to FL350

Figure 20: Pinatubo, incident 91-16: Hourly-averaged concentrations of volcanic ash predicted by NAME between 04:00 UTC and 05:00 UTC on 17/06/1991.

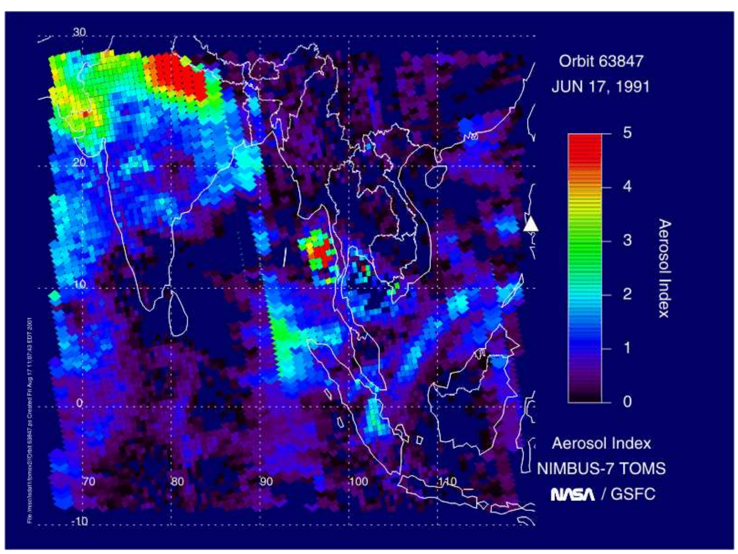


Figure 21: Aerosol index on 17th June 1991 detected from the TOMS instrument on the NIMBUS 7 polar orbiting satellite (obtained from the TOMS Volcanic Emissions Group, UMBC/NASA GSFC (`http://so2.gsfc.nasa.gov/`)). The location of Pinatubo is marked with a white triangle.

flying missions during which the on-board instrumentation detected diffuse ash clouds on several occasions [9]. The aircraft then returned to Edwards Air Force Base in California where analysis showed that the aircraft engines had sustained damage. Given the multiple encounters with the diffuse volcanic ash cloud, it is difficult to be certain on the details of the encounter which caused the engine damage. Indeed, the engine damage may have been due to accumulated exposure to dilute ash concentrations. Analysis of the engine oil, which was removed following the initial transit flight, revealed a high sulphur content [9], suggesting that the initial encounter described above may have been the primary cause.

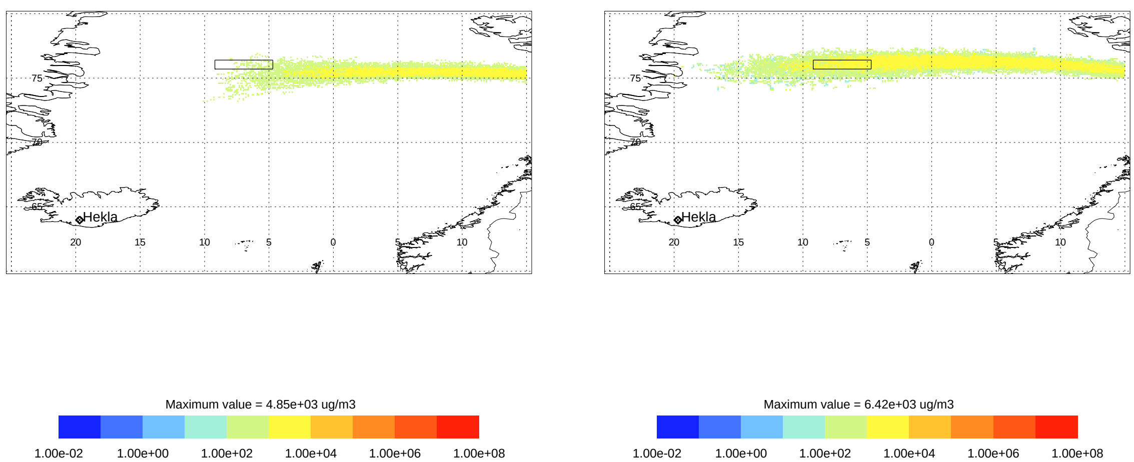
Hekla (63° 59′ N, 19° 42′ W) is one of Iceland's most prominent and active volcanoes. It has a summit elevation of 4,892 feet (∼1.5 km) (present day). An eruption at approximately 18:20 UTC on 26th February 2000 began with a brief explosive phase resulting in an ash cloud with an altitude of around 11 - 12 km. The eruption cloud was monitored using radar located near Keflavík international airport. The crew of the NASA DC-8 research aircraft were aware of the eruption of Hekla but thought their flight track would take them well north of the projected ash cloud. There are some allegations in the literature that the London VAAC forecasts for the plume were incorrect and didn't place the plume far enough north. The London VAAC advisory issued at 21:57 UTC on 26th February 2000, reproduced in Grindle and Burcham [10] and discussed in Grindle and Burcham [9], does not give any information on the plume's forecast location past 09:00 UTC on 27th February (some 20 hours prior to the aircraft encounter). We have been unable to track down subsequent volcanic ash advisories, but recollections from staff working on the eruption at the time are that the VAAC model simulations did place the plume at the encounter location. Subsequent NAME modelling of the event concurs with this (figure 22a below).

