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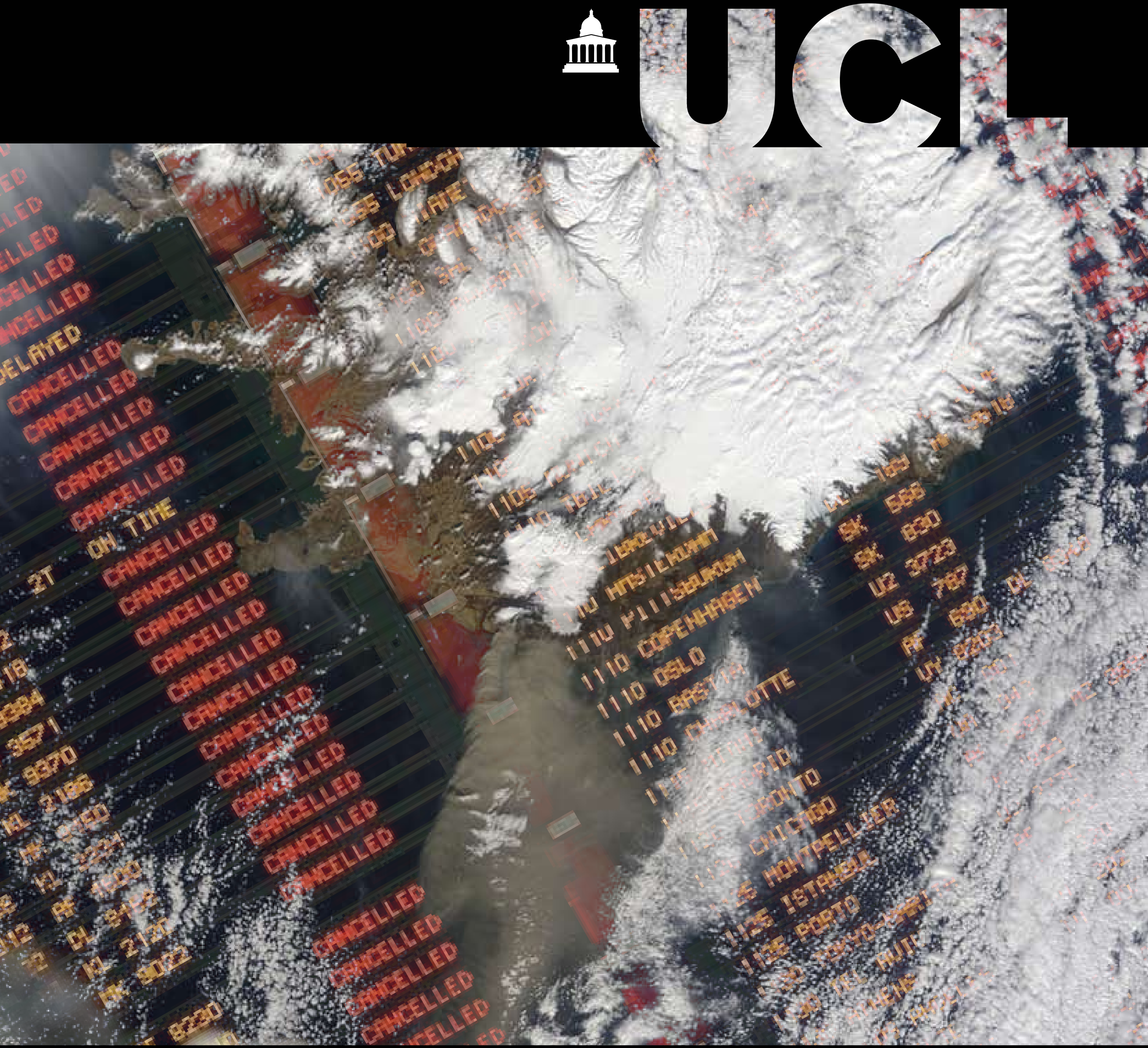

VOLCANIC HAZARD FROM ICELAND

ANALYSIS AND IMPLICATIONS OF THE EYJAFJALLAJÖKULL ERUPTION

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Cover image: Compiled from Eruption of Eyjafjallajökull Volcano, Iceland. Source: NASA, 2010

EXECUTIVE SUMMARY

The explosive eruption on the 14th April 2010 of the Eyjafjallajökull volcano, Iceland, caused an unprecedented closure of UK, European and North Atlantic air space, which must be understood if similar situations are to be better managed in the future. This report examines the Eyjafjallajökull eruption, its impact on aviation and implications for the future, in the expectation of further activity in Iceland. By bringing together expertise from across the University, the UCL Institute for Risk and Disaster Reduction provides an integrated analysis covering volcanology, geophysics, rock and ice physics, meteorology, statistics, mechanical engineering, systems engineering, transport engineering, hazard and risk communication, law and ethics.

We find:

- The current volcanic activity in Iceland is not unusual. Explosive eruptions, comparable to the 2010 Eyjafjallajökull event, occur in Iceland every 20 to 40 years on average. The 1821-23 Eyjafjallajökull eruption lasted 14 months.
- Volcanic activity at Eyjafjallajökull only becomes a major problem over Europe if this activity is coincident with north to north westerly air flow between Iceland and North West Europe, which prevails for only 6% of the time. The implication, however, is that the most recent disruption of air transport in mid-May may not be the last, despite the current (24th May) cessation of ash production.
- The impact of the eruption on regional air space could have been predicted and better prepared for as the growing problem of aircraft-ash cloud encounters has been recognised for decades. Similarly, the potential for ash clouds, specifically from Icelandic volcanoes, to interfere with air traffic in UK, European and North Atlantic air-space was appreciated by the aviation industry well before the start of the Eyjafjallajökull eruption.
- The response to the ash cloud's arrival in UK and adjacent air space was entirely reactive and therefore less effective than it should have been. This was primarily a function of the failure to recognise in advance the potential threat presented by volcanic ash clouds from Iceland. The situation was made worse by the inflexible nature of existing aviation protocols and by the absence of any pre-existing agreement on safe ash levels.
- Volcanic ash in the atmosphere can be highly damaging to the airframes, avionics and engines of civil jet aircraft: ingestion by engines of 2 gm^{-3} of ash has caused loss of power and near-crashes. The newly defined safe limits of ash are *ad hoc* and arbitrary and cannot be scientifically justified. Determining a range of robust best-estimate safe levels of ash for a wide range of situations, aircraft, engine types and pilot responses will cost time and money and will require the commitment of the aviation industry.
- Since the start of the Eyjafjallajökull eruption there has been much speculation about an eruption of the larger neighbouring Katla volcano. With the high frequency of eruptions of Katla, an eruption in the short term is a strong possibility. It is likely to be preceded by new earthquake activity. Presently there is no unusual seismicity under Katla.
- There is no doubt that future explosive eruptions in Iceland and elsewhere, coupled with appropriate meteorological conditions, have the potential to cause further disruption to air transport. It is not possible, however, to predict either when this will occur, or at what scale.
- The Eyjafjallajökull eruption demonstrated the limits of a precautionary approach. This then raises ethical issues, over who is to articulate the values to be taken into account when managing risk.

INTRODUCTION

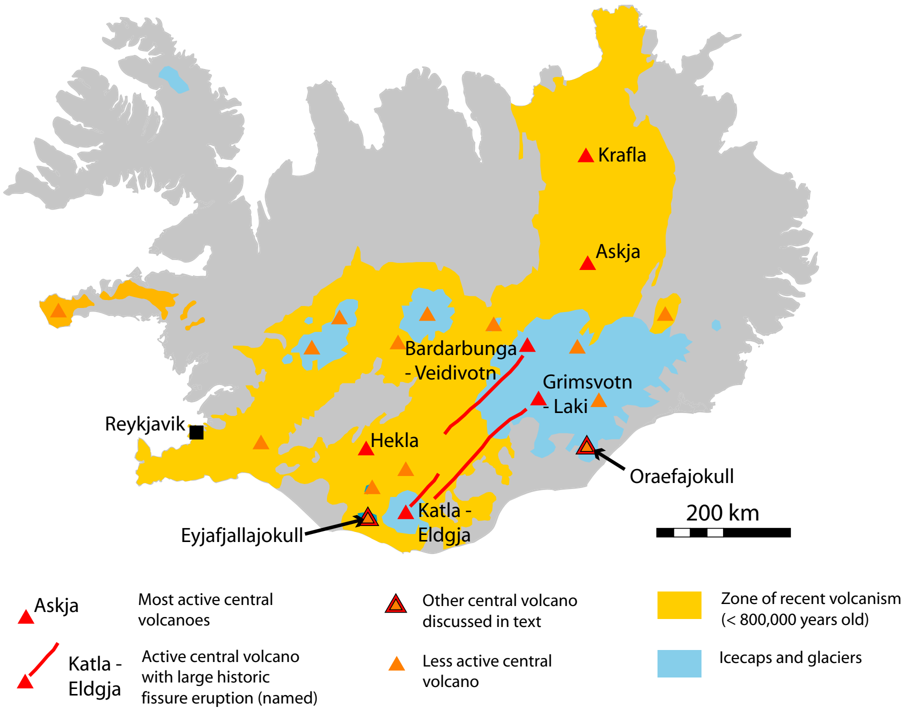

Figure 1. Volcanism in Iceland

The explosive eruption of the Eyjafjallajökull volcano, Iceland, caused an unprecedented closure of UK, European and North Atlantic air space for 6 days in April 2010 and this was followed by further episodes of air travel disruption. As a consequence a number of challenging questions are now being asked of volcanologists, meteorologists, geophysicists, engineers, regulators and airline bosses:

- What are phreatomagmatic eruptions?
- Is the eruption of Eyjafjallajökull unusual?
- Are meteorological conditions abnormal?
- Could the impact of the eruption on European air space have been predicted?
- Has the response to the eruption been appropriate and effective?
- Why is volcanic ash a problem for aircraft?
- Is there a safe concentration of volcanic ash in the atmosphere that aircraft can fly in?
- How long is the disruption likely to last?
- Will neighbouring Katla erupt?
- Are we likely to see this sort of event again?
- How can we better prepare for such events?

Eyjafjallajökull, situated in southern Iceland in the Eastern Volcanic Zone, is a stratovolcano 1666m in elevation with a crater 2-3km across, and is covered by an ice cap 70-200m thick and $100km^2$ in expanse. The explosive eruption of April 2010 was preceded by earthquake activity at depth (with magnitudes 1-3) around December 2009 and an effusive (lava extruding) flank eruption at Fimmvörðuháls, through a fissure vent not covered by the ice cap.

The explosive phase of the eruption started on 14th April from the summit crater, punching through the ice cap and causing melt waters to mix with the rising magma. The cold melt water quenched the magma causing it to fragment explosively into large volumes of very fine ash that were ejected high into the atmosphere; a style of eruption termed *phreatomagmatic* (see following section).

It was this fine ash, considered to be a potential hazard for civil jet aircraft, coupled with an unusually stable weather system and northwesterly winds from Iceland, which resulted effectively in the closure of UK and adjacent air space and air travel disruption over much of Europe. By 21st April 95,000 flights had been cancelled, resulting in chaos and leaving hundreds of thousands of passengers stranded. Under pressure from airlines, the UK Civil Aviation Authority (CAA) established *ad hoc* thresholds for safe ash concentrations that allowed the resumption of commercial flights.

The phreatomagmatic phase of an eruption will diminish if either the water supply is exhausted or is cut off as the volcano builds its edifice. On the 25th April, the Icelandic Met Office reported that external water had not affected the vent activity much since the 18th April; the explosivity was magmatic rather than phreatomagnmatic and the ash produced was coarser. Flow of lava began on 21st April. Since May, the activity has changed to a mild but sustained magmatic explosive eruption producing significant amounts of vesicular ash and pumice. But fine ash is no longer being washed out, so more is getting into the high plume and being widely dispersed.

There are significant variations in the level of activity of the on-going eruption, and on 23rd May ash production was minimal.

Figure 2. Synthetic Aperture Radar (SAR) image of Eyjafjallajökull on 15.4.10. (Source: Icelandic Coast Guard, 2010)

Table 1. Chronology of the eruption of Eyjafjallajökull

1821-23	Previous eruption
12/09	Seismicity starts
20/3/10	Fimmvörðuháls flank eruption
14/4/10	Explosive eruption
15/4/10	6-day closure of UK air space
5/10	Further closures of air space

WHAT ARE PHREATOMAGMATIC ERUPTIONS?

Phreatomagmatic eruptions are characterised by violent explosions that result from the mixing of rising magma with water. In the case of the Eyjafjallajökull eruption, the source of water was its melting ice cap. Water initially chills the magma at the interface to a hot glass, which then shatters; the water penetrates the mass of shattered hot glass and is transformed into high-pressure superheated steam by a runaway process of heat transfer and further magma fragmentation, until a violent explosion results.

The scanning electron microscope (SEM) image of an ash sample shown in figure 3,

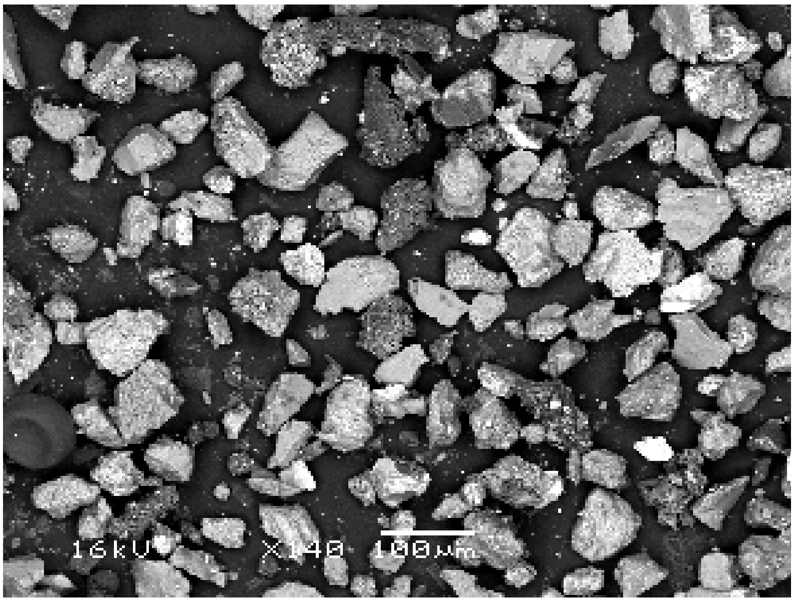

Figure 3. Ash fall collected from Surrey, England, 17/4/10. SEM image shows a textbook phreatomagmatic texture

provides a textbook example of a phreatomagmatic texture comprising:

- ***Agglutinated grains***
  Porous masses of tiny mineral and glass grains formed in the advecting plume. T_m~ 800-1000°C.
- ***Glass shards***
  Sharp grains coated in micron-sized ash. T_m~ 800-1000°C. There is a paucity of vesicular (containing bubbles) glass.
- ***Mineral grains***
  Angular grains showing multiple microfractures arising from thermal and mechanical shock. T_m~ 1000-1900°C. The signature mineral epidote is present, indicating high temperature hydrothermal alteration.

Explosions resulting from magma-water interaction can be relatively moderate, and even suppressed altogether if an over-abundant water supply quenches the magma, but they are especially violent at a water:magma ratio of 1:3. Eruption columns formed are typically water-rich. Condensation of this water usually reduces column height to 10 km or less and scrubs corrosive gases, such as fluorine and sulphur dioxide, from the eruption column.

Table 2. Magma-water interactions in volcanism
Non-explosive interaction
Near-surface inflow of lava into water
Quenching & thermal granulation of magmatic melt
Explosive interaction
Sub-surface interaction of magma and groundwater
Explosive vaporization after structural failure
Volcanic 'molten fuel coolant interaction' after formation of explosive water-in-magma prefix
Thermo-hydraulic explosion, intense shock-wave generation, significant fragmentation of wall-rocks

(Source: Zimanowski, 2001)

The fragmentation process and resulting explosions are especially violent when viscous magmas are involved.

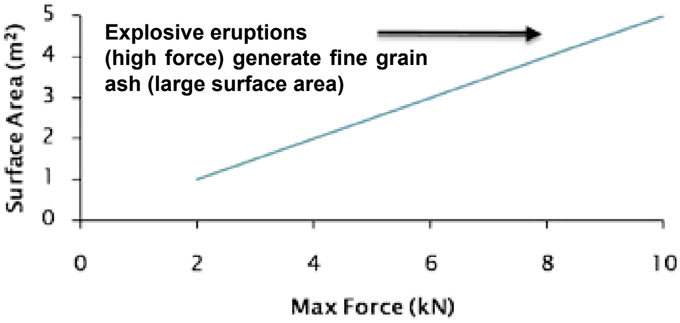

Figure 4. Fragmentation energy (Source: Sharon et al., 1996)

The effect of water mixing with magma is to lower the viscosity threshold for explosive eruptions, with the implication that for Iceland by far the great majority of explosive events are phreatomagmatic explosive basaltic (lower viscosity) eruptions (Gudmundsson et al., 2008).

