Ash and Aviation in Europe: A Stakeholder Analysis of Preparedness for Volcanic Ash from Iceland

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Abstract

International aviation guidelines suggest complete avoidance of ash-contaminated airspace due to its hazardous impact on aircrafts and jet engines. In 2010, however, the eruption of the Eyjafjallajökull volcano memorably demonstrated the limits of this precautionary approach: Forecasted volcanic ash in one of the most densely populated airspaces in the world caused unprecedented economic and societal impacts. It forced the European aviation community to perform a paradigm shift virtually overnight in an attempt to mitigate the damage.

While the global air traffic volume is increasing, so too is, according to latest research, the volcanic activity in Iceland. This research examines the current level of preparedness of the European aviation network for a larger volcanic eruption and introduces practical measures to improve risk management.

The network comprises global, international and national regulators, crisis coordination and network managers, providers of information on weather and ash, and engines, as well as air navigation service providers and aircraft operators. The stakeholder performance is analyzed on both an individual and group level and demonstrates how risk management has improved since 2010.

To test the network's procedures in light of a larger volcanic eruption, two extreme scenarios of volcanic ash eruptions were developed and explored with the stakeholders. To strengthen risk management and societal resilience to such events, the research formulates improvement measures relating to contingency planning, improved exercises, staffing, communication, research funding and regulatory alignment. The study stresses the need to expand the network to other modes of transportation, to help develop an alternative to air transportation, when airplanes are grounded for a prolonged time due to volcanic ash in the airspace.

Útdráttur

Alþjóðlegar leiðbeiningar um flugumferð leggja til að ekki sé flogið á svæði sem mengað er af gosösku vegna áhættu fyrir flugvélar og þotuhreyfla. Gosið í Eyjafjallajökli árið 2010 sýndi vel áhrif slíkra leiðbeininga: Spá um gosösku á einu þéttsetnasta flugumferðarsvæði heims hafði fordæmalaus áhrif á hagkerfi og samfélög. Þetta varð til þess að evrópski fluggeirinn varð að skipta um stefnu með snöggum hætti til að draga úr óþörfum skaða.

Flugumferð í heiminum fer vaxandi og rannsóknir benda til þess að svo geti einnig átt við um gosvirkni á Íslandi. Þessi rannsókn kannar undirbúning fluggeirans í Evrópu fyrir stærri öskugos og ræðir mögulegar leiðir til að bæta áhættustjórnun.

Hagsmunaaðilarnir, sem þessi rannsókn tekur til, starfa ýmist á heimsgrundvelli, fyrir afmarkaða hópa landa, eða innan eins lands, t.d. við reglusetningu og eftirlit, við flugumferðastjórn eða stýringu viðbragða við atvikum í flugi, þeir veita upplýsingar um veður, gosösku og þotuhreyfla, veita flugleiðsögu og eru í rekstri flugvéla. Starfsemi hagsmunaaðilanna er könnuð, bæði einstakra stofnana og hópa þeirra, og sýnt er hvernig áhættustjórnun hefur verið endurbætt síðan 2010.

Til þess að prófa viðbrögð og vinnuferla með stærri atburði voru tvær áhrifamiklar sviðsmyndir af öskugosum búnar til og kannaðar með hagsmunaaðilunum. Rannsóknin leitast við að styrkja áhættustjórn og viðnámsþol þjóðfélaga við slíkum atburðum með því að setja fram tillögur um umbætur í viðbragðsáætlunum, viðbragðsæfingum, mönnun starfa, samskiptum, rannsóknarfjárveitingum og regluverki. Niðurstöðurnar benda á nauðsyn þess að fulltrúar fleiri samgöngumáta verði kallaðir til samstarfs, svo undirbúa megi valkosti ef ómögulegt reynist að fljúga um langt skeið vegna viðvarandi gosösku í lofti flugumferðarsvæðis.

Zusammenfassung

Vulkanasche kann erhebliche Schäden an Flugzeugen und deren Triebwerken hervorrufen. Internationale Luftfahrtrichtlinien empfehlen daher, jeglichen mit Vulkanasche belasteten Flugraum komplett zu meiden. Der Ausbruch des isländischen Vulkans Eyjafjallajökull im Frühjahr 2010 zeigte jedoch eindrücklich die Grenzen dieses Vorsorgeprinzips: Die Vorhersage von großflächig verbreiteten Aschewolken in einem der am dichtesten besiedelten Flugräume der Welt hatte ungeahnte Verluste für Wirtschaft und Gesellschaft zur Folge. Im Bemühen um Schadensbegrenzungen sah sich die europäische Luftfahrtgemeinschaft gezwungen, quasi über Nacht einen Paradigmenwechsel zu vollziehen.

Zeitgleich zum kontinuierlichen Wachstum des globalen Flugverkehrsaufkommens, indizieren aktuelle Studien eine wachsende vulkanische Aktivität auf Island. Die vorliegende Forschungsarbeit untersucht den Vorsorgegrad des Europäischen Luftfahrtnetzwerks für den Fall eines größeren Vulkanausbruch und präsentiert Maßnahmen zur Steigerung der Risikovorsorge.

Das Netzwerk umfasst globale, internationale und nationale Regulierungsbehörden, Krisen- und Netzwerkmanager, Informationsanbieter zu Wetter-, Triebwerks- und Vulkanaschedaten, sowie Vertreter der Flugsicherung und Fluggesellschaften. Die Leistung der Akteure wird sowohl auf individueller als auch auf Netzwerkebene analysiert, um darzustellen, wie sich die Risikohandhabung des Netzwerks seit 2010 gesteigert hat.

Um die etablierten Abläufe für den Fall eines weitreichenderen Ausbruchs zu erproben, wurden zwei Extremfallszenarien entwickelt und zusammen mit den Akteuren ausgewertet. Die daraus hervorgehenden Maßnahmen zur gesellschaftlichen Resilienzsteigerung gegenüber solcher Ereignisse umfassen Notfallplanung, verbesserte Ablaufübungen, Personalfinanzierung, Kommunikation, Forschungsfinanzierung sowie die Anpassung der regulatorischen Rahmenbedingungen. Die Studie betont die Notwendigkeit einer Netzwerkserweiterung durch andere Verkehrsträger, um eine Alternative zum Flugverkehr zu entwickeln, falls dieser für einen längeren Zeitraum nicht zur Verfügung stehen sollte.

Angie, Angie,
When will those clouds all disappear?
Angie, Angie,
Where will it lead us from here?

In loving memory of my dad.

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Abbreviations and Terms

ADAQ – Atmospheric Dispersion and Air Quality
ATFCM – Air Traffic Flow and Capacity Management
ANSP – Air Navigation Service Provider
AO – Aircraft Operator
ATC – Air Traffic Control
E2010 – Eyjafjallajökull eruption in 2010
EACCC – European Aviation Crisis Coordination Cell
ENHANCE – European project on partnerships for disaster risk reduction
EUR – European airspace
NAT – North Atlantic airspace
EUROCONTROL – European Organization for the Safety of Air Navigation
EVITA – Operational crisis visualization tool to display ash dispersion and air traffic
FL – Flight Level
FUTUREVOLC – European project on long-term monitoring in geologically active regions
HYSPLIT – Hybrid Single Particle Lagrangian Integrated Trajectory Model
IATA – International Air Transport Association
IAVCEI – International Association of Volcanology and Chemistry of the Earth's Interior
IAVWOPSG – International Airways Volcano Watch Operations Group
ICAO – International Civil Aviation Organization
ICETRA – Icelandic Transport Authority
IRGC – International Risk Governance Council
IMO – Icelandic Meteorological Office
IRR – Icelandic Ministry of the Interior
ISAVIA – Icelandic air navigation service provider and airport management
IUGG – International Union of Geodesy and Geophysics
IVATF – International Volcanic Ash Task Force
NAME – Numeric Atmospheric Modelling Environment, ash dispersion model
NASA – U.S. National Aeronautics and Space Administration
NORDRESS – Nordic Centre of Excellence on Resilience and Societal Security
NOTAM – Notice to Airmen
NRC – Nation Research Council
OECD – Organization of Economic Cooperation and Development
SIGMET – Significant Meteorological Phenomena
SO_2 – Sulphur dioxide
SRA – Safety Risk Assessment
VAA – Volcanic Ash Advisories
VAAC – Volcanic Ash Advisory Centre
VACC – Volcanic Ash Concentration Charts
VOLCEX – Volcanic Ash Exercise to rehearse initial response to volcanic ash eruption
VOLCICE – Monthly information flow practice between IMO, ISAVIA and London VAAC
VOLCURE – One-time exercise for aviation stakeholders in Europe
VONA – Volcano Observatory Notification for Aviation
WMO – World Meteorological Organization

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1 Introduction

With increasing interconnectedness, societal security is more and more dependent on the resilience of its infrastructure to natural hazards. A disturbance of air traffic in one part of the world can have long-ranging financial and societal effects on other parts of the world. The eruption of the Eyjafjallajökull volcano (hereafter E2010) in April 2010 illustrated this memorably. The eruption prevented millions of passengers, as well as goods, from reaching their destination. In April 2010 about 80% of Europe's aircrafts were grounded for six days (Ulfarsson and Unger, 2011). In the period April 14 until April 21, 2010, more than 100,000 flights were cancelled with an estimated € 1.3 billion loss of revenue for the airlines (Bolić and Sivčev, 2011) and an 11.7% decrease in air travel demand throughout the month (IATA, 2010). Airspace in Europe was closed on several other occasions until the eruption ended in May 2010. It led to what is known to be the greatest disruption of air traffic since World War II and caused an estimated worldwide loss of € 3.75 billion (Oxford-Economics, 2010).

The negative economic impacts of the eruption were augmented by excessively large no-flight zones. These were the result of global precautionary regulations and the specifics of a fragmented European airspace management. Volcanic ash clouds can become complex transnational hazards that require coordinated efforts from different sectors. While concern about the threat was raised by various entities within the aviation community before 2010, the event was not anticipated by the industry as a whole (Sammonds et al., 2010). The lack of an overarching structure to enable communication between the stakeholders led them to overlook the risk. When the eruption had caused widespread closures of air space in 2010, multiple sectors had to coordinate ad hoc to work jointly towards a solution. This had by then caused larger and longer disruptions than might have been necessary had the aviation community been more appropriately prepared beforehand. During E2010, regulations defining no-flight zones were revised in order to reduce their size while maintaining in-flight safety (Ulfarsson and Unger, 2011).

E2010 had a severe impact on air traffic although, historically, it was not a particularly strong eruption in terms of size or duration. More severe events, lasting longer and/or emitting more volcanic ash, are probable. Historic records (e.g., see Gudmundsson, 1987) suggest that a volcanic eruption occurs in Iceland approximately once every five years. Novel studies hypothesize that this frequency is to increase further due to climate change (Compton et al., 2015). Since volcanic eruptions cannot be prevented, cooperation and preparation are of key importance in mitigating their impacts.

E2010 led to a paradigm shift in the approach to volcanic ash clouds in Europe, both in regulatory terms and in terms of coordination between stakeholders. It provided incentives to a rise in risk awareness among policymakers and showed that a possible increase in the likelihood of new volcanic ash events will lead to a number of challenges: How prepared is the European aviation industry to meet the next volcanic ash eruption? What did we learn from E2010? Did cooperation between stakeholders change? Were regulations improved? How vulnerable is the aviation network to a more severe event? What measures can enhance resilience and mitigate the impact of a future volcanic ash event in Europe?

1.1 Research Objective

This research aims to obtain insights into how the European aviation sector has advanced its risk management with regard to volcanic ash since the eruption in 2010 and to provide recommendations for future improvement. It focuses on the cooperation and information exchange of stakeholders involved in the process of reducing impact of volcanic ash eruptions on the aviation industry.

The objectives are to:

- Determine who the stakeholders and decision-makers are when it comes to volcanic ash and aviation in Europe
- Review the stakeholders' cooperation during E2010 and their advancements since then
- Use extreme-case scenarios to assess the joint preparedness of the stakeholders for more severe events
- Identify measures to increase resilience to future volcanic ash incidents

1.2 Organization of the Dissertation

The dissertation is organized into seven chapters. The current chapter introduces the topic, presents the research objectives and provides an outline to the structure of the dissertation. Chapter 2 provides an overview on volcanism in Iceland and a general background on volcanic ash, risk regulation and aviation. Four scientific papers constitute chapters 3, 4, 5 and 6. Chapter 3 is an article published in the *Transportation Research Record: The Journal of the Transportation Research Board*, chapter 6 is an article published in *Transportation Research Part A: Policy and Practice*, while chapters 4 and 5 contain papers which have been submitted for publication in international peer-reviewed journals. All the papers have in earlier versions been presented at conferences and in research seminars.