The source eruption time profile used in the NAME modelling of the eruption of Hekla on 26th February 2000 is given in table 8 and is based on eruption heights reported in the literature and radar information [21, 40]. ECMWF ERA-Interim meteorological data, with a horizontal resolution of approximately 85 km, and the Met Office's Unified Model (MetUM) global meteorological data, with a horizontal resolution of approximately 60 km (in 2000), are both available. NAME modelling of the aircraft encounter is undertaken using both sources of meteorological data. In this way, some attempt to quantify uncertainties in the modelling due to uncertainties in the input meteorological data can be made.

Start time (UTC)	Stop time (UTC)	Height (km asl)	Emission rate (kg hr^{-1})
18:20 26/02/2000	20:00 26/02/2000	12	1.102×10^{10}

Table 8: Assumed eruption parameters for NAME modelling of the eruption of Hekla in February 2000

The NAME simulations show that the ash plume initially travelled north-eastwards over Iceland and then became elongated in the east-west direction as it continued to travel north-eastwards over the North Atlantic. This resulted in a long filament of dilute ash remaining around 75° - 77° N for the next two days. Figure 22 shows the hourly-averaged volcanic ash concentrations predicted by NAME from FL350 to FL550 and between 05:00 UTC and 06:00 UTC on 28th February 2000 using MetUM global and ECMWF ERA-Interim meteorological data. Although there are differences in the predicted ash plume, both simulations predict the ash plume was present at the time and location of the reported encounter. The predicted ash concentrations in the encounter region are approximately $700\ \mu g\ m^{-3}$ and $4000\ \mu g\ m^{-3}$ using MetUM global and ECMWF ERA-Interim meteorological data, respectively. The flight path shown in Rose et al. [31] suggests that the aircraft would have flown from the northwest towards the southeast through the ash plume on its way to Kiruna, Sweden. The maximum predicted ash concentrations on the flight path are similar, approximately $3,000\ \mu g\ m^{-3}$ using MetUM global meteorological data and approximately $4,000\ \mu g\ m^{-3}$ using ECMWF ERA-Interim meteorological data. These values support evidence from the on-board research instruments which indicated that the aircraft flew through diffuse volcanic ash on this flight [16, 31].



(a) Using MetUM global meteorological data

(b) Using ECMWF ERA-Interim meteorological data

Figure 22: Hekla:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL350 to FL550 and between 05:00 UTC and 06:00 UTC on 28/02/2000. The black box denotes the encounter region.

3.6 Manam, July 2006

On 17th July 2006, a Gulfstream II aircraft engaged in survey work over Papua New Guinea experienced a double engine flameout. The aircraft was flying at 39,000 feet (∼11.9 km) near 6.2° S 144.2° E gradually heading northeastwards on a southeast to northwest mapping pattern in apparently clear air approximately 270 km to the southwest of Manam. At 05:18 UTC (15:18 LT), the right-hand engine cut out, descent was initiated, and the other engine failed a minute later. At 29,000 feet (∼8.8 km), the right-hand engine was successfully restarted, and the left-hand engine was regained at 24,000 feet ($\sim$7.3 km and approximately 3 km above the highest ground level in the area). The aircraft continued on reduced power to Port Moresby where it landed safely [43]. Investigations concluded that engine failure most likely occurred when a filter became blocked by volcanic ash. The encounter became known as the “Gulfstream incident” and was the first multiple-engine flame-out to be associated with ash too diffuse to be observed by the crew.

Manam ($4^\circ\,04'\,48''$ S, $145^\circ\,02'\,14''$ E) is a small volcanic island off the north coast of Papua New Guinea. It has a summit elevation of 5,928 feet ($\sim$1.8 km) (present day). During the period March to July 2006, intermittent, low level activity was reported with small eruptions and visible ash clouds [41]. Satellite imagery indicated volcanic ash plumes rising to altitudes of 3 km. The volcanological observer reported from his post on the mainland that activity during July peaked on the 17th with thick, dark grey ash clouds to a height of about 3 km [43]. At the time of the incident an aircraft within visible range of Manam reported an ash cloud to at least 4.5 km. NAME modelling of an eruption column with a maximum height of 4.5 km shows that low level ash would have been transported northwestwards along the coastline and not towards the encounter location. Ash was not visible on satellite imagery due to local cloud cover. No evidence has been found in the NWP data of convective cell activity in the region at the time which could have caused strong updrafts to transport the ash plume from lower levels to the height of the aircraft encounter ($\sim$12 km). Tupper et al. [44] have showed, however, that relatively weak eruptions in the moist tropics can trigger deep convection which transports volcanic ash to heights of 15 - 20 km.