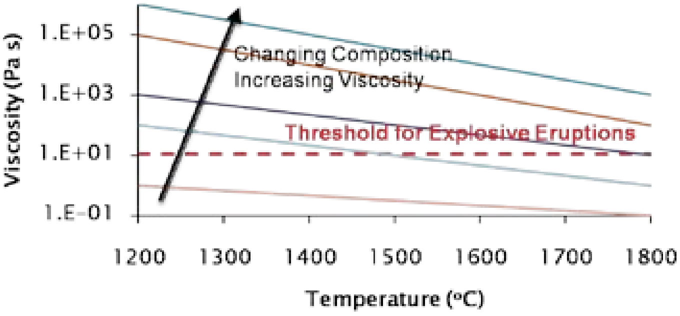

Figure 5. Influence of magma composition (Source: Zimanowski, 2001)

Violent phreatomagmatic eruptions produce especially fine-grained tephra, with a high fraction of glassy particles <1μm across, but because of the abundant water these accrete into larger particles in the eruption column (>10μm across and up to 1mm or more).

Summary: Phreatomagmatic eruptions tend to be violent and explosive. Eyjafjallajökull has exhibited this activity, most notably during the closure of air space in mid-April.

IS THE ERUPTION OF EYJAFJALLAJÖKULL UNUSUAL?

Explosivity of an eruption is measured on the Volcano Explosivity Index (VEI). Non-explosive and small eruptions, with VEIs of 0 and 1, erupt lava flows and small volumes of tephra (airborne particles of ash, pumice etc), by contrast the most explosive eruption of last century, Pinatubo, erupted over 10 km³ of tephra with a VEI of 6:

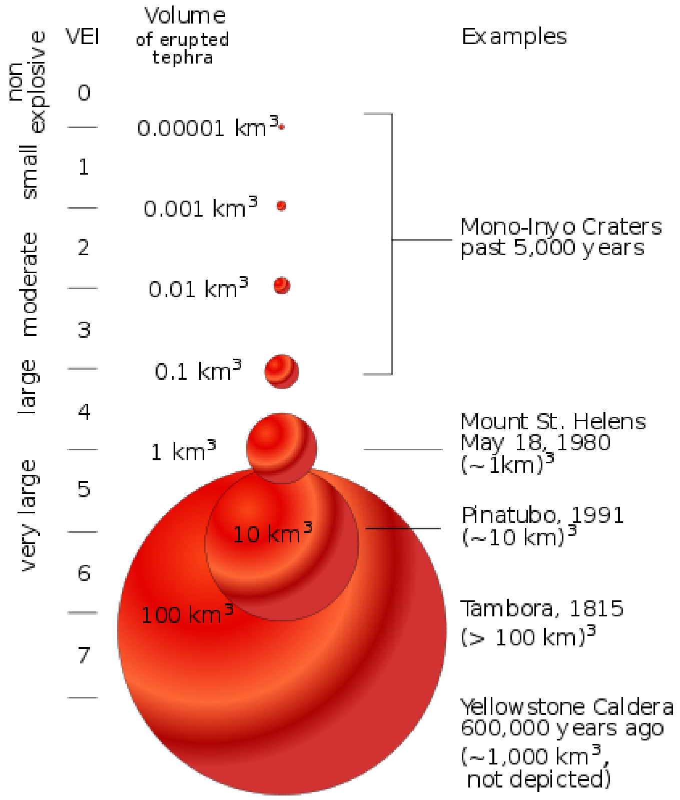

Figure 6. VEI and ejecta volume correlation (Source: Newhall & Self, 1982)

Volcanism in Iceland is the surface expression of the interaction of the deep mantle plume beneath Iceland with a constructive tectonic plate boundary (the mid-Atlantic ridge; figure 1), at which the European and North American plates are moving apart at about 20 mm/yr. Throughout Iceland a number of volcanic zones exist, with each one containing distinct volcanic systems that usually host fissure swarms and a central volcano.

Table 3. VEI's of notable Icelandic eruptions

3	Surtsey	1963-67
3	Eldfell	1973
4	Hekla	1947
4	Eyjafjallajokull	2010
5	Katla	934
5	Hekla	1104
5	Öraefajökull	1362
5	Katla	1918
6	Grimsvötn	8230 BC
6	Laki	1783

Iceland exhibits a range of volcano types and eruption styles, and many eruptions originate beneath ice sheets, adding great variation to the characteristics and styles of volcanic activity. Basalt (magma with low silica content and low viscosity) is most common, but the central volcanoes in particular also erupt andesite, dacite and rhyolite (magmas with higher silica contents and viscosities), which erupt explosively. Consequently, eruption styles have ranged from lava flow-dominated eruptions of low explosivity through to highly explosive 'Plinian' style eruptions of VEI 5 or more. The interaction of magma with water, through the melting of ice as has occurred during the Eyjafjallajökull eruption, produces violent phreatomagmatic explosions from both basaltic and more viscous magmas.

Reconstruction of the historic volcanic record in Iceland has revealed 205 eruptive events at an average of 20–25 eruptions per century. About 150 of these involved significant explosive activity (Thordarson & Larsen, 2007; Gudmundsson et al., 2008). The Eastern Volcanic Zone is by far the most active, with 80 percent of verified eruptions originating here. It contains the six most active volcanic systems in Iceland: Askja, Katla, Hekla, Grímsvötn, Bárdarbunga–Veidivötn, and Krafla. The first four of these and Öraefajökull have produced 20 large explosive eruptions in historic times with VEIs of 5 and 6, compared with a VEI of 4 for the 2010 Eyjafjallajökull event (table 3). Eruption column heights of 20 to 30 km (2 to 3 times the typical height of the largest eruption columns from Eyjafjallajökull) have been witnessed, and significant tephra falls in northern Europe – with deposits up to a few mm thick and particle sizes up to 0.1 mm – occur around once per century (Lacasse, 2001; Haflidason et al., 2000). The climactic explosive phases of these eruptions usually last less than 1 day, although such phases may occur more than once during eruptions lasting some months or more. Dispersion of the tephra in the atmosphere between Iceland and Europe means that tephra falls at sites in Europe from the climactic explosive phases typically last some days. Smaller explosive eruptions, comparable to the 2010 Eyjafjallajökull eruption, occur somewhere in Iceland every 20 to 40 years on average: the 63-year gap between the 1947 Hekla eruption and the 2010 Eyjafjallajökull eruption is unusual, but not exceptionally long.

Summary: The current volcanic activity in Iceland is not unusual.

ARE METEOROLOGICAL CONDITIONS ABNORMAL?

The impact of the Eyjafjallajökull ash plume on European air space is strongly controlled by air flow from Iceland and here we analyse this process. The prevailing meteorological conditions during the main period of closure of much of European air space during 15-23 April 2010 were dominated by north to northwesterly air flow between Iceland and North West Europe (figure 7). Though such conditions are atypical they are not considered to be particularly unusual. Analysis of air flow in the region using monthly mean mid-level (300-700mb) wind direction data from the NCEP/NCAR Reanalysis data set (Kalnay et al., 1996 and Kistler et al., 2001) shows the prevailing wind direction to be southwesterly (~60% of months). Under these conditions any Icelandic ash plume would be directed towards the Arctic Ocean and/or northern Scandinavia and would have much less impact on air transport. Similar conditions to those that prevailed during the first closure of air space occur around 8% of the time. Since the data analysed are monthly means this does not suggest that such conditions persist for a month with this frequency, but that around 8% of months have lengthy periods (long enough to dominate the average) during which such conditions prevail.

In around 30% of months the prevailing mean mid-level wind direction is between northerly and westerly. For the mean monthly direction to be westerly it is likely there is a northerly component to the flow for some time during the month (particularly considering that the normative flow is southwesterly). For example, the mean flow for April 2010 was almost due westerly, though northwesterly during the week 14-21 April when air space was closed. Thus some flow towards North West Europe from Iceland can be expected to occur during around 30% of months. Using the above frequencies an estimate of north to northwesterly flow from Iceland prevailing 6% of the time could be considered conservative.

Figure 7. Ash plume drifting southward from Iceland (Source: NASA, 2010)

Summary: Periods of north to northwesterly air flow from Iceland are atypical, but not unusual, and probably occur about 6% of the time.

COULD THE IMPACT OF THE ERUPTION ON EUROPEAN AIR SPACE HAVE BEEN PREDICTED?

The generation of an ash cloud across the UK and much of Europe as a consequence of an eruption in Iceland is far from unprecedented. A number of ash horizons preserved in the peat-lands of Scotland and northern England, testify to Icelandic eruptions around 4300, 2176, 1150, and 500 years ago that deposited ash across parts of the UK, while Iceland-sourced ash layers are also found in Ireland, Germany and elsewhere in Europe (Barber et al. 2008). In 1875, the explosive eruption of Askja, resulted in visible ash falls across Norway and Sweden (Thorarinsson 1981), and most recently, in 1947, a moderate (4 on the Volcanic Explosivity Index) eruption of Hekla produced significant ash across the region.