Chapter 3 describes the information exchange between the scientific and aviation sectors to provide support to decision-makers. It discusses the state of risk management before and during E2010, and developments since then to increase the system's resilience through cooperation. Chapter 4 introduces the extreme-case volcanic ash scenarios and their impacts on European airspace. These were developed to explore the response of the European aviation community to extreme events. Chapter 5 examines the methods used to interact with the stakeholders in this study, in particular the participatory stakeholder workshop where the scenarios were used. Chapter 6 presents the recommendations developed from the workshop to improve resilience to volcanic ash eruption events. Some material is repeated within the chapters to place the individual papers' objectives in context. Chapter 7 concludes the dissertation with overall findings and recommendations of the research.

2 Research Background

2.1 Volcanic Activity in Iceland

There are 32 active volcanic systems in Iceland (Ilyinskaya et al., 2015). Volcanic systems are considered to be "active" if the last eruption occurred less than 10,000 years ago (Siebert et al., 2010). Iceland is one of the most volcanically active places in the world (Thordarson and Höskuldsson, 2008) due to two geographical specifics. The island is on the Mid-Atlantic Ridge, the plate boundary along which the American and the Eurasian tectonic plates diverge. Through the resulting rift, lava erupts and produces new crustal material on the seafloor (Smithsonian, 2014). While most elevations along the ridge are below sea level, Iceland is located on a geological hot spot which further enhances volcanism and is assumed to have created the island (Einarsson, 1991).

Volcanic eruptions can be divided into three types: Effusive, explosive and mixed eruptions. In effusive eruptions more than 95% of the emitted matter is lava, molten rock. In explosive eruptions, 95% or more of the erupted material is tephra, airborne volcanic ejecta of any size (Thordarson and Larsen, 2007). Mixed eruptions produce both lava and tephra.

Over the last 1100 years, the prevailing number of volcanic eruptions in Iceland were explosive, due to the subglacial location of the majority of the most active volcanic systems (Ilyinskaya et al., 2015). During a subglacial eruption, the rising magma interacts with the melt water, explodes and shatters into fine particles that escape violently (Einarsson, 1991). These eruptions qualify as phreatomagmatic. The main matter produced in phreatomagmatic eruptions is volcanic ash (Gudmundsson, 1987).

Volcanic ash is defined as fragments that measure 2 mm in diameter or less. It is a mix of minuscule pieces of volcanic glass, minerals and powdered rock (Wyllie, 1971). Depending on particle size, magnitude of the eruption and atmospheric conditions, volcanic ash can rise to altitudes as high as 45 km (Self and Walker, 1991). The particles can remain in the air for days and even weeks (Einarsson, 1991; Guffanti and Miller, 2002) and travel across continents.

Of the 32 active volcanic systems in Iceland, 13 have erupted since the island was settled in AD 874 (Thordarson and Höskuldsson, 2008). Icelandic volcanoes are historically known to have widespread impacts on society and the natural environment beyond Iceland. The Laki eruption in 1783–84 is a notorious example of how far-reaching these consequences can be. Large amounts of sulphur dioxide (SO_2) were emitted during the eruption and affected the weather in the Northern Hemisphere for years after the eruption (Thordarson and Self, 2003). The aerosol cloud, described as dry fog, led to a drop in surface temperature north of the equator until 1785 (Grattan, 1998). It is assumed to have caused crop failure and one of the most severe winters in European records (Rudloff, 1967). Some suggest that the devastating impact of the Laki eruption may even have led to political unrest and contributed to triggering the French Revolution (Wood, 1992).

2.2 Recent Eruptions

This section presents a brief outline of Icelandic volcanic systems that are remarkable in their frequency and/or impact with regards to recent (geologically speaking) activity. Figure 2.1 illustrates the location of the volcanoes described below an compares potential ash column heights. Table 2.1 provides a summary of the volcanic systems' key figures at the end of the section.

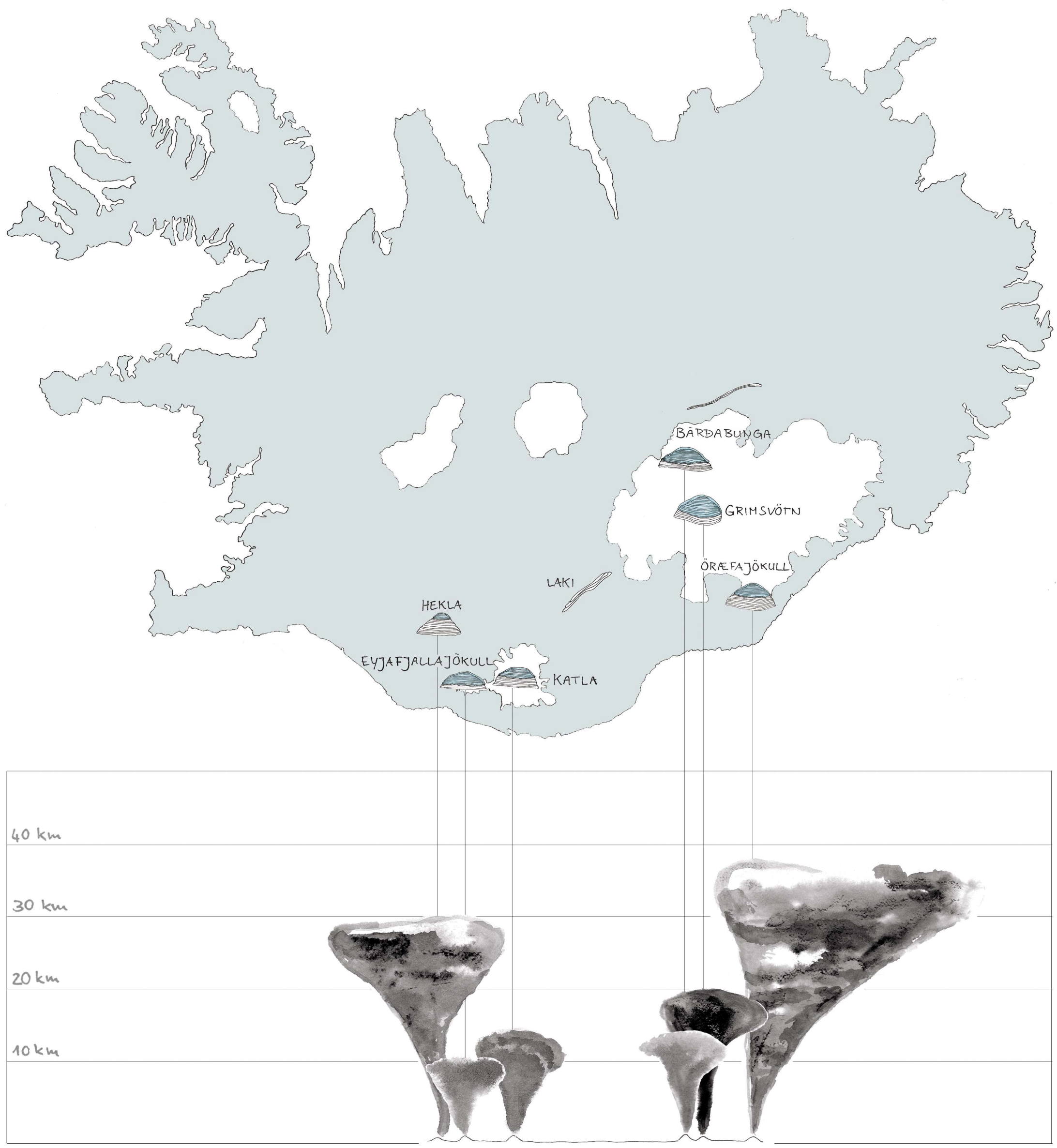


Figure 2.1 Selected volcanic systems and potential ash column heights, Iceland.

The most active volcano in Iceland is Grímsvötn, erupting approximately every 10 years. It is situated under the northwestern side of the Vatnajökull glacier and is partly covered by ice. The ice-covered part of the volcano is characterized by explosive basaltic eruptions while the ice-free part shows basaltic fissure eruptions (Gudmundsson and Larsen, 2016). The last two eruptions of the Grímsvötn volcano, in 2004 and 2011, had impacts on air travel. The 2004 eruption emitted a 13 km high ash plume and caused wide-ranging rerouting of air traffic around the area of the volcano (DLR, 2004). The incident raised awareness of the potential threat that Icelandic volcanism can pose to important air routes in the North Atlantic region (IAVWOPSG, 2008). The latest Grímsvötn eruption in 2011 was the largest eruption in Iceland since 1918. It emitted 0.8 km^3 of basaltic tephra and reached a plume height of 20 km (Tesche et al., 2012; Petersen et al., 2012). While it clearly outweighed E2010 in eruption size, its impact on air traffic was considerably lower, with 1% of flights in Europe cancelled during a period of three days (Global Volcanism Program, 2011).

The Bárðarbunga volcanic system is the second most active system and is located north of Grímsvötn. While the central volcano is fully covered by the Vatnajökull glacier, its fissures are partly ice-free (Larsen and Gudmundsson, 2016a). Discharges of the volcano are diverse in volume and can range between 0.01 and 10 km^3 of tephra, with the majority of eruptions between 0.01 and 1 km^3. Bárðarbunga's last eruption in 2014–15 is the most recent volcanic eruption in Iceland. The fissure eruption was subaerial and lasted 6 months with a lava volume of around 1.6 km^3 (Larsen and Gudmundsson, 2016a). It was the largest effusive (lava-emitting) eruption since the Laki eruption in 1783–84 (Pedersen et al., 2017). The eruption did not produce ash. However, the fissure did emit large volumes of SO_2 which posed a health risk to communities in Iceland and led to increased levels of SO_2 in other European countries (Gíslason et al., 2015; Pfeffer et al., 2018).

Hekla is located in the southwest of Iceland and is the country's third most active volcano. It is covered by a small glacier and its eruptions are usually a mix of tephra and lava (Larsen and Thordarson, 2016). Hekla's volcanic activity can be considerable, both in duration and eruption size. From 1766 to 1768 the volcano was intermittently active for 25 months. Around 3000 years ago, the largest explosive eruption emitted an estimated 10 km^3 of ash material (Larsen and Thordarson, 2016), compared with the 0.27 km^3 emitted during E2010 (Gudmundsson and Höskuldsson, 2016). The volcano is known for its sudden eruptions with a pre-warning time as short as 30 minutes (Soosalu et al., 2005). Such an abrupt outburst poses a threat on-ground and in-air: Evacuation time might be too short for mountaineers who hike along the flanks of the volcano. Concern was also raised about the 20–30 aircrafts that traverse directly over the central volcano on a daily basis and that could be affected by an unanticipated ash plume shooting up (MBL, 2016). While the intervals between eruptions vary from 9 to 121 years, in recent times the volcano has shown a regular frequency of about 10 years. Having last erupted in 2000, Hekla is currently considered "overdue" (Geirsson et al., 2012).

The Katla volcano is located in the south of Iceland, close to Eyjafjallajökull, and is covered by the Mýrdalsjökull glacier. Katla is considered highly active, with more than 20 eruptions in the last 1000 years, and its eruptions are long lasting and large. Depending on the material composition, an outburst can continue for weeks and even years at a time (Larsen and Gudmundsson, 2016b). The last eruption in 1918 ejected an estimated 0.7 km^3 of tephra and produced an ash column of 14 km in height. According to Larsen and Gudmundsson (2016b), plume heights up to 20 km can be assumed for larger eruptions of

Katla. The eruption pattern of the last centuries suggests an eruption twice per century (Thorarinsson, 1960). The current resting phase of the volcano has been the longest recorded, and E2010 raised expectations of a new eruption in Katla in the near future. At least two of Katla's recent eruptions occurred simultaneously with eruptions of the Eyjafjallajökull volcano, one in 1612 and the other in 1821 (Sturkell et al., 2003).

The most infamous of recent eruptions in Iceland is the March−May 2010 eruption of Eyjafjallajökull. At first this was an effusive eruption on the side of the mountain, emitting lava streams that attracted tourists and locals to the spectacle. Events changed dramatically in the middle of April, when a major phreatomagmatic eruption began—spewing out volcanic ash which dispersed widely and memorably blocked air traffic in Europe for several days (Ulfarsson and Unger, 2011; Gudmundsson and Sigurdsson, 2012). E2010 was the largest recorded eruption of Eyjafjallajökull. Within 39 days of continuous activity the volcano emitted 0.27 km^3 of fine–grained tephra. The ash was widely distributed across Europe, from northern and central Europe (Colette et al., 2010; Flentje et al., 2010; Groß et al., 2012; Wiegner et al., 2012) to Spain (Revuelta et al., 2012). Furthermore, 0.023 km^3 of lava was emitted during the eruption (Gudmundsson and Höskuldsson, 2016). According to Gudmundsson and Höskuldsson (2016) an eruption of more than 0.5 km^3 is unlikely due to the limited size of the subjacent magma chamber. However, the duration of its volcanic activity can vary considerably: From 1821 to 1823 Eyjafjallajökull exhibited 14 months of intermittent explosive volcanic activity.