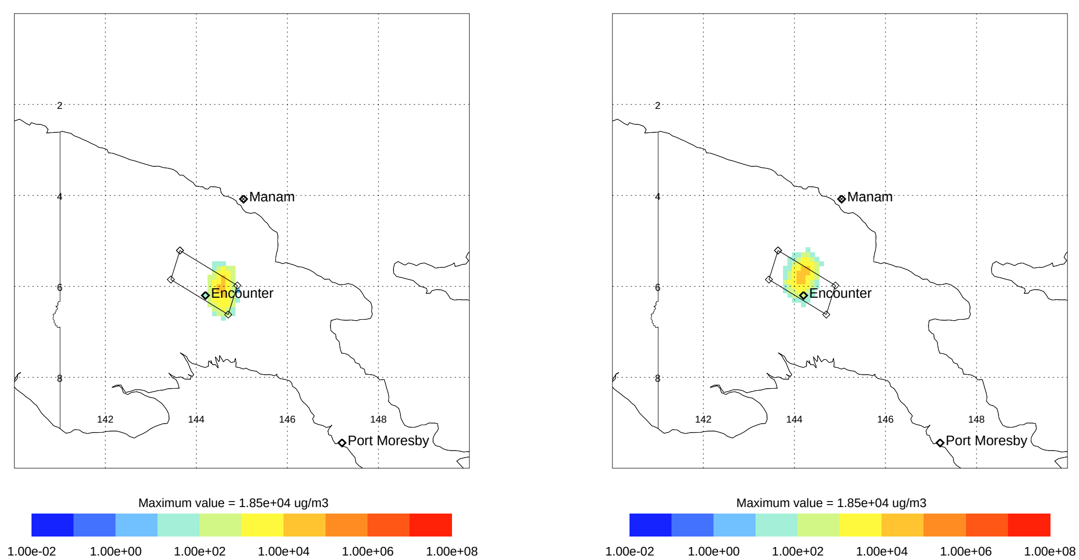
To explain the incident Tupper et al. [43] proposed that there must have been a volcanic eruption column up to around FL390 ($\sim$12 km) at some point prior to the engine failure. However, there is no evidence from observations (ground or satellite) of an eruption of this magnitude. It is plausible that the full eruption column could not be seen due to cloud. At higher altitudes, winds were towards the south west. Tupper et al. [43] used satellite observations of the movement of upper level cirrus to calculate that erupted material would have taken just under 3 hours to travel from the Manam region to the encounter location.

NAME modelling of the incident assumed a continuous eruption for a thirty minute period to a height of 12 km. The chosen duration is short as a sustained eruption to 12 km seems unlikely given the observer’s reports. However, the precise duration chosen is arbitrary. ECMWF ERA-Interim data, with a horizontal resolution of approximately 85 km, and MetUM global data, with a horizontal resolution of approximately 40 km (in 2006), are available and NAME simulations using both sources of input meteorological data have been conducted. An eruption from 01:30 UTC to 02:00 UTC, with global MetUM data, and from 01:00 UTC to 01:30 UTC, with ECMWF ERA-Interim data, places ash in the region at the time and the height of the encounter. The eruption times used with the two sources of meteorological data are relatively similar but give slightly longer transport times than Tupper et al. [43] estimated. The times of the modelled eruption are, however, only approximate; modelled eruption times within an hour or two window also predict ash within the survey region at the encounter time.

Figure 23 shows the hourly-averaged ash plume from FL350 to FL550 predicted by NAME between 05:00 UTC and 06:00 UTC on 17th July 2006, for the source eruption time profile given in table 9, using MetUM global meteorological data and ECMWF ERA-Interim meteorological data. Both simulations predict the ash plume within the survey region but with some small differences in the position of the ash plume. Using global MetUM meteorological data, the reported encounter location lies on the western edge of the predicted ash cloud but using ECMWF ERA-Interim meteorological data it is on the eastern edge of the predicted ash cloud. The aircraft was conducting northwest to southeast transects (gradually moving in a southwesterly to northeasterly direction) and hence could have traversed the plume on multiple occasions before the engines cut-out. However, the near-simultaneous failure of the engines, without an observed reduction in engine power, suggests that a gradual build up of ash was not the cause. Given the uncertainty in the eruption details, it is misleading to state the predicted ash concentration at the encounter location since different modelled eruption start and stop times place the aircraft location at different positions within the predicted plume. The maximum ash concentrations predicted within the survey region, assuming the source eruption time profile in table 9, are approximately $19,000\,\mu g\,m^{-3}$ for both meteorological data sources.