In the context of aviation safety, the difference between 1947 and 2010 is the advent and rapid expansion of mass air transport. The emergence of volcanic ash as a potentially significant threat to aviation only began to be recognised around 40 years ago, and is primarily a function of two factors: (1) the introduction (in the 1970s) of large, wide-bodied aircraft with engines that operate at high temperatures, and (2) the speedy and sustained growth in air traffic, which, until recently, was expanding at around 5% annually. Volcanic ash and fast-moving (≥ 800 km/hr) jet aircraft are not compatible, and the damaging consequences of the two coming together are manifold. By the late 1970s, a number of encounters between jet aircraft and ash clouds, notably over Japan and Alaska, had resulted in minor damage, but it was the near-loss of two Boeing 747 aircraft in the 1980s, due to the action of volcanic ash, that highlighted the potential seriousness of the issue. Between 1980 and 1998, alone, volcanic ash clouds, up to 3000 km from their source, have wrought damage to aircraft engines, avionics and airframes, amounting to more than USD250 million (Miller & Casadevall, 2000). The problem refuses to go away, and encounters continue to occur between ash clouds and civil jet aircraft, with a minimum of ca. 100 recorded events between 1973 and 2000 (see figure 8), (Guffanti & Miller, 2002), occurring primarily as a consequence of ineffective or non-existent warnings or inaccurate estimates of ash cloud locations.

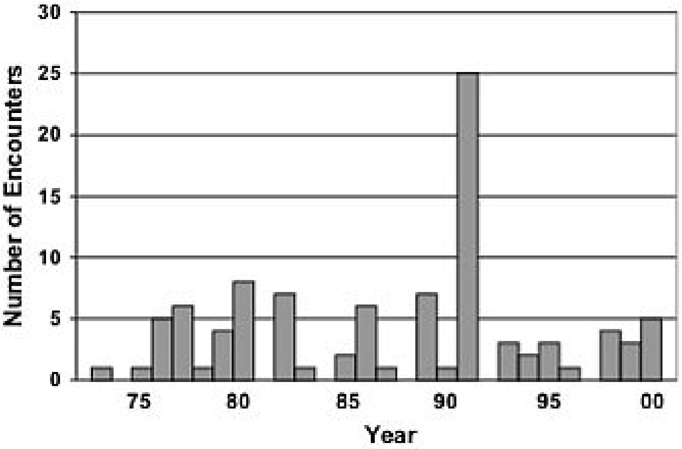

Figure 8. Number of reported aircraft encounters with volcanic ash clouds from 1973-2000 (Source: Guffanti & Miller, 2002)

Given that civil aviation protocols (prior to the current eruption) have required the simple and straightforward response that discernable volcanic ash clouds must be avoided at all costs, it was inevitable that improved remote sensing capabilities, which allowed the detection and tracking of diluted ash clouds remote from their source volcanoes, would be likely to present problems to airline traffic. In fact, this issue was highlighted in 2007 at the 4th International Workshop on Volcanic Ash (Rotorua, New Zealand), where it was recognised that 'as remote sensing techniques improve, it is likely that the aggregate areas where ash is sensed or inferred will increase, possibly leading to over-warning for ash and cost-blowouts for airlines' (International Airways Volcano Watch Operations Group [IAVWOPSG], 2008a).

Furthermore, the specific threat to the aviation industry from a future Icelandic eruption was acknowledged at the Fourth Meeting of the IAVWOPSG, held in Paris in 2008. Here the Group considered a suggestion from the Icelandic Meteorological Office (IMO) that the installation of a second Doppler weather radar in eastern Iceland would assist monitoring of volcanic activity in the area. The IAVWOPSG agreed that this 'would be likely to optimise radar coverage over

Iceland for volcanic cloud monitoring'. It also noted that eruptions, such as at Grímsvötn (which erupted in 2004 causing short-term disruption of Icelandic air traffic) 'could have a major impact on aircraft operations over the NAT [North Atlantic] Regions since Icelandic volcanoes were situated close to important air routes'. Although the Group agreed that a second radar would be a useful tool in relation to measuring the nature, height and extent of eruption columns and plumes, it determined that a detailed technical evaluation would be needed before it could make a definitive assessment of the proposal, and such an evaluation was outside the terms of reference of the Group (IAVWOPSG, 2008b).

Summary: The growing problem of aircraft-ash cloud encounters has been recognised for decades. Similarly, the potential for ash clouds, specifically from Icelandic volcanoes, to interfere with air traffic in UK, European and North Atlantic air-space was appreciated by (at least) some elements of the aviation industry well before the start of the Eyjafjallajökull eruption.

HAS THE RESPONSE TO THE ERUPTION BEEN APPROPRIATE AND EFFECTIVE?

The havoc arising from the eruption of Eyjafjallajökull has been presented in many circles as being a consequence of the event being both unprecedented and unexpected – neither is the case. As previously discussed, ash from Icelandic eruptions have reached the UK and Europe on numerous occasions. Despite this, the potential threat from Icelandic eruptions – both in relation to impact on the aviation industry and to human health – is not included on the UK National Risk Register, established in 2008 to point-up likely threats to the nation.

It is rare for any volcano to erupt without pre-cursory warning signs, and Eyjafjallajökull followed this pattern. Prior to the start of the eruption on March 20th, the possibility of an eruption had been flagged for some time. Seismicity had been significantly above background levels since December 2009, climbing further in the three weeks preceding the start of activity and accompanied by deformation since the start of the year.

Prior to the ash cloud reaching UK air space on April 15th the volcano had been in eruption for almost four weeks, a period of time ample for contingency plans to have been put in place should the potential threat of ash to UK air space have been recognised and appreciated in advance. Ideally, these would have addressed those problems associated with maintaining safe flying in crowded air space blanketed periodically by a dilute ash cloud; most notably (i) ensuring infrastructure was in place to allow adequate monitoring of the cloud in order to determine concentration levels; (ii) evaluating the appropriateness and effectiveness of programs capable of forecasting ash cloud evolution; (iii) working with engine and aircraft manufacturers and the airlines to agree safe ash levels and working procedures that minimised disruption to flights. These issues have now, of course, been (or are being) addressed, but within the less than ideal pressurised environment of crisis management rather than the relatively composed setting of hazard preparedness.

The reality of the situation was that airlines, passengers and other stakeholders were caught completely by surprise when, on the basis of a Volcanic Ash Advisory issued by the London Volcanic Ash Advisory Centre (operated by the Met Office), the UK national air traffic control NATS banned all non-emergency flights in UK controlled airspace on 15th April. Similar action took place on the continent. (See Box 1 for further details of the volcanic ash warning framework and its evolution).

With little experience of dealing with volcanic ash hazard and no forward planning, aviation authorities in countries affected by the ash cloud followed international protocols designed to prevent aircraft coming into contact with any discernable cloud of volcanic ash, and enforced blanket bans on all flights.

Box 1. Framework for warning the aviation community of volcanic ash hazard

In response to dangerous close encounters between aircraft and ash clouds in the 1980s, the International Civil Aviation Organisation (ICAO) established the International Airways Volcano Watch (IAVW), charged – in the simplest terms – with keeping volcanic ash clouds and civil aircraft apart. On advice from the WMO (World Meteorological Organisation), the ICAO designated an array of Volcanic Ash Advisory Centres (VAACs), which became operational during the course of the 1990s. Currently, there are nine VAACs, each having responsibility for advising international aviation of the location and movement of ash clouds within a particular region. The London VAAC is responsible for monitoring and forecasting ash movement over the UK, Iceland and the north-eastern part of the North Atlantic Ocean. In addition to providing volcanic ash advisories (VAA), to the aviation community, VAACs also interface, as appropriate, with volcano observatories, Meteorological Watch Offices (MWOs), which issue significant meteorological information (SIGMET), and air traffic control centres. Countries with volcanoes monitor activity via dedicated observatories that use a variety of techniques to evaluate when an eruption will occur and how its hazards may develop. Detecting whether a volcano is emitting ash can be problematic (e.g. Webley & Mastin, 2009), especially if the volcano is remote, so satellite imaging is used to detect any thermal anomalies or ash plumes, as conventional radar techniques cannot detect ash particles (Prata and Tupper, 2009). In addition LIDAR (Light Detection And Ranging) is playing an increasingly important role in detecting ash (Sassen et al., 2007). Once a monitoring observatory has detected that a volcano is ejecting ash, it assigns an aviation colour code that ranges from green, through yellow, orange to red (table 4) reflecting increasing levels of activity and ash generation, allowing aviation stakeholders to take appropriate action (Gardner, 2006). This colour code is standardised within ICAO protocols and triggers VAACs, MWOs, National Air Traffic Control Services (NATS) and airline companies to follow agreed procedures. There are limitations to the appropriateness of colour codes. Most notably, they are designed to warn of ash hazard in the immediate vicinity of an erupting volcano, and are not suited to providing warnings of distal ash clouds. Although internationally standardised in 2005, the aviation colour codes are used routinely only in the USA, and are not globally implemented. It is noteworthy that in the case of the Eyjafjallajökull eruption, the aviation colour red alert (defined as: 'Eruption is imminent with significant emission of volcanic ash into the atmosphere likely OR eruption is underway or suspected with significant emission of volcanic ash into the atmosphere') was indicated only in the sixth ash advisory issued by the London VAAC.