The Öræfajökull volcano is the largest among the Icelandic volcanoes, both in height and volume (Thorarinsson, 1958). The volcano is located under the Öræfajökull glacier as part of the Vatnajökull glacier. Öræfajökull has erupted twice in the last 1000 years, in 1362 and 1727–28. The latter was of moderate magnitude (0.1–0.5 km^3 of tephra volume). In contrast, the eruption in 1362 is one of the largest eruptions in Iceland in historical times. It emitted 10 km^3 of tephra and produced an ash plume estimated to have reached 35 km in height. Traces of this ash have been found in Greenland and Northern Europe (Höskuldsson, 2015). The devastating consequences for its immediate environment are reflected in the volcano's name ("*öræfi*", Icelandic for wasteland).

Table 2.1 Key figures of selected volcanic systems with respect to atmospheric contamination

Volcanic system	Max. tephra volume in km^3	Max. column height in km	Max. eruption duration	Record of tephra fallout on European mainland	Recent significant eruptions
Eyjafjallajökull	0.27	10	> Year	Yes	**Eyjafjallajökull 2010**: Widespread disruption of air traffic, estimated 5 billion USD in global economic damage
Grimsvötn	0.8	20	Months	Yes	**Laki 1783–84**: Lowering of surface temperature in Northern Hemisphere 1783–85 **Grímsvötn 2011**: 1% of European flights cancelled over 3 days
Katla	~ 2	14	Months	Yes	**Katla 1918**: Large glacier outburst
Bárðabunga	10	~ 14	Months	Yes	**Holuhraun 2014–15**: Gas pollution impacted ecosystems and local population
Hekla	10	30	> Year	Yes	**Hekla 1766–68**: Among the largest lava eruptions in Iceland since the settlement
Öræfajökull	10	35–40	Weeks	Yes	**Öræfajökull 1362**: Devastating damage to immediate environment

2.3 A Digest to the History of Aviation and Volcanic Ash

In 1952, the first commercial jet engine-powered passenger aircraft flew from London to Johannesburg and commenced the era of commercial air travel (Boyne and Lopez, 1979). The transition from propeller-driven planes to aircraft with jet engines shortened travel times considerably, but it was met with some concern as jet engines ran on higher operating temperatures and required more expensive engine parts and more expensive fuel.

Thirty years later, in the summer of 1982, the captain of flight BA009 from London to Auckland made the following infamous in-flight announcement:

"This is your captain speaking: We have a small problem. All four engines have stopped."

At that point, no one was able to tell why the engines had stopped working nor why they resumed functioning 12 minutes later (Stewart, 1999). The crew further witnessed St.

Elmo's fire (a bright blue or violet glow) on the windscreen, smoke and the odor of sulfur that accumulated in the passengers' cabin. Visibility was impaired due to what appeared like a sandblasted windshield, despite the radar indicating clear skies. Investigations after the safe landing of the aircraft in Jakarta explained the cause of the power loss: The aircraft had flown through the volcanic ash cloud of the erupting Mt. Galunggung in Indonesia. The dryness of the ash made the cloud invisible to the weather radar that detects clouds by moisture.

The incident called the public's and aviation community's attention to the threat that volcanic ash poses to aircraft (Smith, 1983; Tootell, 1985; Miller, 1994). Volcanic ash is sharp matter, a mix of hard glass particles and pulverized rock (Casadevall et al., 1996). When an aircraft encounters volcanic ash, the impact on the aircraft and the engines can be severe. In flight, ash particles get absorbed by jet engines. The melting point of ash (around 1,110°C), lies below the operation temperature of commercial jet engines (around 1,400°C) which causes the particles to melt in the combustion chambers and solidify on the engine blades and can cause the engine to stop. In the case of flight BA009, it was believed that the cooling of the engines during the descent of the aircraft led to the shattering of enough solidified ash to restart the engines (Stewart, 1999). The observations of the crew turned out to be characteristic of encounters with volcanic ash (ICAO, 2012).

Figure 2.2 illustrates the diverse abrasive damage which sharp volcanic ash particles can cause to an aircraft (Casadevall et al., 1996).

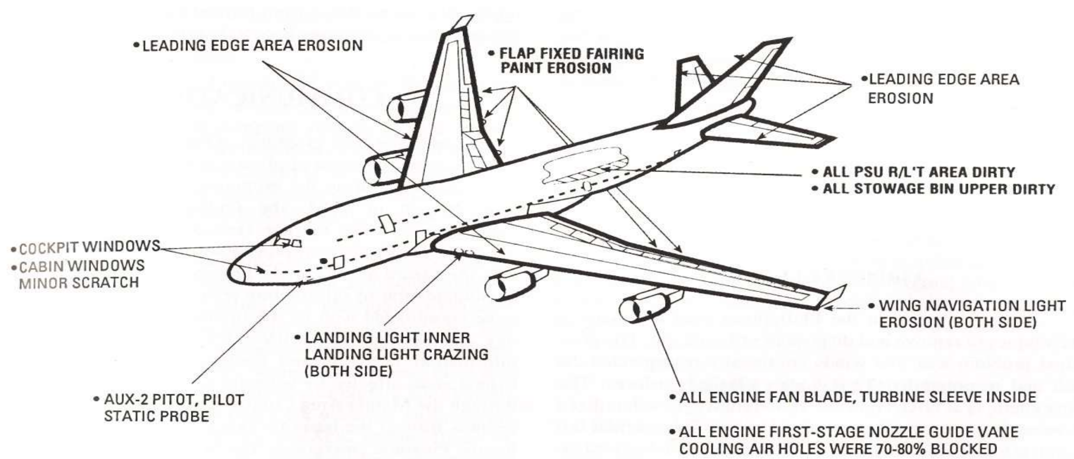


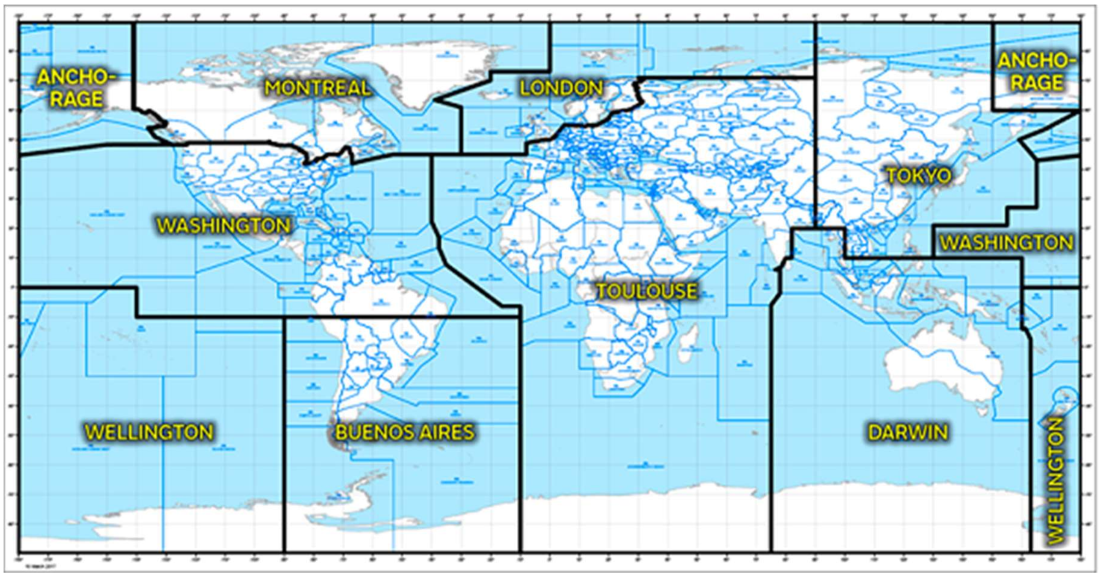
Figure 7. Damage to exterior surfaces of a 747–400 jumbo jet following an encounter with the June 15, 1991, ash cloud from Mount Pinatubo.

(Source: Casadevall et al., 1996)

Figure 2.2 Damage to exterior surface of a jumbo jet encountering an ash cloud from Mount Pinatubo, June 15, 1991.

Numerous incidents of aircrafts crossing volcanic ash-contaminated airspace followed (Guffanti et al., 2010). Among those were examples of far-travelled ash. In 1989, an aircraft in Texas lost power in one engine as it encountered a volcanic ash cloud from the Mt. Redoubt volcano in Alaska, 5,400 km away from the source volcano and 35–55 hours after the ash was emitted (Casadevall, 1994).

The aviation community thereupon established a network of observation, education and information to increase aviation safety (Casadevall, 1993). The resulting regulations and preparations were precautionary and aimed at avoiding volcanic ash-contaminated airspace. The International Civil Aviation Organization (ICAO) designated 9 globally distributed Volcanic Ash Advisory Centers (VAACs) to coordinate and issue information on atmospheric volcanic ash in their respective regions. Figure 2.3 illustrates the assigned airspace for the nine VAACs: Anchorage, Buenos Aires, Darwin, London, Montreal, Tokyo, Toulouse, Washington, and Wellington.

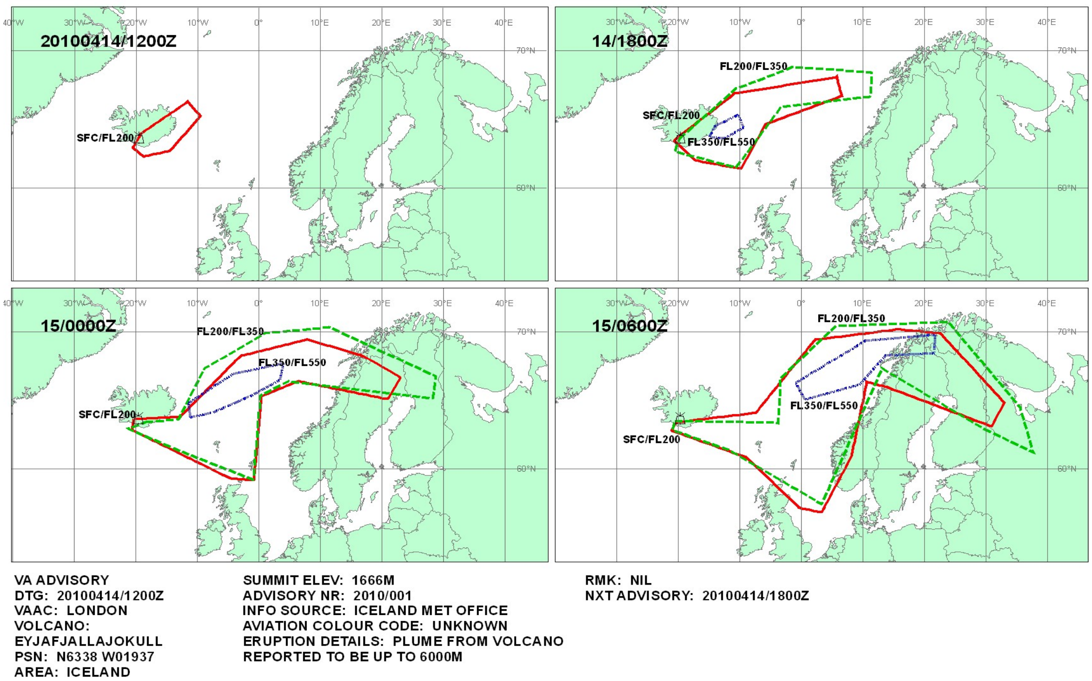


(Source: UK Met Office, 2017)

Figure 2.3 Boundaries of Volcanic Ash Advisory Centres (VAACs).

In case of a volcanic eruption, the respective VAAC produces Volcanic Ash Advisories (VAA) as text files and Volcanic Ash Graphics (VAG). These are forecast maps indicating the distribution of volcanic ash, illustrating contamination above 200 µg/m^3 for three different flight levels (FL): FL 000–200, FL 200–350 and FL 350–550 (FL are measured in 100 feet: FL 200 denotes 20,000 feet). The advising text and charts are issued every 6 hours (UK Met Office, 2014a).

Figure 2.4 demonstrates an example sequence of VAG, produced by the VAAC London.



(Source: UK Met Office, 2010)

Figure 2.4 Volcanic Ash Graphic produced by the Volcanic Ash Advisory Centre London on April 14, 2010.