Meteorological data	Start time (UTC)	Stop time (UTC)	Height (km asl)	Emission rate (kg hr^{-1})
MetUM global	01:30 17/07/2006	02:00 17/07/2006	12	9.619×10^9
ERA-Interim	01:00 17/07/2006	01:30 17/07/2006	12	9.619×10^9

Table 9: Assumed eruption parameters for NAME modelling of the eruption of Manam in July 2006



(a) Using MetUM global meteorological data

(b) Using ECMWF ERA-Interim meteorological data

Figure 23: Manam:- Hourly-averaged concentrations of volcanic ash predicted by NAME from FL350 to FL550 between 05:00 UTC and 06:00 UTC on 17/07/2006. The black box denotes the region where the survey aircraft was carrying out traverses.

4 Results and discussions

In most of the case studies modelled, NAME predicts the presence of an ash cloud at the time and at, or close to, the location of the aircraft encounter. This gives confidence that the model is forecasting well the transport and dispersion of the volcanic plume. The main exception is in the case of Pinatubo for which the modelling is further complicated by the scale of the eruption and the presence of an umbrella cloud. Table 10 summarises the NAME predicted ash concentrations and the major limitations or difficulties encountered in each case study. Predicted ash concentrations at the reported encounter location and the maximum value in the nearby vicinity are given. The latter are provided as an estimate of the uncertainty in the ash concentrations due to uncertainty in the aircraft location and flight path.

Eruption / Aircraft encounter	Concentration at encounter location ($\mu g\, m^{-3}$)	Maximum concentration nearby ($\mu g\, m^{-3}$)	Major limitations
Galunggung	900 (12 km) 5,000 (15 km) 20,000 (20 km)	45,000 (12 km) 250,000 (15 km) 750,000 (20 km)	Uncertain eruption details and aircraft location
Soputan	0	200,000	Errors in NWP winds. Uncertain eruption height. Close proximity of aircraft to volcano $\Rightarrow$ strong flight path dependency.
Redoubt	55,000 (Loc3)	70,000	
Pinatubo Incident 91-01 Incident 91-03 Incident 91-11 Incident 91-04 Incident 91-12 Incident 91-16	 400 0 $\star$ $\star$ $\star$ $\star$	 2,000,000 <1 (60,000†) $\star$ $\star$ $\star$ $\star$	Large scale of eruption. Uncertain flight path. Typhoon Yunya, errors in NWP data. Umbrella cloud modelling.
Hekla	700 (MetUM global) 4,000 (ERA-Interim)	3,000 (MetUM global) 4,000 (ERA-Interim)	Uncertain encounter location. Effect of subsequent flights.
Manam	$\star$ (MetUM global) $\star$ (ERA-Interim)	19,000 (MetUM global) 19,000 (ERA-Interim)	Uncertain eruption details

Table 10: Best estimates of the concentrations of volcanic ash encountered by aircraft and the major limitations or difficulties encountered in estimating these concentrations. $\star$ - values not given due to very large uncertainties involved. † - maximum nearby value above the aircraft (FL350-FL550)

In most of the case studies investigated here, the NAME modelling suggests that maximum concentrations in the nearby region of the aircraft encounter location were at least $4,000\ \mu g\, m^{-3}$. This study has demonstrated that the modelling uncertainties involved can be large and hence confidence in the predicted ash concentrations is low. Some attempt has been made to quantify these uncertainties and it has been demonstrated that uncertainties of orders of magnitude in predicted ash concentrations are possible. In the case of Galunggung, uncertainties in the encountered ash concentrations due to uncertainties in the eruption height were assessed by modelling a range of possible eruption heights. An increase in the eruption height from 12 km to 20 km resulted in an order of magnitude increase in the predicted ash concentrations. For the Soputan case study, uncertainties in the aircraft's location and errors in the NWP winds, as indicated by satellite imagery, result in significant uncertainty in the location of the aircraft within the predicted ash plume. Consequently, the predicted ash concentrations encountered by the aircraft range from zero (outside of the predicted plume) to $200,000\ \mu g\ m^{-3}$ within the centre of the predicted plume. For both the Hekla and Manam case studies, the availability of more than one source of input meteorological data enabled uncertainties in the predicted ash concentrations due to uncertainties in the NWP winds to be assessed. Again an order of magnitude difference in the predicted ash concentrations at the encounter location is possible due to uncertainties in the input NWP data, although predicted concentrations within the centre of the ash plume are similar.