Table 4. Aviation Color Code Used by USGS Volcano Observatories

Colour	Description
Green	Volcano is in typical background, noneruptive state or, after a change from a higher level, volcanic activity has ceased and volcano has returned to noneruptive background state.
Yellow	Volcano is exhibiting signs of elevated unrest above known background level or, after a change from a higher level, volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
Orange	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, ***OR***, eruption is underway with no or minor volcanic-ash emissions (ash-plume height specified, if possible).
Red	Eruption is imminent with significant emission of volcanic ash into the atmosphere likely, ***OR***, eruption is underway or suspected with significant emission of volcanic ash into the atmosphere [ash-plume height specified, if possible].

(Source: AVO, 2010)

This action does not reflect a failure of the extant ash warning system for aviation; rather it is a function of the failure of the aviation community to agree, in advance, safe ash concentration thresholds. In fact, once the ash cloud was detected, the established warning system worked to the extent that:

- The standardised ICAO protocols were followed
- The precautionary approach, arising from the priority to keep aircraft and ash apart, ensured that safety was not compromised while uncertainties remained about ash concentrations
- The structure of the decision making process and the relationship between the VAAC and CAA/NATS appears to have worked in so far as it produced a decision to close air space according to ICAO protocols

The Met Office has been accused, in some circles, of being at least partly responsible, due to a variety of difficult to justify reasons, for the six-day shutdown in April. At this time the London VAAC was issuing maps with their volcanic ash advisory without any data on concentrations levels (excepting that the cloud outline is defined by the 200 μgm^{-3} threshold). At the time, this was all that was required according to prevailing aviation protocols for avoiding discernable ash clouds, irrespective of the concentration of particles. Once it became obvious that spatial information on the concentrations of ash was essential if safe limits were to be established that would allow air space to reopen, the Met Office's NAME (Numerical Atmospheric-dispersion Modelling Environment) computer model, developed to monitor the dispersion of particulate clouds, was able to supply ash concentration forecasts that allowed a range of thresholds to be established at the request of the aviation community. This model had been previously validated against other VAAC capabilities in international experiments, and in real emergency incidents, including volcanic eruptions and the 2005 Buncefield oil depot explosion. According to the Met Office, NAME output, during this event, has also been verified favourably against (admittedly less than ideal) observations. At time of writing (May 22nd), the Met Office is issuing 18-hour and 5-day ash forecast charts for a range of altitudes.

In the broadest terms, therefore, the response to the ash cloud has been less effective than it could have been, not because of inadequate observation or modelling of ash concentrations, but because the real threat of ash from Icelandic volcanoes was not recognised. This absence of awareness ensured that no attempt was made to prepare for the potential arrival of an ash cloud in UK, European and North Atlantic air space, either in the build-up to eruption or in the first few weeks of eruption itself. The purely reactive response, once the cloud arrived, was made worse by the inflexible nature of the existing protocols and by the absence of any pre-existing agreement on safe ash levels.

Summary: The response to the ash cloud's arrival in UK and adjacent air space was entirely reactive and therefore less effective than it could have been. This was primarily a function of the failure to recognise in advance the potential threat presented by volcanic ash clouds from Iceland. The situation was made worse by the inflexible nature of existing aviation protocols and by the absence of any pre-existing agreement on safe ash levels.

WHY IS VOLCANIC ASH A PROBLEM FOR JET AIRCRAFT?

Volcanic ash presents a problem for modern jet-powered (in particular) aircraft for two main reasons. Firstly, such ash is silica-rich and therefore abrasive, especially when striking an aircraft at a relative speed in excess of 800 km/hr. Secondly, the composition of most volcanic ash is such that its melting temperature lies within the operating temperature range (> 1000°C) of modern, large, jet engines (Miller & Casadevall, 2002). The effects of ash on an aircraft depend on specific circumstances, which include the concentration of volcanic ash in the cloud, the length of time the aircraft spends within the cloud, and the actions taken by the pilots while in the cloud.

The primary effects of ash on aircraft involve abrasion of forward-facing surfaces, such as the windshield and leading edges of the wings, together with accumulations of ash in surface openings – most importantly the engines. Ingestion of ash into engines causes abrasion damage to compressor fan blades. More critically, melting of ash and the accumulation of re-solidified ash on turbine nozzle guide vanes, can - and has - resulted in compressor stall and complete loss of engine thrust (Miller & Casadevall, 2000). Most commercial aircraft power-plant are turbofans, wherein the low pressure compressor acts as a fan that supplies air to the engine core and to a by-pass duct. The bypass air flow either passes to a separate ‘cold nozzle’ or mixes with the low pressure turbine exhaust gases, before expanding through a ‘mixed flow nozzle’ to give better fuel efficiency, higher thrust and lower noise level. The operating temperature in the combustor typically reaches 1100 to 1400°C, easily high enough to melt any ash particles present in the combustion chamber. This silica-melt may fuse onto the blades and other parts of the turbine, as seen in figure 9, causing an engine stall. The standard procedure of the engine control system when it detects the onset of a stall is to increase power which, in this case, would only exacerbate the problem.

More specific effects of ash on jet aircraft, determined by experiment, are summarised in Box 2.

The combined consequences for an aircraft flying into an ash cloud can be degraded engine performance (including flame out), loss of visibility, and failure of critical navigational and operational instruments (Guffanti & Miller, 2002). The most critical effects are those that compromise engine performance in flight. These constitute a serious safety hazard requiring preventative risk-management strategies, which, until the recent crisis could be summarised as ‘avoid at all costs’. This somewhat extreme strategy was largely the consequence of two serious encounters between civil jet aircraft and ash clouds in the 1980s.

In 1982, the night-time coming together of a BA747 aircraft and the ash plume from Indonesia’s Galunggung volcano, resulted in loss of power to all four engines and the plane dropping in excess of 7,500m in 16 minutes before the engines restarted, allowing the aircraft to make an emergency landing. In 1989 a KLM747 also lost power to all four engines, after encountering an ash cloud from Alaska’s Redoubt volcano. After dropping close to 4,500m in four minutes, the plane’s engines were eventually restarted just 1–2 minutes from impact. Total damage

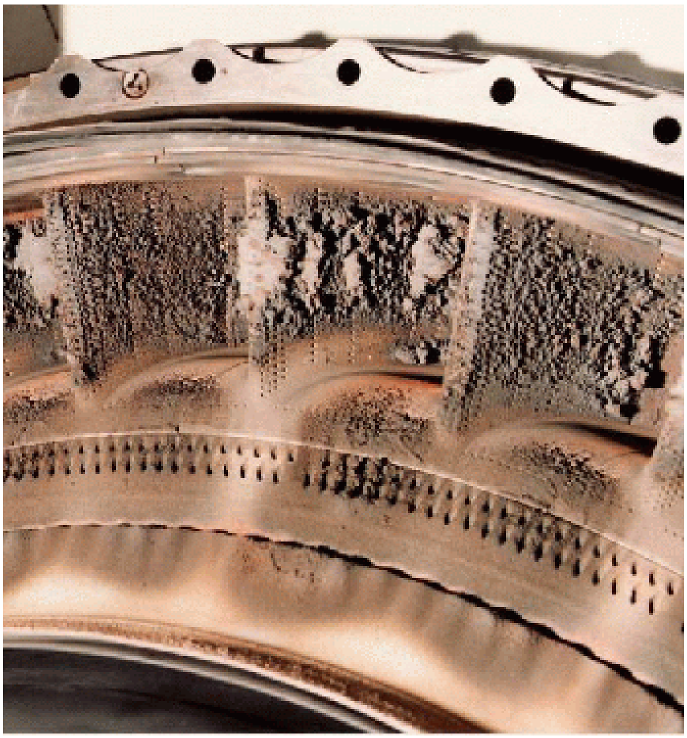

Figure 9. Engine damage from ash encounter in 1982 (Photo: Eric Moody, British Airways)

to engines, avionics and airframe amounted to more than USD80 million. The advent of the 1990s saw a further USD100 million damage sustained by commercial aircraft (some in the air; others on the ground) as a consequence of the 1991 eruption of Pinatubo in the Philippines.

Summary: Volcanic ash in the atmosphere can be very damaging to the airframes, avionics and engines of civil jet aircraft. On two occasions, ingestion of ash has caused loss of power to all four engines of Boeing 747 aircraft, resulting in near-crashes.