In the Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Cloud from 2007, the International Civil Aviation Organization (ICAO) describes the guidelines regarding ash-contaminated airspace:

"*Unfortunately, at present there are no agreed values of ash concentration which constitute a hazard to jet aircraft engines. […] it is worth noting at this stage that the exposure time of the engines to the ash and the thrust settings at the time of the encounter both have a direct bearing on the threshold value of ash concentration that constitutes a hazard. In view of this, the recommended procedure in the case of volcanic ash is exactly the same as with low-level wind shear, regardless of ash concentration — AVOID AVOID AVOID*" (ICAO, 2007).

It suggests that, with present knowledge, potential societal and economic costs of ash encounters (USGS, 2004) always outweigh the costs of rerouting or flight cancellation. The guidelines were based on the uncertainty regarding the impact of different ash concentrations. In the following years, there was no attempt by the industry to decrease the uncertainty. This can be explained by the distribution of financial loss in an encounter with or avoidance of volcanic ash. The jet engine is usually delivered with a maintenance liability by the jet engine manufacturer (Rolls-Royce interview, May 2015). While the loss of revenue when avoiding volcanic ash lie with the aircraft operator, the costs of maintaining the engine after an encounter with ash lies with the engine manufacturer. Such a set-up did not offer incentives to conduct costly research to determine safe ash concentrations. Any deviation from "no ash" would potentially increase the manufacturers' liability and costs, while the potential gain would remain with the aircraft operators.

Although a volcanic ash cloud from Iceland interfering with one of the most densely populated airspaces in the world has been recognized as a threat (e.g., Sveinbjörnsson et al., 2002), it was not followed by proactive measures (Sammonds et al., 2010). The guideline to avoid volcanic ash at all costs was challenged in spring 2010, when those costs rose to unprecedented numbers. Chapter 3.5 presents a detailed overview of the process of regulatory changes in Europe during and following E2010.

2.4 Risk, Regulation and Communication: Volcanic Ash in the Context of Risk

Volcanic eruptions are extreme natural phenomena, whose ash emissions can be "powerful social and economic magnets" (Blaikie et al., 1994, p. 185). Blaikie et al. (1994) refer to the fertilizing character of volcanic ash on agricultural farmland and the resulting draw for people to live off the fertile lands close to volcanoes. While this is well known to be true of the vicinity of Mt. Vesuvius in Italy or Mt. Krakatora in Indonesia, such benefits are not limited to warmer climates. They have also been enjoyed by Icelandic farmers, who reportedly noted better grass growth following the Katla and Hekla eruptions in the 20th century (Blong, 1984).

The Eyjafjallajökull eruption in 2010 started out as a seemingly minor volcanic event attracting local and visiting spectators (Donovan and Oppenheimer, 2010), but then took an unexpected turn, emitting an ash cloud that became a transboundary hazard and risk to international aviation.

This section presents a brief digest that situates this research in the context of risk governance. Risk-related definitions are introduced, followed by the process of risk evaluation and its application in the regulation of risks. The section continues with a general overview of the role of scientific knowledge in regulation and concludes with the notion of communication in that context. This summary does not claim to provide an exhaustive discussion but rather aims to familiarize the reader with the main concepts and provide a necessary background for this research.

2.4.1 From Phenomenon to Risk

Natural phenomena that bear the potential to cause harm to humans or what they value are referred to as natural hazards (Royal Society, 1983; NRC, 1996). Hazard and risk accompany each other and are sometimes used interchangeably (Oxford Dictionary entry for *hazard*, 2018; Scheer et al., 2014). However, they are most commonly regarded as different subjects that deserve individual definitions.

The concept of risk has been defined in different contexts, and definitions vary according to the areas in which it is addressed (Renn, 2008). With regards to a certain technology, risk can, e.g., be defined as "the probabilities of physical harm due to given technological […] processes" (Beck, 1986, p. 4). In more general terms, risks can be broadly defined as the likelihood of harm or loss of different kinds from a hazard, and what is 'at risk' is often described (NRC, 1996). Risk is seen as socially constructed, as a result of perception of an uncertain phenomenon (Luhmann, 1993; OECD, 2003). It is informed by experience and knowledge about past events and selected by human actors (Renn et al., 2011).

In the context of natural hazards, Blaikie et al. (1994) refer to risk as a "complex combination of vulnerability and hazard" (p.21). The term 'vulnerability' refers to the extent of being prone to damage or injury from a hazard. The same authors describe vulnerability with regard to natural hazards as the capacity of an affected party to "anticipate, cope with, resist and recover from natural hazard" (p. 9). What poses a risk to one party may present a non-risk or even an opportunity to others. The same accounts for the ash emitted by the eruption in 2010, which on the one hand presented a risk to airlines while on the other hand led to improved crops for farmers in the south of Iceland (MBL, 2010).

2.4.2 The Process of Risk Analysis

The process of defining the risk to which a target is exposed due to a certain hazard and identifying appropriate measures to manage it is understood as risk analysis. It encompasses the elements of risk assessment, risk management and risk communication (Renn, 2008). Risk assessment concerns the estimation of a risk in relation to a hazard, while risk management processes the identified risk and determines measures for mitigation and/or control. Risk communication broadly refers to the exchange of information, advice and opinion on the former two steps of risk assessment and risk management.

Risk assessment has traditionally been regarded as the hard quantitative and objective core (Ruckelshaus 1985; Jasanoff, 1993). The traditional role of science was seen to contribute to hazard identification to determine an agent potentially harmful to an exposed population (Lave, 1987). Scientists use laboratory work and/or field observations to study a hazard and generate and collect knowledge within the stage of risk assessment in a dose-response relationship considering exposure and vulnerability (NRC, 1983). Risk management and risk communication have been viewed as qualitative fields that are influenced by the theories of social scientists.

The boundaries, however, become blurry and the relationship between risk assessment and risk management varies, depending on the approach taken. Hood et al. (1992) emphasized that risk assessment and risk management should not be considered separately, since risk is socially constructed by itself. Due to the nature of risk, a strict separation of "social values and world views from the process of identifying, estimating and evaluation risks" is not possible (Hood et al., 1992, p. 137). While earlier approaches called for a strict separation of the two elements to avoid a political agenda influencing the generation of scientific knowledge (NRC, 1983), more recent approaches are more integrated (Gerrard and Petts, 1998). The process of risk analysis needs to contain both analytic and deliberative elements in good balance (NRC, 1996).

An example of this integration is the model of the International Risk Governance Council (IRGC, 2005; Renn, 2008; Lidskog, 2017), which includes risk estimation, risk characterization and risk evaluation. Risk estimation is described there as a systematic assessment of risk and concern, taking into account both scientific analysis and social and economic implications (IRGC, 2005). This is followed by risk characterization, in which a risk profile is established to judge the estimated risk according to its severity. Risk characterization is a prelude to decision-making in the risk management step and should depend on an iterative, analytic-deliberative process (NRC, 1996). The NRC (2009) argues that risk characterization should also be involved in the very beginning stages to shape risk assessment, as this can be a time-consuming step (NRC, 2009). In the risk evaluation phase, the accepted tolerability of a risk is reviewed and the need for risk measures is determined. Since the judgement on complex issues is not just about a single risk, this phase considers, e.g., risk-benefit analyses and risk-risk trade-offs (Renn et al., 2011).

While an analytic-deliberative process is important, it does not guarantee the end of all disputes, and some risks are too complex and ambiguous for the conflict to be resolved (Lidskog et al., 2011).

Many risks cannot solely be calculated from probability and causality, but are rather seen as 'systemic' (OECD, 2003). Systemic risks have to be analyzed holistically within their larger context of societal processes. Here the analysis needs to focus on interdependencies and ripple effects (Slovic, 1987; Kasperson et al., 1988; Hellstroem, 2011). Systemic risks are by no means confined to national borders and can affect multiple sectors. They are defined by complexity, uncertainty and ambiguity (OECD, 2003). Here, complexity refers to a multi-causal structure; uncertainty includes the limits of scientific knowledge and data to determine probability and outcome; and ambiguity refers to the existence of a variety of legitimate views and values.

Klinke and Renn (2002) suggest a "precaution-based risk management" if uncertainty is too great and cannot be reduced in the foreseeable future. Precautionary strategies anticipate harm before it occurs (Von Moltke, 1988) and can serve as a temporary approach until uncertainty is reduced (Bennett, 2000). The application of this approach can, however, generate new costs and harms (Wiener, 1998) in itself and can have severe implications on an international scale (Klinke and Renn, 2002). The precautionary approach was followed by the ICAO in establishing the global aviation guidelines for responding to volcanic ash (ICAO, 2007). In this context, the precautionary approach was based on historic records of engine-ash encounters (Alexander, 2013). It was, however, not supported by a thorough risk assessment to determine the likelihood of an eruption impacting the airspace for several days nor in depth dose-response assessment of the effect of volcanic ash on jet engines. Although scientific findings indicating the risk posed to the European Air space were available (IAVWOPSG, 2008), they were not used for risk characterization in Europe. The European risk management approach for aviation and volcanic ash was not updated despite increasing air traffic volumes, which turned E2010 into an emerging systemic risk (Castellano, 2011).

2.4.3 Risk and Regulation

In the modern world, referred to as "risk society" by Beck (1986) and later "world risk society" (Beck, 2009), there is increasing uncertainty due to interconnectedness between natural, technical, social and economic risks (Renn, 2008). This, as well as the connection between the local and global dimensions (Beck, 2009), make it necessary to introduce governance to ensure that risk is widely handled. The contemporary approach to addressing risk problems has thus shifted from state (government)-centric to multi-level governance systems (Rosenau, 1992; Lidskog, 2008).

The term 'governance' has been defined as formal and informal structures and processes for collectively binding decisions (Keohane and Nye, 2000). It involves government and non-government actors and aims to provide guidance and restraint to collective activities as a group, society or international community (Nye and Donahue, 2000). The term ‘risk governance’ applies this definition to a risk context (IRGC, 2005; Renn, 2008) to regulate, reduce or control risk problems (Renn et al., 2011).

Risk regulation is concerned with the prevention of harm through anticipation of possible events and therefore includes choices over prioritization of risks (Power, 2007; Hutter, 2013). The dimension of risk regulation varies greatly between policy domains. Hood et al. (2001) use the framework of risk regulation regimes and identify three driving forces that shape different regimes. According to Hood et al. (2001), regimes develop in response to pressure from a serious market failure, or in response to strong general public opinion and/or pressure exerted from organized groups.

Due to its low probability, the risk of volcanic ash was not at the top of the European risk agenda prior to 2010 (Alexander, 2013). This may reflect the fact that the right experts on these matters were not included in the risk assessment (Hutter and Lloyd-Bostock, 2013). Market failure and short-term strong public opinion and pressure from organized groups led to a change during E2010. The regulatory approach to volcanic ash in Europe shifted from the precautionary zero tolerance no-flight zone to graded zones of volcanic ash concentrations (Lawless, 2011), which Brannigan (2010) assesses as a paradigm shift from passenger safety to protecting airlines from disruption.

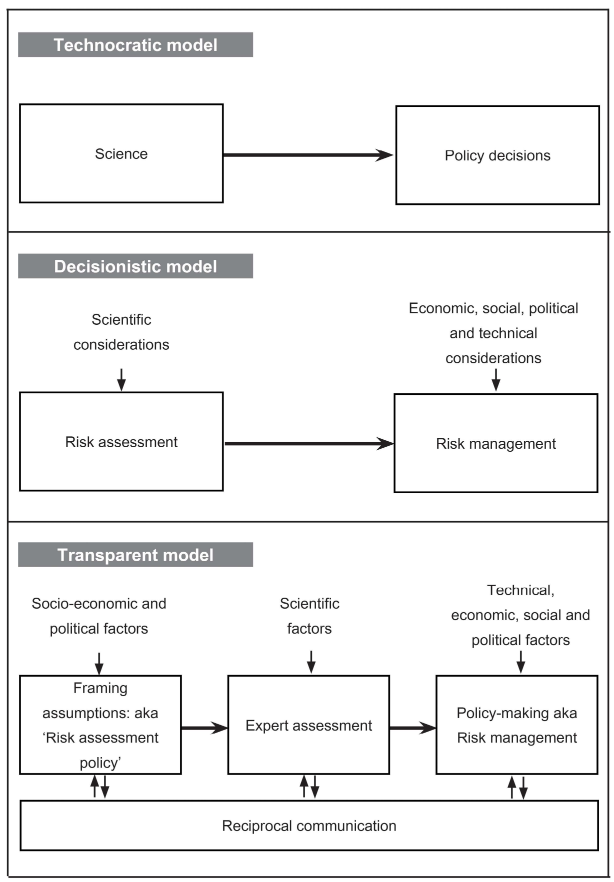
During E2010, regulators became the center of the blame game in an event that shed light on the fragility of transnational air travel and the vulnerability of critical infrastructures (O’Regan, 2011). National regulators quickly became the scapegoat and center of a policy fiasco (Budd et al., 2011) despite being bound by internationally agreed-upon rules, and blame was used by interest groups in E2010 to exert pressure to reopen the airspace. Hutter and Lloyd-Bostock (2013) argue that the older notion of a “risk society” gives the false impression of manageability of risks which creates unrealistic expectations of the regulatory bodies. Regulators assume the challenging role of controlling undesirable risk and managing vulnerability and demands for safety, while simultaneously allowing business to continue (Haines, 2011). In walking this fine line, they are often either blamed for being too risk-seeking or too risk-averse. Douglas (1992) suggests that the desire to shift the blame to an external body in times of crisis might be part of the reason why regulatory bodies were created in the first place.