Reducing these uncertainties presents a number of challenges:-

1. Accurate information on the source parameters (start time, end time and eruption height) for all phases of the eruption are essential.

2. Precise information on the aircraft's location and flight path is key. Care needs to be taken to ensure these are accurate, perhaps by making use of the black box recorder, and noted correctly. In addition, since effects are sometimes reported to have lasted up to 30 minutes, equating to travel distances of hundreds of kilometres, flight path details are required to determine the maximum ash concentration encountered by the aircraft. Detailed flight path information is also required to calculate time integrated effects (dosage) necessary for situations where the effects were deemed to be caused by cumulative exposure rather than a sudden encounter with the ash cloud.

3. Modelling of historic cases are constrained by meteorological data (from historical NWP model runs or re-analyses) which has a coarser resolution than current NWP data used for operational forecasts. Consequently the uncertainties in the modelled ash plumes are somewhat larger than would be expected today.

4. To accurately model large scale eruptions, a representation of umbrella cloud dynamics needs to be included.

Accurate eruption source parameters are important for volcanic ash plume modelling in general but particularly so for eruptions that are short-lived or encounters which occur close to volcanoes, as is the case in several of the case-studies investigated here. For eruptions in poorly monitored locations or those occurring at night, constraining the eruption details can be very difficult. In recent years, monitoring of some volcanic eruptions using radar has improved [21, 27], but even these observation methods can have issues in some situations. In addition, satellite data cannot be relied upon if there is cloud cover. Minor changes in eruption height can cause large variations in predicted concentrations if the winds are in different directions at the altitudes of the ash emissions. In cases where the eruption properties vary in time, detailed information is required to model multiple eruption episodes.

The case studies described here highlight some of these issues. Based on the observed eruption height information, the encounter with the ash plume from Manam cannot be explained. To predict ash in the encounter location, an eruption height which is at odds with that reported is required. In addition, uncertainties in the eruption start time and duration impact strongly on the position of the predicted ash plume relative to the reported encounter location and hence on the predicted ash concentration at the encounter location. For the Galunggung encounter, uncertainties in the eruption height result in at least an order of magnitude uncertainty in the predicted ash concentrations. In contrast, modelling of multiple eruption episodes for the Mount Redoubt and Mount Pinatubo cases enabled the evolution of the ash clouds and details of the encounters to be better understood.

The large differences between predicted concentrations at the reported encounter location and the maximum concentrations predicted nearby highlight the need for accurate aircraft location and flight path information. Detailed information on the aircraft's position and altitude, including a flight path, is available for the Mount Redoubt encounter and this allows a good understanding of the event to be obtained. However, imprecise location references for the Galunggung encounter, misquoting of latitude and longitude coordinates for the Soputan encounter and inconsistent reports of the Hekla encounter location, give less confidence in the accuracy of these aircraft encounter locations.

The impact of errors in the NWP meteorological data on modelled concentrations is illustrated well in the Hekla case. Although the two available NWP datasets predict ash at the plume encounter location, differences in the positions of the northerly and westerly edges of the plume lead to large differences in predicted ash concentrations. The ash concentration at the encounter location is significantly higher with the ERA-Interim data since the aircraft encounter location is nearer the centre of the ash plume. The maximum estimated concentrations nearby are similar, but still differ by 25%.

The larger scale of the Pinatubo eruption over the other case studies highlights one of the current limitations of conventional dispersion models, in that they do not represent the gravity currents associated with umbrella clouds in volcanic eruptions. Accurate modelling of the horizontal spread of the umbrella cloud is therefore not possible in these models at present. However, given that gravitational spreading is, at times, the dominant motion of the plume, refining dispersion models so that they include better representations of these volcanic dynamics is desirable.

Finally, some of the encounters studied here took place near to the volcano (e.g. the encounter with the ash cloud from Soputan) and the modelling assumption that between 90% and 99.9% of the emitted ash had already fallen out may not by appropriate. This may result in an under-prediction of ash concentrations at the encounter locations. Furthermore, the particle size distribution assumed (table 1) may not be accurate for near-source locations. In particular, particles larger than 100 μm may still be airborne and may therefore need to be represented in the modelling.

5 Conclusions

This work has examined the concentrations of ash that may have been encountered during known aircraft encounters with volcanic ash clouds. In most cases the dispersion model predicts ash in these locations, but the uncertainties involved prevent confident prediction of ash concentrations. Many of the causes of uncertainty are outside of the modeller's control, for example, eruption source parameters and flight information. The lack of such data prevents comprehensive reconstructions of past events and indeed could potentially present significant problems for analysis of future events. Some reductions in modelling errors are possible through improvements to the representation of volcanic ash and the dynamics of eruption clouds in dispersion models and this is particularly important for large eruptions on the scale of Pinatubo 1991.