Box 2. Damage effects of volcanic ash on jet aircraft (after Guffanti & Miller, 2002)

- Deposition of ash on hot-section components
- Erosion of engine compressor blades and rotor-path components
- Blockage of fuel nozzles and cooling passages
- Contamination of oil systems and bleed-air supply
- Opacity of windscreen and landing lights due to 'sandblasting'
- Erosion of antenna surfaces
- Plugging of the pitot-static system used to indicate aircraft speed

IS THERE A SAFE CONCENTRATION OF VOLCANIC ASH IN THE ATMOSPHERE THAT AIRCRAFT CAN FLY IN?

Past damaging encounters between civil jets and volcanic ash clouds have occurred close to erupting volcanoes where the concentration of ash in the atmosphere is high. Aircraft that have experienced rapid engine shutdown appear to have been exposed to ash concentrations of around 2 gm^{-3}, which translates to an engine throughput of about 1000 kg/hr. Examination of the KLM747 that experienced loss of engine power over Alaska in 1989, revealed around 80 kg of ash in each turbine.

Since the serious encounters of the 1980s, the recommended aviation industry risk strategy has been for pilots to avoid volcanic ash plumes or to exit them as soon as possible using a descending turn and following a reverse bearing. Such strategies were designed, however, to prevent the coming together of aircraft and columns of dense ash close to erupting volcanoes in places like Alaska and Indonesia, where volcanic activity is near ubiquitous. They were not established to handle the lower risk associated with more dilute ash clouds relatively remote from source. Furthermore, they were designed for air-routes with room to manoeuvre, which made avoidance and alternative flight paths possible. They were not suited to a situation that involved a large, extended, ash cloud – initially of unknown density – spread across the crowded air space of the UK and western Europe.

With no other guidelines available, therefore, the decision of the UK NATS, and similar organizations on the continent, to issue a near blanket no-fly ban once a discernable volcanic cloud was detected, must be viewed as justifiable. This is reflected in a statement on May 15th, in which Andrew Haines, Chief Executive of the UK CAA accused the aviation industry of 'buck passing' by blaming safety regulators for outdated volcanic ash protocols that were unable to cope with the situation presented by the Eyjafjallajökull eruption.

The core of the problem lies in the fact that, prior to the eruption, the aviation industry had still not agreed a safe threshold of ash in the atmosphere, below which aircraft would be permitted to fly. Until April 2010, more than 30 years of civil aircraft encounters with ash clouds had failed to concentrate the minds of stakeholders sufficiently to establish an agreed safe limit. The issue was highlighted in 2008 at the 4th meeting of the International Airways Volcano Watch Operations Group (IAVWOPSG, 2008b) where the situation seems to have been explained away partly as a consequence of difficulties in attracting formal aviation industry representation at science-focused workshops on volcanic ash. Two years later, as Eyjafjallajökull started to erupt, no progress appears to have been made, and as noted in the summary of outcomes of the 5th International Workshop on Volcanic Ash convened in Santiago (Chile) in March 2010, two days after the start of the current Eyjafjallajökull eruption, 'there continues to remain no definition of a "safe concentration" of ash for different aircraft, engine types or power settings'.

This remained the situation until April 20th, when – in response to enormous external pressures – there appears to have been a shift by the UK CAA to adopt a 'reasonably practicable' approach, broadly similar to that described in the Health & Safety at Work etc Act 1974. This resulted in the re-opening of air space following discussions on tolerance levels in low density ash areas with engine manufacturers that agreed safe ash concentration limits. These *ad hoc* thresholds were guided by output from the UK Met Office atmospheric dispersion modeling program. Details of the April 20th limits and other CAA actions that had the effect of a progressive relaxation of flight restrictions in UK air space are shown in Table 5.

Table 5. Progressive relaxation of CAA flight restrictions in UK air space

Date	Action
20 April	Three zones defined based upon ash concentrations in air space: • No Risk: below 200 μgm^{-3} • Enhanced Procedures Zone (EPZ) (Red Zone): 200 μgm^{-3} to 2000 μgm^{-3} • No Fly Zone (NFZ) (Black Zone): above 2000 μgm^{-3}
11 May	Removal of 60 nautical mile 'no fly' buffer zone around areas of ash density thought to be in excess of 2000 μgm^{-3}
17 May	Introduction of Time Limited Zones (TLZs) (Grey Zone): defined as volumes of air space 'where ash concentrations are predicted to exist within which flight for a limited time duration may be permitted before engine manufacturer tolerance levels are exceeded'. These permit flights in air space where ash concentrations are deemed to fall between 2000 μgm^{-3} & 4000 μgm^{-3} provided – amongst other caveats - that the operator has a safety case supported by data from the aircraft and engine manufacturers.

(Source: CAA 2010a and 2010b)

Current thresholds appear to represent an attempt to reduce the risk to ALARP (as low as reasonably practicable (figure 10). The ALARP region lies between unacceptably high and negligible risk levels and even if the risk has been judged to be in the ALARP region it is still necessary to consider introducing further risk reduction measures to drive the remaining (residual) risk downwards. The ALARP level is only reached when the time, effort and cost of further reduction measures become disproportionate to the additional risk reduction obtained. The original values that defined the ALARP upper and lower limits in this case, viz. 2000 μgm^{-3} and 200 μgm^{-3} are *ad hoc* and without scientific basis and were generated by a Met Office program that was designed for entirely different purposes. It is noteworthy, however, that the 2000 μgm^{-3} above which the safety risk was deemed to be unacceptable is still 3 orders of magnitude less than the 2 gm^{-3} ash concentration in the two known cases of engine shutdown in mid-flight. The decision taken by the UK CAA to set the upper threshold ash density based on a value generated by the Met Office NAME program can be viewed as a form of risk transfer in light of the absence of guidelines and support from engine manufacturers who knew that this upper threshold ash density is unlikely, based on the previous two known cases, to cause catastrophic mid-flight failure

The establishment and incremental evolution of *ad hoc* safety thresholds would not have been required had a safe ash limit been previously agreed. It may be, however, that it is not possible to define such a limit that will be sufficiently robust to guarantee normal engine performance across a full range of situations, engine types, aircraft and pilot responses (Guffanti & Miller, 2002). While analyses of previous multi-engine shutdown incidents have shown that the ash concentration when it happens is approximately 2 gm^{-3}, it is still not known, even to the engine manufacturers, whether there is a threshold ash density above (and below) which the silicate melting risk will (and will not) pose an immediate problem to engines in mid-flight. Equally importantly, barring a complete in-flight engine stall, damage to turbine blades is, in general, a medium to long-term cumulative process that cannot be accurately accessed by borescoping (using a flexible endoscope), unless the engine is pulled apart and a detailed study undertaken on the flow and strength performance of the blades. There are currently few data that can help to constrain how much ash a jet engine can tolerate. Consequently, any further easing of the current *ad hoc* and arbitrary thresholds should be seen as largely pragmatic responses to commercial pressures, rather than based on hard engineering science. To determine a range of robust, best-estimate safe levels of ash for a wide range of aircraft, engine types, situations and pilot responses will require time, money and the wholehearted commitment of the aviation industry.

In addition to leading directly to severe disruption, the failure of the aviation community to set safe ash levels also resulted in a witch-hunt that looked for someone to blame. As regulator, the CAA suffered most, attacked by the public and – most ironically – by the airlines, for being over cautious. As previously discussed, the pre-cautionary approach for which the regulator was blamed, was determined by an ‘avoid ash at all costs’ protocol that had been agreed and followed by airlines for decades. Nevertheless, the resulting disruption exposed the limitations of the precautionary approach. When the general public is exposed to risks it cannot avoid or control, there is always a strong case for regulatory intervention. Unlike airlines, the CAA does not benefit from the risk exposure of the general public. As the repercussions of the 6-day blanket ban on flights in April became clearer, however, the limits of the ‘public body hence more credible’ logic became apparent. The precautionary approach that led to the blanket ban was a direct continuation of the logic that led to the CAA’s power to open or close UK skies: what mattered was the possibility of significant harm. Yet precautionary measures inevitably generate new risks. The ban on flights not only meant increased risks for all those travelling by other means; it also threatened the livelihood of whole economies. Once the appealing simplicity of the precautionary approach breaks down, an array of difficult questions arises, including: which risks (and which benefits) ought to be taken into account? Who is to articulate the values (beyond safety) that ought to be addressed when managing risks?