2.4.4 Science and the Regulation of Risk

The input of scientific knowledge to risk regulation varies greatly. When describing the different roles of science in the process of governing risk, Millstone et al. (2004) introduce the distinction between ‘technocratic’, ‘decisionistic’ and ‘transparent’ models over the course of time (see Figure 2.5). The ‘technocratic’ model portrays scientists as the main source of information in decision-making. Their scientific input is seen as ‘objective’ and socially and politically neutral. The ‘decisionistic’ model presents a two-step process to decision-making and redefines the role of science in risk policy-making. In addition to the first step of ‘purely scientific’ risk assessment, a second step follows that takes non-scientific considerations into account, the risk management. The scientific input informs policy-makers and is still considered to be socially, politically and economically independent. This approach considers scientific knowledge sufficiently certain and uncontroversial within the scientific community (Millstone, 2009). Furthermore, it assumes a neutral place in which scientific risk assessment takes place without social, economic or political considerations.

Among others, Jasanoff and Wynne (1998) pointed out the diverse ways in which scientific advice is influenced. They found both the ‘technocratic’ and the ‘decisionistic’ approach dated. Recent presentations of risk are hybrid in nature, taking both scientific and normative considerations into account (Millstone, 2009). Non-scientific assumptions are used to estimate how much evidence is necessary to sustain a regulatory judgement (Jasanoff and Wynne, 1998; Millstone et al., 2004).

Although science and policy are often portrayed as separate, integrative models dominate the policy-making process (Jasanoff, 2004). The ‘transparent’ or co-evolutionary model (Millstone, 2009) uses socio-economic and political traits to frame the risk in the pre-risk assessment to create a risk assessment policy. At the stage of risk framing, relevant risk topics are identified and discussed. The process makes an upstream, goal-oriented judgement about what is important and is characterized by reciprocal interaction between the different stages. Scientific results are one factor next to societal and economic factors. The transparent model emphasizes the importance of “framing assumptions” to inform risk assessment and downstream risk management practices.



(Source: Millstone, 2004)

Figure 2.5 Technocratic, decisionistic and transparent model

Scientific research that is initiated through political considerations in order to set up regulations can be referred to as regulatory science (see also 'trans-science' in Weinberg, 1972). How regulatory science should be defined and whether it is a separate field rather than an occasional hybrid of science and politics is a subject of debate (Irwin et al., 1997, after Shackley and Wynne, 1995). Instead of providing a general definition, Irwin et al. (1997, p. 245) characterize regulatory science by action, for it "encompasses a multifarious range of technical, innovative, legal and administrative activities [...] often involving what might be conventionally termed basic science but always with a practical application in mind."

The purpose of regulatory science, however, is to achieve "techniques, processes and artefacts to further the policy development" (Jasanoff 1990, p. 77). Jasanoff (1990) stresses the difference between regulatory and research science with regards to content. She emphasizes the three following components: 1) Knowledge production with explicit emphasis on filling gaps in knowledge, in comparison to 'open-ended' research; 2) knowledge synthesis, where meta-analysis of data plays an extended role, in contrast to the innovative nature of academic science; and 3) prediction as the requirement to make a statement about the severity of a risk albeit partly with high uncertainty (Jasanoff, 1990).

Despite some appropriate criticism concerning the idealization of academic science (Irwin et al., 1997), these are important features of regulatory science and help in understanding the environment in which regulatory science acts as well as the demands it faces. Depending on the political and social context, too close a connection to the regulator can decrease the credibility of 'objective' scientific risk assessment (Löftstedt, 2005). Objectivity has, however, been questioned by e.g. Jasanoff (2011), who states that while policy-makers earn trust through the use of objective knowledge, objectivity is "easy to claim but hard to accomplish 'in practise,'" as it is socially constructed. She emphasizes the cultural specificity of knowledge that is produced for policy, which needs to be considered when applying regulatory science in a global context.

2.4.5 Risk Regulation and Communication

Covello et al. (1987) define risk communication as the "act of conveying or transmitting information between parties about a) levels […] b) significance or meaning of […] risk or c) decisions, actions aimed at managing or controlling risk" (p. 179). Risk communication evolved from a one-way transmission of information to a two-way exchange, from speech to dialogue, by involving the audience (Fischhoff, 1995; Pidgeon et al., 2005).

Trusting the communicator is seen as the foundation for successful risk communication (Renn and Levine, 1991; Löfstedt, 2005). Scholars have reflected on the personal traits that create a trustworthy communicator. Covello et al. (1987) specify competence, expertise and objectivity as essential attributes and agree with Lee (1986) that sharing similarities with the counterpart increases the trustworthiness of the communication. On the other hand, arrogance breeds distance and mistrust (Renn and Levine, 1991). Among the "seven cardinal rules in risk communication," as referred to by Covello and Allen (1988), for building trust in the communication process are: accepting the counterpart as a legitimate partner, listening to them, being honest and open, and coordination and collaboration with other credible sources.

Though these rules may reflect self-evident behavior, non-compliance with them is the most common reason for failed communication strategies (Löftstedt, 2005). Trust is fragile and there is a psychological tendency to mistrust (Slovic, 1993). Mistrust has been referred to as the root of conflicts and the non-acceptance of risk analysis (Flynn and Slovic, 1993; NRC, 1996). The practical effects of improved risk analysis and characterization have been shown to depend on successful efforts to rebuild trust through improved participation (Slovic, 1993).

Similar tendencies have been described regarding the relationship between experts (Rothstein et al., 1999) and the conduct of scientists in crisis teams (Newhall et al., 1999). There is a persistent significance of local social relations within the globalized regime, as described by Rothstein et al. (1999). According to their study, increased internationalization and complexity reinforce the value of "existing relations of trust and familiarity" (Rothstein et al., 1999, p. 261). It shows that formal arrangements do not automatically guarantee a smooth and trustful scientific interaction but need to be enforced through personal relations. This finding was supported in a study on the cooperation between scientists from Iceland and the UK during E2010 (Reichardt, 2011) that found that face-to-face contact was the driving force for trust between the engaging parties. Further factors included expertise, respectful and equal approach, neutrality and empathy (Reichardt, 2011).

Renn et al. (2011) stress that effective mutual communication is crucial in risk governance and should be present at all stages. They emphasize the point that communication should not only be organized but needs to be facilitated such that knowledge, perspectives and concerns can be exchanged.

Risk governance process models have been further developed toward stakeholder involvement and communication at all stages (IRGC, 2005; Renn, 2008; Lidskog, 2017). The framework of the International Risk Governance Council (IRGC, 2005) was adapted by Klinke and Renn (2012) to ensure inclusive governance with stakeholder and public involvement as a core feature, and with interrelated phases to improve the governance of systemic risks. Renn et al. (2011) describe the importance of extensive stakeholder inclusion as threefold: It facilitates the exploration of different perspectives and information from different input; second, it is argued that those who are affected by risks have a right to have a say in the process of risk governance; and third, it increases the social robustness of the risk management outcome (Renn et al., 2011, after Roca et al., 2008).

In the wake of E2010, new regulations were introduced to manage the emerging systemic risk that volcanic ash poses to European air traffic and beyond. The concepts introduced here around risk, regulation and communication and their application to the processes following E2010 provide a risk-related background to the study. The event acted as a catalyst to introduce new measures into the regulatory process and expand the interaction between diverse stakeholders from the aviation network and related sciences. The stakeholders and their roles are described in the following section, the advancement of their interaction is discussed in Chapter 3.

2.5 The Stakeholders' Network

E2010 demonstrated the entanglement of systems in today's society, in which a local natural phenomenon can disturb global mobility (Lund and Benediktsson, 2011). It requires various actors to form an alliance and cooperate in order to mitigate the impact of volcanic ash clouds on air traffic. The network includes global, international and national regulators, crisis coordination and network management, and providers of information on weather, engines and ash, as well as air navigation service providers and aircraft operators.

Since the European airspace is composed of multiple national and international airspaces, the disruption of air traffic due to E2010 was managed and coordinated on both national and international levels. The effective decision-makers were mainly at the national level, following regulations, contingency plans, and recommendations from international and global regulatory bodies while using information provided by national and international institutions. This section describes the main stakeholders and their roles in managing volcanic ash risk for aviation.

2.5.1 Global Regulator: ICAO

ICAO is an agency of the United Nations. It develops and issues global standards and recommended practices for aviation and supervises all VAACs, as well as the International Volcanic Ash Task Force (IVATF) (ICAO, 2014b). Furthermore, ICAO maintains and publishes the global aviation response contingency plan for volcanic eruptions (ICAO, 2009). The contingency plan describes the actions and guidelines for air traffic control in airspace affected by a volcanic eruption. The current regulation prompts more decision-making freedom to the aircraft operators. Guidance for operators and authorities is provided in the ICAO publications 'Flight Safety and Volcanic Ash' and 'Safety Management Manual (SMM)'. These documents provide recommendations on the Safety Risk Assessment (SRA) for flying in ash-contaminated airspace, which was introduced after E2010 (ICAO 2012b, 2013).

2.5.2 European Air Traffic Manager: EUROCONTROL

EUROCONTROL is the European Organization for the Safety of Air Navigation, which plans air traffic control and develops airspace regulations and procedures for all of Europe. EUROCONTROL contains the central flow management unit which ensures that available capacity is used effectively (EUROCONTROL, 2014a). During E2010, EUROCONTROL developed into a leading agency in response to volcanic eruptions affecting European airspace. This role was formalized in 2011, with EUROCONTROL providing the chairman of the European Aviation Crisis Coordination Cell (EACCC) (European Commission, 2011). The crisis coordination follows the contingency plan issued by the International Civil Aviation Organization (ICAO).

Although the London VAAC is the official source of information about volcanic activity with ash emission originating in Iceland, EUROCONTROL receives first-hand information about the onset of an eruption from the IMO. The ash concentration data is fed into a visualization tool called EVITA (EUROCONTROL, 2015) that displays the characteristics and height of the ash clouds, which air traffic controllers can then use to advise pilots to change altitude or course.

2.5.3 Information Provider: Jet Engine Manufacturer Rolls-Royce

The effects of volcanic ash on aircraft engines are of crucial importance to the aviation industry. Rolls-Royce is one of the leading global aircraft jet engine manufacturers (Statista, 2013). Although they are not directly involved in the management of volcanic ash response, Rolls-Royce is a stakeholder that plays a vital part as jet engine manufacturer and as information provider. Factors such as ash accumulation over time, the cost of engine maintenance (even if the inspection shows no damage), and grounding of planes for inspection or repair play a part in the economic impact of an eruption. This stakeholder provides guidance to the airlines, the Civil Aviation Safety Agencies, national governments, and military operators. During E2010, Rolls-Royce was asked to provide expert advice on increasing the ash concentration thresholds.

2.5.4 Information Provider: VAAC London

The London VAAC coordinates and issues long-range information on atmospheric volcanic ash densities to facilitate decision-making for aviation safety. It covers volcanic activity in the UK, Iceland, and the northeastern part of the North Atlantic Ocean (UK Met Office, 2012a) and is a part of the UK Met Office. In the event of a volcanic eruption in Iceland, the London VAAC receives information on the eruption from the IMO and issues advisories and forecast maps for volcanic ash density distribution. The volcanic ash advisory messages describe the expected positions of the ash plume for up to the next 24 hours. Furthermore, the VAAC produces Volcanic Ash Concentration Charts (VACC) and annotated satellite images which are publicly available.

Both researchers and forecasters from the London VAAC and the IMO liaise frequently during an eruption. The VAAC is in continuous exchange with expert teams within the UK Met Office as well as other VAACs to both provide and receive information on the dispersion model's outputs. Teleconferences between forecast cycles are set up to provide and discuss information with Civil Aviation Authorities, air traffic controllers and aircraft operators.