Simple analyses of some of the uncertainties involved have demonstrated that variations in predicted ash concentrations of orders of magnitude are possible. Consequently, this work does not provide sufficient information on which to derive unsafe concentration thresholds for aviation. To increase confidence in the use of predicted concentrations, further effort is needed to reduce errors and understand and quantify the uncertainties involved.

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References

[1] Casadevall, T.J., 1994. The 1989-1990 eruption of Redoubt Volcano, Alaska: impacts on aircraft operations. *J. Volcanol. Geotherm. Res.,* **62,** pp 301-316.

[2] Casadevall, T.J., Delos Reyes, P.J. and Schneider, D.J., 1996. The 1991 Pinatubo eruption and their effects on aircraft operations, In: Newhall, C.G. and Punongbayan, R.S., eds, Fire and Mud - Eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and the University of Washington Press,* pp 1071-1088.

[3] Davies, T., Cullen, M.J.P., Malcolm, A.J., Mawson, M.H., Staniforth, A., White, A.A. and Wood, N., 2005. A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Q. J. Roy. Meteor. Soc.,* **608,** pp 1759-1782.

[4] Derwent, R.G., Simmons, P.G., Manning, A.J. and Spain, T.G., 2007. Trends over a 20-year period from 1987 to 2007 in surface ozone at the atmospheric research station, Mace Head, Ireland. *Atmos. Environ.,* **41,** pp 9091-9098.

[5] Diamond, J., 1986. Down to a sunless sea, the anatomy of an incident. *The Log,* **April 1986,** pp 13-16.

[6] Dunn, M.G. and Wade, D.P., 1994. Influence of volcanic ash clouds on gas turbine engines, in Casadevall, T.J., ed., Volcanic ash and aviation safety; Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety held in Seattle, Washington, in July 1991: *U.S. Geological Survey Bulletin* **2047,** pp 107-117.

[7] Fero, J., Carey, S.N. and Merrill, J.T., 2009. Simulating the dispersal of tephra from the 1991 Pinatubo eruption: Implication for the formation of widespread ash layers. *J. Volcanol. Geotherm. Res.,* **186,** pp 120-131.

[8] Gloster, J., Jones, A., Redington, A., Burgin, L., Sorensen, J.H., Turner, R., Dillon, M., Hullinger, P., Simpson, M., Astrup, P., Garner, G., Stewart, P., D'Amours, R., Sellers, R. and Paton, D., 2010. Airborne spread of foot-and-mouth disease - model intercomparison. *Vet. J.,* **183,** pp 278-286.

[9] Grindle, T.J. and Burcham, F.W., 2002. Even minor volcanic ash encounters can cause major damage to aircraft. *ICAO J.,* **2,** pp 12-30.

[10] Grindle, T.J. and Burcham, F.W., 2003. Engine damage to a NASA DC-8-72 airplane from a high-altitude encounter with a diffuse volcanic ash cloud. *NASA/TM-2003-212030,* National Aeronautics and Space Administration.

[11] Guffanti, M., Casadevall, T.J. and Budding, K., 2010. Encounters of aircraft with volcanic ash clouds; A compilation of known incidents, 1953-2009. *U.S. Geological Survey Data Series 545,* **ver. 1.0.**

[12] Hanstrum, B.N. and Watson, A.S., 1983. A case study of two eruptions of Mount Galunggung and an investigation of volcanic eruption cloud characteristics using remote sensing techniques. *Aust. Met. Mag.,* **31,** pp 171-177.

[13] Hobbs, P.V., Radke, L.F., Lyons, J.H., Ferek, R.J., Coffman D.J. and Casadevall, T.J., 1991. Airborne measurements of particle and gas emissions from the 1990 volcanic eruptions of Mount Redoubt. *J. Geophys. Res.,* **96,** pp 18735-18752.

[14] Hoblitt, R.P., Wolfe, E.W., Scott, W.E., Couchman, M.R., Pallister, J.S. and Javier, D., 1996. The preclimactic eruptions of Mount Pinatubo, June 1991, In: Newhall, C.G. and Punongbayan, R.S., eds, Fire and Mud - Eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and the University of Washington Press.*

[15] Holasek, R.E., Self, S. and Woods, A.W., 1996. Satellite observations and interpretation of the 1991 Mount Pinatubo eruption plumes. *J. Geophys. Res.,* **101,** pp 27635-27655.