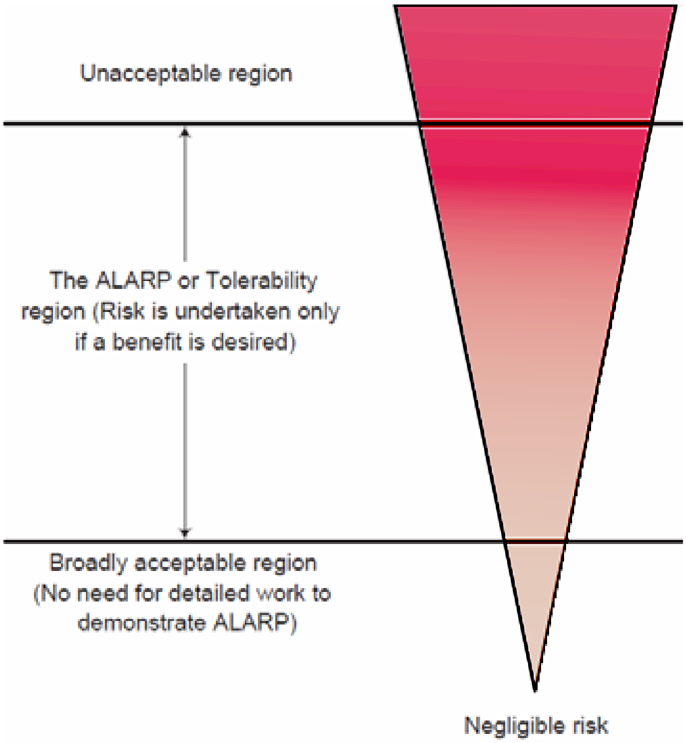

Figure 10. The ALARP region (Aven, 2003)

When the UK CAA established thresholds for safe ash concentration that allowed the resumption of commercial flights, it was keen to emphasize that its decision was based on data that were ‘finally’ communicated to it by the aviation industry. Reciprocally, the aviation industry expressed relief at the regulator ‘finally’ specifying a safe level of ash.

The strict liability regime's raison d'être is to protect vulnerable consumers from reckless, profit-driven risk-management: can it be said to induce a no-less dangerous agnostic attitude meant to shield risk-managers from responsibility?

Summary: The recently defined safe limits are *ad hoc* and arbitrary and cannot be scientifically justified. Determining a range of robust, best estimate safe levels of ash for a wide range of situations, aircraft, engine types and pilot responses will cost time and money and the commitment of the aviation industry. The eruption demonstrated the limits of a precautionary approach.

HOW LONG IS THE DISRUPTION LIKELY TO LAST?

The most obvious transport impacts from the volcanic ash cloud have been the well-publicised cancellations of air flights across the UK and Europe and the associated global disruption of air transport and stranding of passengers. The deeper problem of the vital importance of air transport in supporting the industrial base, however, is much less apparent.

The twentieth century manufacturing model means that transport systems are an essential component of the industrial process. Today manufacturers keep hardly any stock as they operate on the principle of 'Just-In-Time' delivery, which means that factories might now hold only a few hours' stock. To maintain this situation there is heavy reliance on air transport. Consequently, had the flight bans continued for much longer, the economic impact would have been even more severe. Not only would this have been felt by the airlines, but across the manufacturing spectrum. Because of the wide distribution of component producers around the world, large swathes of the developing world as well as the industrialised nations would have been impacted. For business continuity and planning, and the provision of essential goods and services, it is essential to have an idea of how long disruption might continue.

Phreatomagmatic eruptions in Iceland, such as the recent activity at Eyjafjallajökull, typically produce short-lived strongly explosive episodes within longer mainly magmatic eruptions that may last months or more. Whilst it is particularly common for the first stage of activity at glaciated volcanoes to be strongly phreatomagmatic as the vent is cleared of ice, explosive episodes can occur at various times during eruptions. The 14 month-long 1821-23 eruption of Eyjafjallajökull is amongst the longer Icelandic explosive eruptions, but is not exceptional. During that event there were three main explosive phases lasting from 1 to 25 days in December 1821, June 1822 and July 1822 (Larsen, 1999). At this stage it is not possible to say how much longer the current eruption at Eyjafjallajökull will continue, but it could be anything from a few more months to a year or more. There is also the possibility of increased phreatomagmatic activity if new vents or fissures open up under the ice sheet.

Summary: Activity at Eyjafjallajökull only becomes a major problem over Europe if increased activity is coincident with north to northwesterly air flow between Iceland and North West Europe. Our conservative estimate suggests that such air flow may prevail for 6% of the time. The implication is that the most recent period of air traffic disruption in mid-May, may not be the last, and may recur as long as the eruption continues.

WILL NEIGHBOURING KATLA ERUPT?

Since the start of the Eyjafjallajökull eruption there has been much speculation about an eruption of the larger Katla volcano. On 20th April the Icelandic President said ‘The time for Katla to erupt is coming close. It is high time to start planning for the eventual Katla eruption’.

Katla is 1,500m high and partially covered by the Mýrdalsjökull ice cap, which extends across 600 km². It contains a 10km diameter caldera, 700m deep and filled with ice. Eyjafjallajökull and Katla are subject to intense monitoring by the University of Iceland. Whilst it is true that historic eruptions of Eyjafjallajökull (1612 and 1821-23) have been followed soon after by eruptions of Katla, the later is a far more active volcano that erupts more frequently, with some 21 eruptions recognised in the historic period. These include much larger (up to VEI 5) explosive eruptions (most recently in 1625, 1755 and 1918) that are unconnected to activity at Eyjafjallajökull.

In our preliminary Bayesian statistical analysis of the activity of Katla (figure 12), the hazard rate plot indicates Katla has two states: one in which it erupts every 20 to 70 years (with increasing hazard rate), and the other a more quiescent state in which it erupts less frequently, at intervals of about 200 years. So the coincidence of the 1612 and 1821-3 eruptions could be simply a result of independent eruption cycles at the two volcanoes being in phase.

Analysis of the seismic energy released around Katla over the last decade or so (figure 13) is interpreted as providing evidence of a rising cryptodome (intrusive magma body) at Godabunga on the western flank of the volcano (Sturkell et al., 2010). Earlier seismic energy release at Katla is associated with the inflation of the volcano, which indicates it is close to failure, although this does not appear to be linked to seismicity around Eyjafjallajökull. From the seismicity, we have calculated the thermodynamic parameter, q, which measures long-range interactions and long-term memory (Vallianatos, 2009). q has a value of ~1.5, which does indicate there are long-range interactions in the seismicity.

Figure 11. Eyjafjallajökull and Katla (Source: Veðurstofa Islands, 2010)

Table 6. Eruptions of Eyjafjallajökull and Katla

Eyjafjallajökull	Katla
550 ± 50 yr	500 540 590 ± 50 yr
	610 680 780 820 ± 50 yr
920 ± 50 yr	904? 920 934 950 960
	1150 ± 50 1177 1262 1311 1357
	1416 1440 1450 ± 50 1500
	1550 ± 50 1580
1612	1612
	1625 1660 1721 1755
1821-23	1823
	1860 1918
	1955? 1999? No ice cap breakthrough
2010	

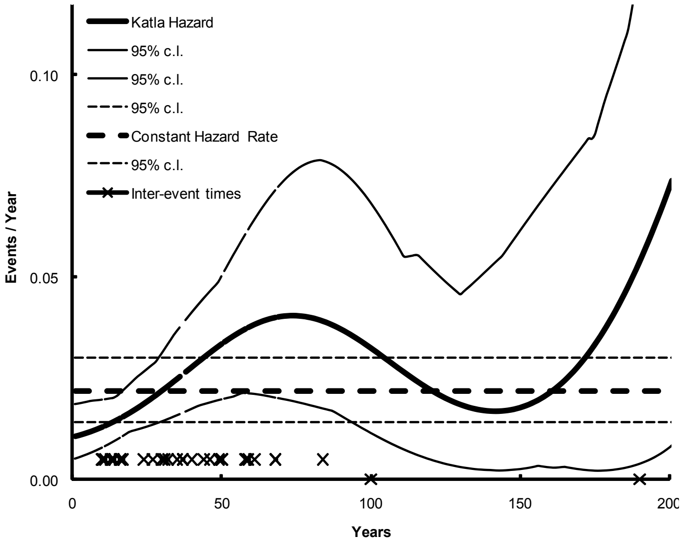

Figure 12. Hazard rate for eruptions of Katla (Applying methodology of La Rocca, 2008)