2.5.5 Volcanic Eruption Monitoring Agency: IMO

The Icelandic Meteorological Office (IMO) is the official volcanic monitoring agency in Iceland. The IMO's responsibilities are monitoring, forecasting, and issuing warnings related to meteorology, seismology, and volcanic activities (IMO, 2014). As the national volcanic monitoring agency, it observes pre-eruption activity, monitors activity during eruptions, and monitors airborne volcanic ash in the North Atlantic region. In case of an event, the IMO monitors the initial hazard and provides the main source parameters, estimates ash volume and plume height, and oversees and monitors fixed and mobile measuring devices.

As the central, local information provider, the IMO informs the following agencies: The Civil Protection Agency (in Icelandic: Almannavarnir); the civil air traffic control for the north atlantic airspace (NAT), which is ISAVIA ohf; and the London VAAC. The IMO also sends a formal message to air traffic control centers, a so-called SIGMET (Significant Meteorological Information) message. VONA (Volcano Observatory Notification for Aviation) are also promptly sent to a wide group of emails addresses to communicate any changes at volcanoes and in the volcanic activity. The IMO ensures regular interaction with these stakeholders to inform them on the status of the eruption and the weather.

As the eruption progresses, the IMO collects information about the plume and relevant weather conditions. It is assisted by other Icelandic institutions, such as the Icelandic Coast Guard, which e.g., carries out research flights to confirm the height of the ash plume, and the Institute of Earth Sciences at the University of Iceland which, among other things, collects and analyzes ash samples. The Icelandic Environment Agency also collects ash samples for analysis.

2.5.6 Civil Aviation Authority: ICETRA

The Civil Aviation Authority (CAA) is a regulatory body that oversees the regulation of national civil aviation. The Icelandic CAA is executed by the Icelandic Transport Authority (ICETRA). The institution regulates standards for the airworthiness of aircrafts as well as for air traffic control to be carried out by a separate air navigation service provider. It monitors the work of ISAVIA and the IMO. ICETRA is responsible for the state's volcanic ash contingency plan and can authorize airspace closure. It further monitors and approves the SRA of aircraft carriers. Although there are discussions between the CAAs from different states, each national authority has its own regulatory sovereignty and makes decisions autonomously (EASA, 2013).

2.5.7 Local Air Traffic Manager: ISAVIA

The Icelandic air navigation service provider and airport management agency ISAVIA is in charge of managing the air traffic in its airspaces (ISAVIA, 2014) in the northeastern Atlantic.

ISAVIA's procedures are initiated by a phone call from the IMO. ISAVIA has a checklist based on the contingency plan. In the event of a system failure or if an eruption event is not detected by the IMO, an aircraft might be the first to spot an eruption; in this case, the first report might be in reverse order, from ISAVIA to the IMO. ISAVIA opens the crisis center and provides information and advice to aircraft operators once an eruption has started. After notifying agencies and personnel, a circle with a radius of 120 nautical miles around the eruption site is declared a no-fly zone by NOTAM (Notice to Airmen to warn of potential hazards). This zone is valid until a new SIGMET from the IMO depicting the forecasted area of ash is issued. Staff from ISAVIA, along with an IMO employee, meet with stakeholders and airlines twice a day, providing an update on the monitored situation to adjust the responses. ISAVIA also participates in teleconferences with EUROCONTROL.

2.5.8 Aircraft Operators: Icelandair

In the study, the Icelandic company Icelandair represents stakeholders from the sector of aircraft operators. Aircraft operators make decisions within the regulatory framework overseen by the respective civil aviation administrations. As part of the private sector and as service providers to passengers and cargo shippers, they face direct legal and economic consequences from decisions on airspace closure or due to flight incidents. With the regulatory changes after E2010, aircraft operators provide their SRA to the CAAs in advance in order to receive permission to fly under certain circumstances of volcanic ash contamination. The airline receives updates on the volcanic eruption through SIGMETs from the IMO, NOTAMs from ISAVIA and teleconferences from EUROCONTROL in addition to volcanic ash forecasts from the London VAAC as well as in-house advisory.

3 Cooperation between Science and Aviation Sector Service Providers in Europe for the Risk Management of Volcanic Ash

This chapter contains the peer-reviewed journal article:

Reichardt, U., G. F. Ulfarsson and G. Pétursdóttir, 2017. Cooperation between Science and Aviation Sector Service Providers in Europe for the Risk Management of Volcanic Ash. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2626, pp. 99–105.

3.1 Abstract

The eruption of Eyjafjallajökull in April–May 2010 (hereafter E2010) revealed the fragility of air traffic in case of an ash-producing volcanic eruption. This study examines developments since E2010 in cooperation between science and aviation sector service providers toward efforts for improved resilience against a new volcanic eruption. The research builds on literature and interviews with representatives from research and regulatory institutes, air traffic managers, aircraft operators, and engine manufacturers across Europe.

The article describes how scientific advice was requested to revise the regulatory precautionary approach and reopen airspace during E2010. The paper depicts the increased effort of scientific advancement in the understanding of ash characterization as well as in the modelling of volcanic ash plumes and the atmospheric environment. Furthermore, cross-disciplinary workshops and the Memorandum of Understanding between Icelandic and British institutions are examined to document increased cooperation between scientists and aviation sector service providers to provide support to decision-makers.

However, the science needed for improved risk management is complex and depends on the effects of volcanic ash on jet engines. The concentration levels decided upon over the course of a few days in 2010 have not been revised and the aviation industry does not seem to prioritize research into these issues. A dialogue is needed between science, governance, and engine manufacturers as well as more collective research funding to test jet engines to improve informed decision-making, rather than leaving such research only to the manufacturers and internal political agendas.

Keywords: risk management; volcanic ash; aviation; regulatory science; aviation sector service provider

3.2 Introduction

The eruption of Eyjafjallajökull in April–May 2010 (hereafter E2010) revealed the fragility of air traffic in case of an ash-producing volcanic eruption. The volcanic ash plume was large and widely dispersed due to lightweight particles (Sammonds et al., 2010). The ash cloud caused widespread air travel disruption in Europe which reverberated around the world; more than 100,000 flights were cancelled during an 8-day period, impacting about 48% of the total European air traffic and about 10 million passengers (Bye, 2011). The event called for a coordinated response with scientific advice to replace the prevailing zero-ash-tolerance for flight routes by ash concentration thresholds (Ulfarsson and Unger, 2011). In 2010, ad hoc risk assessment in cooperation with scientists was undertaken to establish tolerable ash concentration levels to unlock the crisis while maintaining air safety (Bolić and Sivčev, 2011).

Recent studies on the acceleration of land rise in Iceland due to glacial retreat and the possible impacts of deglaciation in Iceland on volcanic activity (Pearce, 2012; Schmidt et al., 2013; Compton et al., 2015) point toward a possible increase in the number of volcanic eruptions in Iceland in the future. Combining this with historical records of volcanic activity in Iceland (Gudmundsson, 2008; Thordason, 2008), it is possible that a new eruption with impacts on airspace similar to E2010 or greater could in the future occur about every 7 years (Schmidt et al., 2013).

If the question is not whether but when the next Icelandic volcanic ash cloud impacts North Atlantic and European airspace, the consequent question is whether the system has improved since 2010. The management of volcanic ash risk to aviation is complex and requires active cooperation of a number of aviation sector service providers. The term *service provider* is used according to the definition in ICAO document 9974 on Flight Safety and Volcanic Ash and involves the air traffic services, engine manufacturers as well as maintenance organizations, meteorological, and volcanological services. This paper examines how the cooperation between science and service providers for the risk management of volcanic ash in North Atlantic and European airspace developed after 2010. As good communication between scientists is of fundamental importance, "one essential ingredient in the development of science is the combination of already existing ideas" (Barber, 1968). The paper will look at the efforts undertaken to bridge the gap between science and aviation service providers to facilitate decision-making and increase the governed system's resilience.

This article draws on research started in a project on aviation sector response to volcanic eruptions, a case study within the ENHANCE project on Enhancing Risk Management Partnerships for Catastrophic Natural Disasters in Europe (Ulfarsson et al., 2013; Ulfarsson et al., 2014; Reichardt et al., 2015a; Reichardt et al., 2015b).

In the following section, the methods for information collection will be explained. This is followed by a brief description of the state of the risk management before and during E2010 and the role of science in connection with regulations. Then the paper examines the developments since E2010 with regard to cooperation of science and service providers to improve the aviation system's resilience during a volcanic ash eruption.

3.3 Methods

The data for this study is derived from a literature review and interviews with stakeholders and experts. The literature review builds on a broad spectrum of work from social, natural, and engineering science as well as policy documents from institutions related to aviation and volcanic ash. The review provides an overview of existing knowledge and different fields of research linked to the analysis of the effects of volcanic ash on aviation.

Research was undertaken to identify stakeholders and experts mentioned in official documents and reports. Representatives from the Volcanic Ash Advisory Centre (VAAC) London, the Icelandic Meteorological Organization (IMO), the European Organization for the Safety of Air Navigation (EUROCONTROL), the Icelandic Air Navigation Service Provider (ISAVIA), the Icelandic airline Icelandair, the University of Geneva, the University of Iceland, Reykjavik University, and jet engine manufacturer Rolls-Royce were interviewed about their experience, the decision-making processes at the time of E2010, and the impact E2010 had, along with responses and developments since then. These were face-to-face interviews with guideline questionnaires and lasted from 70 minutes to about 3 hours. All interviews were conducted in English, recorded and transcribed verbatim. They were partly complemented through additional communication with the interviewees via email and phone.

3.4 Risk Management of Volcanic Ash in the North Atlantic and European Airspace before 2010

The threat that volcanic ash poses to aircraft jet engines was brought home to the public and the aviation community when a British Airways B747 lost power on all four engines while flying through the volcanic ash cloud of Mt. Galunggung, Indonesia, in the summer of 1982 (Smith, 1983; Tootell, 1985; Miller, 1994). Numerous encounters followed, including ones with engine damage (for an overview of known encounters until 2009, see Guffanti et al., 2010), some showing the still-potent effect of ash clouds that had travelled great distances from the eruption (Casadevall, 1994).

After examining the threat of ash to aircraft, especially the observed immediate harmful impact of ash on jet engines with resulting high maintenance costs and shortened life span of the engines, Casadevall (1993) states that the only way to manage the risk is a precautionary approach where airplanes avoid clouds of volcanic ash completely. The International Civil Aviation Organization (ICAO) outlined the following guidelines to aircraft operators regarding ash-contaminated airspace (ICAO, 2007):

"Unfortunately, at present there are no agreed values of ash concentration which constitute a hazard to jet aircraft engines. […] it is worth noting at this stage that the exposure time of the engines to the ash and the thrust settings at the time of the encounter both have a direct bearing on the threshold value of ash concentration that constitutes a hazard. In view of this, the recommended procedure in the case of volcanic ash is exactly the same as with low-level wind shear, regardless of ash concentration — AVOID AVOID AVOID".

The aviation community established a network of observation, education, and information to avoid volcanic ash clouds and thus increase aviation safety. In the 1990s, ICAO designated nine globally distributed Volcanic Ash Advisory Centers (VAACs) to coordinate and issue information on atmospheric volcanic ash in their respective regions (Tokyo VAAC, 2016). Forecasts on volcanic ash cloud distributions in the UK, Iceland, and the northeastern part of the North Atlantic Ocean are covered by the VAAC London, which is a part of the UK Meteorological Office (UK Met Office, 2014a). For volcanic activity in Iceland, the London VAAC receives information on the eruption from the Icelandic Meteorological Office (IMO) and issues forecast maps for volcanic ash density distribution in airspace. In order to facilitate the avoidance of contaminated airspace, the maps indicate airspace with estimated ash contamination above 200 $\mu g/m^3$ (Brooker, 2010). The issue of safety limits was raised in scientific workshops, but with the option of rerouting flights, the aviation sector is not particularly motivated to invest in costly tests to establish safe-to-fly thresholds (Sammonds et al., 2010).

In 2008, EUROCONTROL conducted what was the pioneer of volcanic ash exercises in the European region, VOLCURE. It was a one-time exercise for aviation stakeholders with the scenario of an ash cloud that moves over the UK, Ireland, the Benelux countries and France, before moving over to Scandinavia (interview with representatives from EUROCONTROL, February 2015). It was agreed that the European region was to use the contingency plan of the UK and Iceland and expand it for Europe. Following the ICAO recommendations, the prime assumption was that ash-contaminated airspace should not be used. The results of the exercise did not lead to further preventive measures (interview with representatives from EUROCONTROL, February 2015). Scientists' warnings of the potential impact of an Icelandic eruption on the North Atlantic and European airspaces (Sveinbjörnsson et al., 2002) were not taken into consideration by regulatory bodies to develop further contingency plans at the time.