[16] Hunton, D.E., Viggiano, A.A., Miller, T.M., Ballenthin, J.O., Reeves, J.M., Wilson, J.C., Lee, Shan-Hu, Anderson, B.E., Brune, W.H., Harder, H., Simpas, J.B. and Oskarsson, N., 2005. In-situ aircraft observations of the 2000 Mt. Hekla volcanic cloud: composition and chemical evolution in the Arctic lower stratosphere. *J. Volcanol. Geotherm. Res.,* **145,** pp 23-35.

[17] ICAO, 2002. Doc 9691 - Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds (1st Edition).

[18] ICAO, 2009. Volcanic ash contingency plan EUR region (2nd Edition). **EUR Doc 019,** *issued by the ICAO EUR/NAT Office,* Paris.

[19] Johnson, R.W. and Casadevall, T.J., 1994. Aviation safety and volcanic ash clouds in the Indonesia-Australia region, In: Casadevall, T.J., ed., Volcanic ash and aviation safety: proceedings of the first international symposium on volcanic ash and aviation safety. *U.S. Geological Survey Bulletin*, **2047,** pp 191-197.

[20] Jones, A.R., Thomson, D.J., Hort, M. and Devenish, B., 2007. The U.K. Met Office's next generation atmospheric dispersion model, NAME III, In: Borrego, C. and Norman A.-L., eds, Air Pollution Modeling and its Application XV11 (proceedings of the 27th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application). *Springer,* pp 580-589.

[21] Lacasse, C., Karlsdóttir, S., Larsen, G., Soosalu, H., Rose, W.I. and Ernst, G.G.J., (2004). Weather radar observations of the Hekla 2000 eruption cloud, Iceland. *Bull. Volcanol.,* **66,** pp 457-473.

[22] Leadbetter, S.J. and Hort, M.C., 2011. Volcanic ash hazard climatology for an eruption of Hekla volcano, Iceland. *J. Volcanol. Geoth. Res.,* **199,** pp 230-241.

[23] Marenco, F., Johnson, B., Turnbull, K., Newman, S., Haywood, J., Webster, H. and Ricketts, H., 2011. Airborne lidar observations of the 2010 Eyjafjallajökull volcanic ash plume. *J. Geophys. Res.,* **116,** D00U05, doi:10.1029/2011JD016396

[24] Mastin, L.G., Guffanti, M., Servranckx, R., Webley, P., Barsotti, S., Dean, K., Durant, A., Ewert, J.W., Neri, A., Rose, W.I., Schneider, D., Siebert, L., Stunder, B., Swanson, G., Tupper, A., Volentik, A. and Waythomas, C.F., 2009. A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions. *J. Volcanol. Geotherm. Res.,* **186,** pp 10-21.

[25] Newhall, C.G. and Self, S., 1982. The volcanic explosivity index (VEI): an estimate of explosive magnitude for historic volcanism. *J. Geophys. Res.,* **87,** pp 1231-1238.

[26] Oswalt, J.S., Nichols, W. and O'Hara, J.F., 1996. Meteorological observations of the 1991 Mount Pinatubo eruption, In: Newhall, C.G. and Punongbayan, R.S., eds, Fire and Mud - Eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and the University of Washington Press,* Seattle and Philippine Institution of Volcanology and Seismology, Quezon City, pp 625-636.

[27] Petersen, G.N. and Arason, þ., 2010. Radar observations of the altitude of the volcanic plume during the eruption of Eyjafjallajökull, April - May 2010. Submitted to *J. Geophys. Res.*

[28] Pieri, D., Ma, C., Simpson, J.J., Hufford, G., Grindle T. and Grove, C., 2002. Analyses of in-situ airborne volcanic ash from the February 2000 eruption of Hekla Volcano, Iceland. *Geophys. Res. Lett.,* **29,** pp 19.1-19.4, doi:10.1029/2001GL013688.

[29] Przedpelski, Z.J. and Casadevall, T.J., 1994. Impact of volcanic ash from 15 December 1989 Redoubt Volcano eruption on GE CF6-80C2 turbofan engines, in Casadevall, T.J., ed., Volcanic ash and aviation safety; Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety held in Seattle, Washington, in July 1991: *U.S. Geological Survey Bulletin* **2047,** pp 129-135.

[30] Redington, A.L., Derwent, R.G., Witham, C.S. and Manning, A.J., 2009. Sensitivity of modelled sulphate and nitrate aerosol to cloud, pH and ammonia emissions, *Atmos. Environ.,* **43,** pp 3227-3234.

[31] Rose, W.I., Millard, G.A., Mather, T.A., Hunton, D.E., Anderson, B., Oppenheimer, C., Thornton, B.F., Gerlach, T.M., Viggiano, A.A., Kondo, Y., Miller, T.M. and Ballenthin, J.O., 2006. Atmospheric chemistry of a 33-34 hour old volcanic cloud from Hekla Volcano (Iceland): Insights from direct sampling and the application of chemical box modelling. *J. Geophys. Res.,* **111,** D20206, doi:10.1029/2005JD006872.