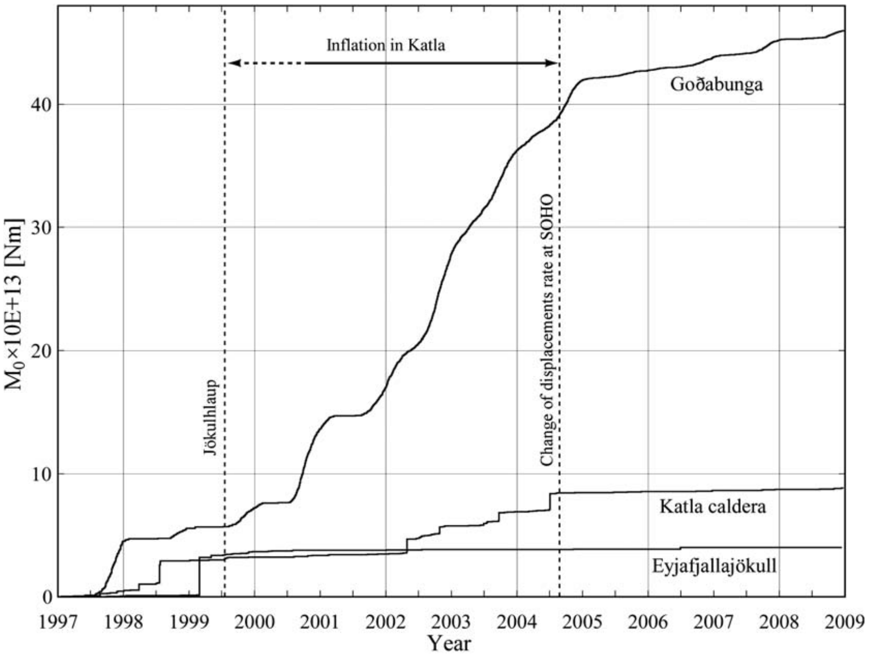

Figure 13. Seismic energy released in the Katla area (Source: Sturkell et al., 2010)

Summary: We conclude that given the high frequency of Katla activity, an eruption in the short term is a strong possibility. It is likely to be preceded by new earthquake activity. Presently there is no unusual seismicity under Katla.

ARE WE LIKELY TO SEE THIS SORT OF EVENT AGAIN?

There is good evidence to suggest that volcanic activity in Iceland since AD1200 has a 130–140 year periodicity, with intervals of lesser activity lasting 50–80 years alternating with higher activity of similar duration (Larsen et al., 1998). Within this periodicity, eruption magnitude and volume of material erupted are not constrained (figure 14).

Since 1980 Iceland may have entered a new cycle of more frequent activity, which could equate to 6–11 eruptions per 40 years (Larsen et al., 1998). The heightened activity may be related to an episode of rifting along the constructive plate boundary running through Iceland.

The sources of future ash hazard across Europe may be volcanoes located outside Iceland. Within the north Atlantic and the western half of Europe there are a number of volcanic regions that have the potential to produce highly voluminous ash plumes that reach high altitude. In particular the Azores (e.g., Furnas), the Canary Islands (e.g., Tenerife), Italy (e.g.,Vesuvius, Campi Flegrei and Etna) and the Aegean (e.g., Santorini) are worthy of mention (figure 15).

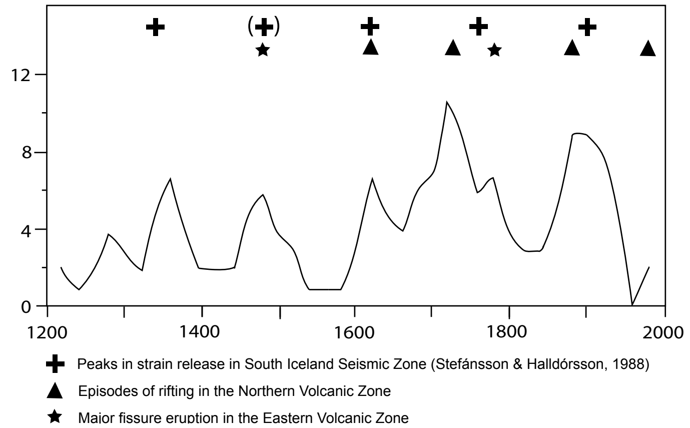

Figure 14. Forty year running average of number of eruptions within Vatnajökull (Source: Larsen et al., 1998)

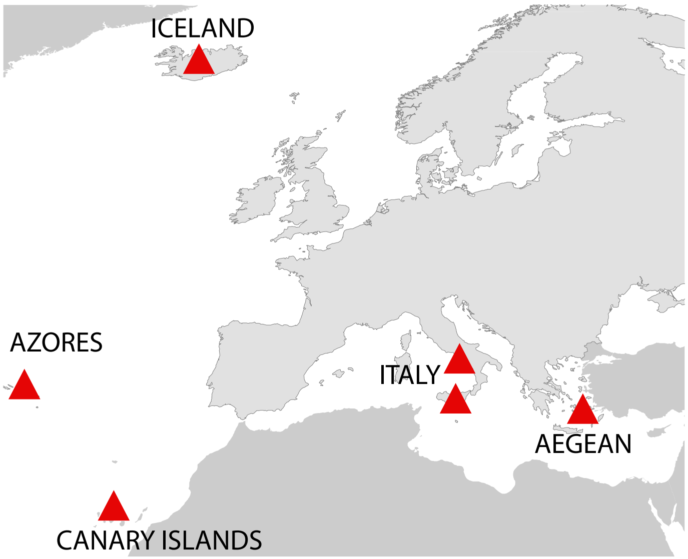

Figure 15. Possible sources of ash hazard in the western part of Europe and the North Atlantic

There is no doubt that future moderately to highly explosive eruptions in Iceland and elsewhere, coupled with appropriate meteorological conditions, will cause further disruption to air transport. Potential volcanic sources of ash are well known, but it is very difficult to predict when an eruption will occur and at exactly what scale. However, although highly complex, it is possible to model scenarios for future volcanic eruptions, which include location of the potential ash source, duration and explosivity of the eruption, volume and particle size of ash generated, atmospheric residence time of the ash plume, and meteorological conditions.

Summary: Air traffic is highly likely to be disrupted by future eruptions at volcanoes in Iceland or elsewhere in the region. Consequently there is a serious need to be better prepared in order to minimise impacts. In this regard, we present a series of recommendations in the next section.

HOW CAN WE BETTER PREPARE FOR SUCH EVENTS?

The air travel infrastructure (including aircraft, airports, air traffic control, airlines, aviation authorities, manufacturers, and travel agents) together comprises a complex system that was very significantly disrupted by the Eyjafjallajökull eruption. With foresight and investment, it would not be difficult to reduce disruption significantly. Critically, it has to be recognised that:

- For whatever reason, air travel across the UK and Europe may again be disrupted for a prolonged period (e.g. following a series of terrorist incidents) and contingency plans for this should be established.
- Ways need to be established to maximise safe air travel during such periods.

In relation to the hazard associated with volcanic ash, we make the following recommendations:

Recognition – the potential threat presented by volcanic ash to aviation should be added to the National Risk Register and should include ash sourced at other volcanic centres in the region (such as the Canary Islands and Vesuvius and Campi Flegrei in Italy) as well as at Icelandic volcanoes. Associated problems arising from volcanically-sourced clouds of sulphur dioxide should also be included.

Characterisation – national capabilities for measuring and predicting the extent and character of volcanic ash around our air space should be enhanced, including developing a better understanding of the volcanic hazard from Iceland and other European and Atlantic sources of ash. Modelling of scenarios for future eruptions and ash plume dispersion should be undertaken.

Analysis – while the 200 and 4000 μgm^{-3} thresholds are useful, they are not explicitly based on empirical experience other than that they appear to be ‘safe’. These levels need to be reviewed. Such analysis should take into account the type of aircraft, age of aircraft, engine make, flight path, frequency of service, ground maintenance capabilities, pilot behaviour and other characteristics, so that a clear and consistent picture of risk is obtained. Although this makes a clear ‘no fly’ message more convoluted it would prevent the necessity of a highly disruptive blanket ban. Acknowledging the emotive nature of the issue and the vested interests and commercial pressures involved, and to balance precaution and pragmatism, we propose an independent review panel with appropriate expertise to set robust, best-estimate, safe levels for volcanic ash.

Regulation – to minimise chaos, ill-feeling and exploitation, regulation should be considered to manage the actions of organisations such as airlines at times of emergency. These might include approval of night operations at airports; insistence that no plane flies with empty seats (even at higher classes) if passengers with valid tickets are stranded (i.e. no-charge upgrades to fill seats); and fixing fares during the affected period.

Communication – a communications centre should be established that advises the public and which all affected bodies are required to support. This would avoid the huge expense of individuals trying without success to contact airlines and other transport bodies. Efforts should be made to enable such a communications plan to make use of the resources available to the media in communicating advice objectively.

Planning – at a national level plans should be developed to deal with the long term grounding of aircraft, including consideration given to the financial impact on stakeholders as well as arrangements for repatriation of travellers. At an international level, we reiterate the principal recommendation of the UK Government Natural Hazards Working Group (2005), *vis-a-vis* the establishment of an international science panel to catalogue, evaluate and raise awareness of regional natural hazards with the potential to affect more than one nation.

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