3.5 Regulatory Response During and After E2010

When Eyjafjallajökull erupted on April 14, 2010, it emitted an ash cloud 30,000 feet into the atmosphere which was carried toward the UK and Northern Europe. It impacted one of the most densely populated airspaces in the world, with up to 30,000 flights across European airspace per day (NATS, 2014). Following the ICAO instructions of 'zero tolerance' and the London VAAC's forecasted movement of the ash cloud toward the British territory, the UK started reducing air traffic and closing airports, followed by other European airports (CAA UK, 2010). Three days into the closure, the financial implications from loss of revenue by the aircraft operators (Mazzocci, 2010) pressured regulators to step away from the zero-tolerance rule to find a reasonably safe solution that would allow airports to open again.

As there was no designated regulatory body to manage this crisis on an international level, committees were first formed during the crisis. In cooperation with scientists, air traffic managers, airlines and engine manufactures, the UK Civil Aviation Authority sought to determine the ash concentration thresholds below which aircraft could be safely operated, aiming primarily at reopening London Heathrow, Europe's largest airport. The VAAC London was asked to produce Volcanic Ash Graphics to display the expected extent of the ash cloud given different concentration thresholds. These graphics revealed that a threshold of 2000 µg/m³ would unlock Heathrow. Engine manufacturers were asked to give a statement on whether it was safe for the jet engines to fly in this ash concentration. They used historical reports on ash found in jet engines that had suffered shutdown midflight. The engines were believed to have encountered volcanic ash concentrations of 2 g/m³. Hence, on April 20, 2010, engine manufacturers agreed that jet engines could tolerate up to 2000 µg/m³ of volcanic ash without facing catastrophic failure, given appropriate maintenance and provided that visible ash is avoided (CAA UK, 2010). Figure 3.1 presents a comparison of how the threshold was changed in spring 2010.

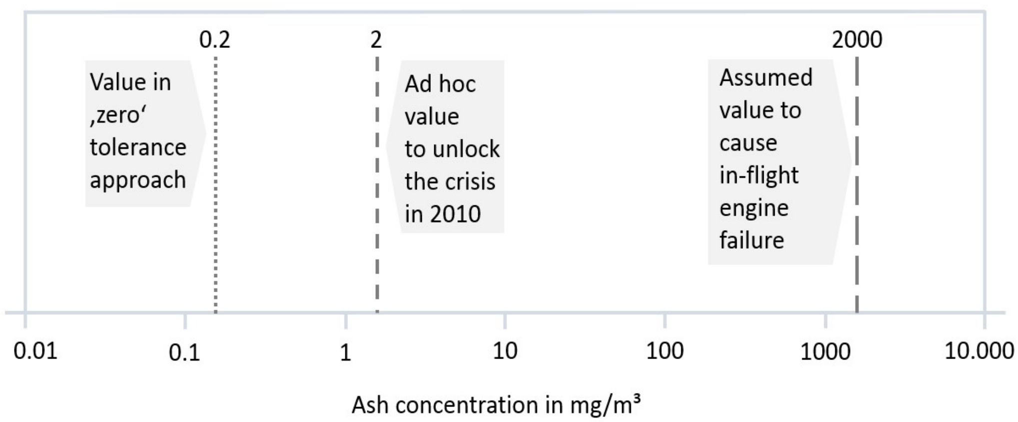


Figure 3.1 Comparison of the ash threshold change during the 2010 Eyjafjallajökull eruption in Europe.

The European Commission (EC) consulted EUROCONTROL, as a network manager and organization for the safety of air navigation, to provide suggestions to regulators on how to solve the crisis with a coordinated European approach (Alemanno, 2010). EUROCONTROL proposed three options on how to govern the risk (European Commission, 2010):

- 1) Status quo with closed airspace wherever ash is assumed.
- 2) Close the airspace next to the volcano and leave the decisions to the aircraft operators for all other airspace.
- 3) Declare the area with high ash concentration as a no-flight zone and leave the decision-making to the aircraft operators.

Based on expert opinions requested by the EC vice president responsible for transport and test flights (Sanderson, 2010), option 3 was selected and the no-flight zone was split into two parts: a red and a black zone. The output of the numerical ash dispersion model NAME, used by the London VAAC, was modified to produce maps displaying these different ash concentration levels. The maximum ash concentration limit for areas where air traffic was allowed (red zone) was raised from 200 to 2000 µg/m³, given adherence to specific inspection and maintenance requirements, with an absolute no-flight (black zone) set above 2000 µg/m³. At a later stage, this regulation was revised and extended with a third (grey) zone for estimated ash density levels of 2000–4000 µg/m³ which aircraft could traverse if obeying greater restrictions (EASA, 2010), and the absolute no-flight zone was then set for ash densities above 4000 μg/m^3.

The refined differentiation of the ash forecasts was the first of a number of changes in the risk management of volcanic ash that were introduced to the European aviation community following the air traffic disturbances due to E2010 in April 2010. Most remarkably, the decision-making was shifted from national authorities to aircraft operators. To date, the majority of the European airspace will remain open during a volcanic ash event (Reichardt et al., 2015b). For airline operators to decide whether to fly in ash-contaminated airspace or not, a safety risk assessment (SRA) is needed, describing the safety risk procedures when encountering volcanic ash in-flight. Prior to an eruption the SRA must be approved by the state of the operator. As of November 2016, the majority of European states mutually recognized the SRA.

For a coordinated approach at the European level in times of crisis, the European Aviation Crisis Coordination Cell (EACCC), with EUROCONTROL as chair, was created (Bolić and Sivčev, 2011). The function of the EACCC is to manage and coordinate when circumstances disturb normal aviation operations. The EACCC forms a platform to collect and distribute information, suggests solutions to support regulators and decision-makers, and implements decisions that are made. The coordination cell consists of European stakeholders such as representatives from the EU member state holding the presidency of the European Council, the European Commission, the European Union Agency for Aviation Safety (EASA), national militaries, national air traffic managers, airports and airspace users, and state focal points with connection to national crisis management as well as experts on the nature of the crisis (EUROCONTROL, 2014b). To practice and adapt volcanic ash contingency plans and procedures, an annual volcanic ash exercise (VOLCEX) has been introduced and run by ICAO. A volcanic ash scenario is simulated to practice the emergency with the EACCC, service providers, regulators and aircraft operators.

3.6 Science and Regulation in the Heat of a Crisis

The change of approach for permitting flights in potentially ash-contaminated airspace during E2010 called for short-term risk assessments and cooperation with scientists to support the VAAC and advise governments.

Scientific research that is initiated through political considerations in order to set up regulations can be referred to as regulatory science (see also ‘trans-science’, cf. in Weinberg, 1972). How regulatory science should be defined and whether it is a separate field rather than an occasional hybrid of science and politics is a subject of debate (Irwin et al., 1997, after Shackley and Wynne, 1995). Instead of providing a general definition, Irwin et al. (1997, p. 245) characterize regulatory science by action, for it “encompasses a multifarious range of technical, innovative, legal and administrative activities [...] often involving what might be conventionally termed basic science but always with a practical application in mind.”

The purpose of regulatory science, however, is to achieve “techniques, processes and artefacts to further the policy development” (Jasanoff 1990, p. 77). Jasanoff (1990) stresses the difference between regulatory and research science with regards to content. She emphasizes the three following components: 1) Knowledge production with the explicit emphasis to fill gaps in knowledge, in comparison to ‘open-ended’ research; 2) knowledge synthesis where meta-analysis of data plays an extended role, in contrast to the innovative nature of academic science; and 3) prediction as the requirement to make a statement about the severity of a risk albeit partly with high uncertainty (Jasanoff, 1990). Despite some appropriate criticism concerning the idealization of academic science (Irwin et al., 1997), these are important features of regulatory science and help with the understanding of the environment in which regulatory science acts and the needs it faces.

Scientific advice helped within a few days to revise thresholds that had been in effect globally for more than a decade. Such cooperation of policy-makers and (regulatory) scientists can, however, be problematic. It may lead to loss of credibility, as the public tends to fear that short-term political agendas may reduce integrity and the quality of experts’ advice as well as political decisions.

Löfstedt (2003) discusses the regulatory structures within the EU where agencies conduct risk assessment independently from political leadership. Pointing to short-term regulations driven by politicians, he notes that “in order to regulate properly (using rigorous scientific risk assessments) there is a need for long regulatory time horizons that only agencies can deliver” (Löfstedt 2003, p. 1331). Agencies in that sense work independently from political leadership and hence do not change their manpower with the political cycle. To help objectify decisions further, those agencies consult with advisory committees which provide independent expert views and counsel on a particular topic. Advisory committees present a quick, cheap, and flexible way to seek advice from knowledgeable experts to support the experts in regulation (Jasanoff 1990, p. 1). However, the short life of ad hoc expert groups may cause them to miss out on problems that are noticeable only through profound long-term assessment and supervision.

For E2010, scientific advice was needed on two fronts. On the one hand, modelers, experts in space- and ground-based monitoring from the fields of volcanology, meteorology, and atmospheric dispersion were consulted to work on volcanological input parameters and comment on accuracies of the output of the ash dispersion model. On the other hand, engineers’ advice was necessary to define how much ash jet engines could take without lasting damage or catastrophic failure.

The following section describes the development of the British–Icelandic cooperation between the VAAC London and the Icelandic Meteorological Office (IMO) as well as British and Icelandic research institutions. Furthermore, it describes how information from long-term scientific research is introduced into the workings of an operational information provider.

3.7 Information Providers and Science: Developments after E2010

E2010 stressed the cooperation of the VAAC London and the IMO as the incident required an enhanced exchange of information. Communication between the IMO and the VAAC during non-emergency times was elevated to regular interactions: While these agencies primarily communicated when need required before E2010, a weekly email exchange about the status of volcanoes was implemented after the event (interview with representatives from VAAC London, 2014). This was done to streamline information flow between the IMO and the VAAC in order for institute staff to be updated on possible emerging risks from volcanoes. VOLCICE is a regular event (to date, once per month) introduced to practice the information flow between the Icelandic Air Navigation Service Provider (ISAVIA), the IMO, and the VAAC (IMO, 2016). It practices first response procedures to a volcanic eruption according to the current contingency plan, using the day's weather. To better understand the partner's work, staff exchange between the IMO and VAAC London has been initiated (interview with representatives from the VAAC London, July 2014).

The cooperation of the VAAC and the IMO with British and Icelandic research institutions consolidated on an institutional level in May 2010. A Memorandum of Understanding (MoU) between the British Geological Survey, the British National Centre for Atmosphere Science, the UK Meteorological Office (in which the VAAC London is located), and the IMO (provided with data from the University of Iceland) was signed to set forth "the goal and general objectives agreed by the Parties for their cooperation and terms and conditions under which they will cooperate" (IMO, 2012).

The collaboration comprises: 1) Enhanced observational capabilities for volcanic activity in Iceland; 2) high resolution modelling especially for volcanic ash plume dispersion, transport and deposition; 3) multi-hazard warning services and emergency response; 4) public weather service activities; and 5) enhanced cooperation between the appropriate scientific institutions, initially in volcanology and meteorology (IMO, 2012). Despite the MoU's nonbinding nature, its existence strengthens and facilitates collaboration between the institutions and allows a rapid enactment of cooperation to be brought to an institutional and formal level if need arises.

To prepare the European aviation industry and regulatory framework for a volcanic ash eruption event, the Secretary General of the ICAO formed the International Volcanic Ash Task Force (IVATF) in May 2010. It reviewed the response to the E2010 eruption, assessed areas of improvement with regard to volcanic ash and aviation, and defined actions to address aviation risks (ICAO, 2012b). The group consisted of a multi-disciplinary team of experts working in sub-groups on Atmospheric Sciences, Airworthiness, Air Traffic Management, and International Airways Volcano Watch Coordination (ICAO, 2012b). The aim was to establish guidance for further research, issue recommendations for risk management and deliver "practical tools to counter future volcanic ash events" (ICAO, 2012c).

The task force has, e.g., issued recommendations for volcano observation measurements, material testing for jet engines, the definition of threshold values for 'visible ash' as an unsafe factor for operations, and air traffic management contingency plan templates for regional use to operate risk management of volcanic ash events.

The group delivered a final report in 2012 and further work is carried out by the International Airways Volcano Watch Operations Group (IAVWOPSG) as well as other ICAO groups (ICAO, 2012b). Information provisions include development in scientific research and modelling and inclusion into the system of decision-making, as stated in the IVATF report (ICAO, 2012c).

After E2010 a number of scientists started building a new connection with operators from the VAACs. An important lesson from E2010 is that scientists and operation service providers should join forces to advance knowledge about ash characterization and modelling of volcanic ash plumes.