[32] Rose, W.I., Nadeau, P., Carn, S. and Schneider, D.J., 2008. Aged Volcanic Clouds: Are they an aviation hazard and why?, *AGU Fall Meeting Abstracts,* pp A4+, `http://adsabs.harvard.edu/abs/2008AGUFM.A52A..04R`

[33] Ryall, D.B. and Maryon, R.H., 1998. Validation of the UK Met Office's NAME model against the ETEX dataset. *Atmos. Environ.,* **32,** pp 4265-4276.

[34] Seach, J. Galunggung volcano. *Volcano Live,* `http://www.volcanolive.com/galunggung.html`.

[35] Self, S., Zhao, J.-X., Holasek, R.E., Torres, R.C. and King, A.J., 1996. The atmospheric impact of the 1991 Mount Pinatubo eruption, In: Newhall, C.G. and Punongbayan, R.S., eds, Fire and Mud - Eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and the University of Washington Press,* Seattle and Philippine Institution of Volcanology and Seismology, Quezon City, pp 1089-1115.

[36] Smithsonian Institution, 1982. Galunggung. *Scientific Event Alert Network Bulletin (SEAN),* **7,** 6.

[37] Smithsonian Institution. Galunggung - eruptive history http://www.volcano.si.edu/world/volcano.cfm?vnum=0603-14=&volpage=erupt.

[38] Smithsonian Institution, 1985. Soputan. *Scientific Event Alert Network Bulletin (SEAN),* **10,** 5.

[39] Smithsonian Institution, 1989. Redoubt. *Scientific Event Alert Network Bulletin (SEAN),* **14,** 11.

[40] Smithsonian Institution, 2000. Hekla. *Bulletin of the Global Volcanism Network,* **25,** 2.

[41] Smithsonian Institution, 2006. Manam. *Bulletin of the Global Volcanism Network,* **31,** 6.

[42] Sparks, R.S.J., Bursik, M.I., Carey, S.N., Gilbert, J.S., Glaze, L.S., Sigurdsson, H. and Woods, A.W., 1997. Volcanic Plumes. *John Wiley & Sons Ltd,* Chichester, UK.

[43] Tupper, A., Guffanti, M., Rose, W., Patia, H., Richards, M. and Carn, S., 2007. The "Gulfstream incident": Twin-engined flame-out over the Papua New Guinea highlands. *Fourth International Workshop Workshop on Volcanic Ash, 26-30 March 2007, Rotorua, New Zealand,* **VAWS/4 WP/07-03.**

[44] Tupper, A., Textor,C., Herzog, M., Graf, H-F. and Richards, M.S., 2009. Tall clouds from small eruptions: the sensitivity of eruption height and fine ash content to tropospheric instability. *Nat. Hazards,* **51,** pp 375-401, do1:10.1007/s11069-009-9433-9.

[45] Tupper, A. and Wunderman, R., 2009. Reducing discrepancies in ground and satellite-observed eruption heights. *J. Volcanol. Geotherm. Res.,* **186,** pp 22-31.

[46] Webster, H.N., Abel, S.J., Taylor, J.P., Thomson, D.J., Haywood, J.M. and Hort, M.C., 2006. Dispersion modelling studies of the Buncefield oil depot incident. *Hadley Centre Technical Note,* **69,** Met Office. http://www.metoffice.gov.uk/publications/HCTN

[47] Webster, H.N., Thomson, D.J., Johnson, B.T., Heard, I.P.C., Turnbull, K., Marenco, F., Kristiansen, N.I., Dorsey, J., Minikin, A., Weinzierl, B., Schumann, U., Sparks, R.S.J., Loughlin, S.C., Hort, M.C., Leadbetter, S.J., Devenish, B.J., Manning, A.J., Witham, C.S., Haywood, J.M. and Golding, B.W., 2012. Operational prediction of ash concentrations in the distal volcanic cloud from the 2010 Eyjafjallajökull eruption. *J. Geophys. Res.,* **117,** D00U08, doi:10.1029/2011JD016790.

[48] Witham, C.S., Hort, M.C., Potts, R., Servranckx, R., Husson, P. and Bonnardot, F., 2007. Comparison of VAAC atmospheric dispersion models using the 1 November 2004 Grimsvötn eruption. *Meteorol. Appl.,* **14,** pp 27-38.

[49] Wolfe, E.W. and Hoblitt, R.P., 1996. Overview of the eruptions, In: Newhall, C.G. and Punongbayan, R.S., eds, Fire and Mud - Eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and the University of Washington Press,* Seattle and Philippine Institution of Volcanology and Seismology, Quezon City, pp 3-20.

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