The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and the World Meteorological Organization (WMO) organized the IAVCEI–WMO workshop in 2010, the first to bring together scientists from various fields and experts from the VAAC London. A group of 52 specialists in modelling and space- and ground-based monitoring from the fields of volcanology, meteorology, and atmospheric dispersion met at the WMO headquarters in Geneva to talk about what needed to be done and researched in terms of ash grain size distribution, volcanic mass eruption rates and plume height, uncertainties of the models and ash particle aggregation to be taken into account in models (Bonadonna et al., 2012).

While this first workshop initiated communication about technical aspects and spurred a number of new research projects, the second workshop in 2013 was more political, including how to institutionalize the cooperation and strategies for operational implementation of scientific findings (Bonadonna et al., 2014). Prof. Bonadonna of the organizing committee for the IUGG–WMO workshop, sponsored by the International Union of Geodesy and Geophysics (IUGG) and the WMO, stated that good connections were established between scientific and operational institutions. However, she notes that those were still dependent on individual relations. As this runs the risk of losing the connection if a person leaves the institute, regular interaction must be maintained to provide continuity. Embedding scientific findings into operations requires a common language between scientists and regulators. According to Bonadonna, the dialogue between scientists and regulators about the meaning of probability and uncertainty is crucial and should be improved (interview with Prof. Bonadonna, May 20, 2015).

3.8 Research Advances on the Ash Density Threshold for Jet Engines

While scientific advances in understanding the composition and dynamics of volcanic ash are of interest per se, the crucial question from the point of operational decision-making is how the ash affects jet engines and aircrafts.

Jet engines operate at temperatures over 1400°C, while ash melts and fuses to engine components at around 1100°C (Casadevall et al., 1996). Jet engine failures have occurred 150–600 miles (250–950 kilometers) from the volcanic sources (Guffanti and Miller, 2002). In addition to engine failure, low-density ash can cause erosion and material build-up on engine components which can reduce the lifetime of engine components. This requires especially vigilant maintenance procedures in order to detect possible early engine component failure. What that means in terms of long-term operation and safety of jet engines is not fully understood. Further research is needed to better understand the effects of ash on jet engines, based on ash composition, density, and exposure.

When determining flight zones accurately, the underlying question is, "How much ash is safe?" As a representative from EUROCONTROL said, "I would like to know what 'dangerous' is. What is the ash concentration level that will block my engine? Statements about a blocking level, and levels that have economic impact, are crucial" (interview with representatives from EUROCONTROL, February 2015). This was a recurring statement throughout the interviews which has also been emphasized by other scholars (e.g., Watson, 2015). The ad hoc introduction of thresholds to define low, medium and high concentrations of ash as a measure for safe airspace to operate in during E2010 were based on experts' opinion with the aim of reopening Heathrow airport. Although research is encouraged (ICAO, 2012b) to estimate the impact of ash levels on engines (Rolls-Royce, 2013), the questions posed in 2010 about the ash tolerance of jet engines (Sanderson, 2010) still remain unanswered today and impact the significance of ash measurements and forecasts.

Although aircraft and engine manufacturers demonstrated their goodwill through participating in interdisciplinary meetings in the aftermath of E2010, their presentations show that the industry is cautious in making precise statements about engine tolerance (BOEING, 2010; Rolls-Royce, 2010). While the unique composition of the ash of every volcanic eruption is stressed, benefits of further investigations have been presented as marginal, pointing at uncertainties from ash forecasting (BOEING, 2010). Another presentation stressed that attempts to improve the ash resilience of jet engines would negatively affect the environment as modified engines would require more fuel (Rolls-Royce, 2010).

The International Volcanic Ash Task Force issued recommendations on the volcanic material that should be used to test jet engines (ICAO, 2012b). These were taken into account in a multi-year research project by NASA, Vehicle Integrated Propulsion Research (VIPR), which conducted simulations, performed engine testing, and tested vehicles with an 'engine to end-of-life' run to improve understanding of the impact of ash on engines (NASA, 2012). The ingestion test that took place in summer 2015 was awaited by the scientific community (ICAO, 2014a). However, instead of testing the impact of gradually increasing ash intake, only two concentrations, 1000 $\mu g/m^3$ and 10,000 $\mu g/m^3$, were tried (NASA, 2013). How this will relate to the current (as of November 2016) threshold in European regulation of 2000–4000 $\mu g/m^3$ remains to be seen, as the results have not been fully analyzed and published (NASA, 2015).

The 'safe to fly chart' presented by Rolls-Royce (Rolls-Royce, 2013) shows a reassessment of the data basis for the concentration threshold and uncertainties of the model. It shows that the ash intake that led to engine failure in 1982 was overestimated, which might be worth taking into account in future regulations for air traffic. It further connects concentration levels and exposure duration and shows a variety of assumptions that must be taken into account when conducting ash safety risk assessments (Rolls-Royce, 2013). The chart stresses the need for further research, including tests of ash impact on fans, compressors, combustors, and turbines. Such studies are expected to reduce modelling uncertainty substantially (Rolls-Royce, 2013). However, as of November 2016, this research has not been approved within the company (follow-up communication on the interview with a representative at Rolls-Royce, May 2015).

Will the uncertainty about how much ash a jet engine can take affect air traffic when the next ash cloud from Iceland reaches the North Atlantic and European airspaces? According to Rolls-Royce's representative, many airlines will possibly decide not to fly as not all operators are equipped to perform the necessary safety risk assessment. As the effects of ash exposure time on jet engines are unknown, flying through ash contamination may result in the plane being grounded for weeks or even months for maintenance. Although one jet engine could be replaced within 24 hours for a single incident, not enough replacement engines are available for several aircraft of the same type, and the full dis- and reassembly process of an engine can take 50 to 60 days (KLM, 2017). "A crisis of broader impact than the one seen in 2010 could follow" (interview with a representative from Rolls-Royce, May 2015).

3.9 Conclusions

During E2010 the precautionary zero-ash-tolerance 'better safe than sorry' approach for aircraft was replaced by ad hoc recommendations on concentration levels. Since then a number of studies have been conducted to improve understanding of ash characterization, modelling of the volcanic ash plume, and atmospheric environment (JGR, 2012; Langmann et al., 2012) while cooperation between scientists and service providers to support decision-makers has been strengthened.

Scientists and service providers interviewed expressed confidence in the development of these processes and trust that air traffic management will run more smoothly in the North Atlantic and Europe the next time an eruption takes place in Iceland (Bolić and Sivčev, 2012). However, further studies are needed, not least on the ability of jet engines to withstand volcanic ash. As airlines face potentially very high social and economic costs if aircraft encounter ash (USGS, 2004) and with the option of rerouting flights, jet engine manufacturers have not been particularly interested in investigating safe-flight ash thresholds or issuing statements for which they may incur liability. Consequently, the concentration levels decided upon over the course of a few days in 2010 have not been revised and the aviation industry does not seem to prioritize research into these issues. Further research is needed to verify the thresholds to improve their credibility. A dialogue is required between science, governance, and engine manufacturers as well as more collective research funding to test engines and thereby improve informed decision-making, rather than leave such research only to the manufacturers and internal political agendas.

The study continues to test scenarios of volcanic eruptions in Iceland impacting the North Atlantic and European airspace with ash clouds of varying duration and intensity, in order to investigate and improve the reactions of different stakeholders (Reichardt et al., 2017b). Future research is also needed to explore the U.S. side of this picture and the participation of U.S. agencies and institutes in the process.

4 Developing Scenarios to Explore Impacts and Weaknesses in Aviation Response Exercises for Volcanic Ash Eruptions in Europe

An earlier version of this chapter was presented at the *97th Annual Meeting of the Transportation Research Board*:

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4.1 Abstract

Ash from volcanic eruptions can severely interrupt air traffic, as the eruption of Eyjafjallajökull volcano in 2010 (E2010) impressively demonstrated. While the event had an unprecedented impact on aviation, especially in Europe, some research suggests that similar volcanic events might occur at shorter intervals in the future. This study developed two volcanic ash scenarios using Icelandic volcanoes to demonstrate the potential scale of extreme, yet possible events in terms of duration and intensity. This is done to investigate responses either during a long period of continuous risk assessment and maintenance or when facing a large-scale severe interruption of air traffic, while under current regulations.

The NAME model of ash dispersion, used by the London Volcanic Ash Advisory Centre, was used to simulate the ash distribution in the scenarios. The model scenarios used historic data of ash volumes and the weather patterns prevailing in the E2010 event.

The scenarios were presented to aviation experts to help create a picture of the current resilience of the aviation sector and identify opportunities for improvement in the current risk management. The research demonstrates that under both scenarios the impact on air traffic would be significant. Although uncertainties are too numerous to perform a detailed economic risk assessment, the financial consequences in both scenarios were expected to be in the order of billions of euros. Furthermore, the scenarios identified weaknesses in current response exercises to volcanic events suggesting they need to work with more extreme scenarios and at some point test long duration. The method employed in this study served as an example to assess effects of possible impacts of volcanic eruptions on aviation and could be applied to other parts of the world.

Keywords: risk governance; volcanic ash; aviation; resilience

4.2 Introduction

When the Eyjafjallajökull volcano erupted in Iceland in April 2010 (hereafter called E2010), the regulatory response to its ash cloud affected the flight schedules of around 10 million passengers (Oxford-Economics, 2010). With civil aviation authorities (CAA) closing airspace, the event impacted 48% of total European air traffic with more than 100,000 flights cancelled within just a week (Bye, 2011). While the extent of the event was unprecedented, the potential impact of volcanic ash coming from volcanoes in Iceland had been recognized (Sammonds et al., 2010).

E2010 led to increased awareness of the threat of volcanic ash to air traffic in Europe, and numerous advances have taken place since then with regards to research, regulation, and cooperation (Ulfarsson and Unger, 2011; Bolić and Sivčev, 2011; Reichardt et al., 2017a). According to the updated procedures, European airspace now remains open and the decision-making on whether to fly or not is with the aircraft operators, providing their Safety Risk Assessment (SRA) was approved by the corresponding CAA. One of the measures taken to anticipate future events is the annual volcanic ash exercise (VOLCEX).

The VOLCEX exercise is conducted roughly once a year and rehearses the initial response to a volcanic eruption in Europe, biannually practicing on an Icelandic eruption. In a preparatory meeting, the stakeholders agree on a scenario to be tested. The Volcanic Ash Advisory Centre (VAAC) in London runs the NAME model (see Methods) for the eruption scenario in agreed weather conditions (interview with representatives from UK Met Office, October 2014). VOLCEX involves air navigation service providers, air traffic control centers, civil aviation administrations, meteorological offices, VAAC London, VAAC Toulouse, and aircraft operators worldwide.

These exercises are under the supervision of the International Civil Aviation Organization (ICAO) and practice its current contingency procedures during the two-day exercise (EUROCONTROL, 2017a). The exercise focuses on the air traffic response to the onset of a volcanic eruption with ash emission. However, volcanic eruptions can impact the air traffic beyond that initial phase, as the E2010 event demonstrated. Recent studies link global warming and deglaciation with the possibility of increased volcanic activity in Iceland (Pearce, 2012; Schmidt et al., 2013; Compton et al., 2015), leading to conclusions that an eruption similar or greater than E2010 could in the future occur more than once per decade (Schmidt et al., 2013).

This study developed two extreme-case scenarios from Icelandic volcanoes. One investigates situations in which air traffic is interrupted over a long period of time; in the other, the event is of shorter duration but with much greater intensity and ash volume. The scenarios are developed in light of the work done by Schnaars (1987) and Ramirez et al. (2010). The term 'scenario' is defined according to Ramirez et al. (2015) as a "structured conceptual system of equally plausible future contexts […], presented as narrative descriptions […] to provide input for future work." The scenarios present a "strategic planning tool for decision-making under risk" (Brauers and Weber, 1988). Using scenarios in discussions with stakeholders allows consideration of long-term perspectives (Öborn et al., 2013) and the exploration of potential surprising elements along the way (Schweizer and Kriegler, 2012). Ultimately, the aim is to perform applied research that is usable by practitioners (Sandberg and Tsoukas, 2011).

Extreme-case scenarios in this context describe scenarios that feature above-average spatio-temporal dimensions of ash distribution due to a combination of eruption intensity, duration and selected meteorological patterns. The scenarios were selected to capture the "what if..." discussion following an eruption of high intensity as well as an eruption of long duration. In order to expand the preparation beyond recent disasters, the scenarios were set up to go beyond the boundaries of normal expectations, by using a thousand-year timescale. This was done by identifying extreme but historically realistic events (Gudmundsson et al., 2008; Thordarsson and Höskuldsson, 2008).

This article draws on research started in a project on the response of the aviation sector to volcanic eruptions, a case study within the ENHANCE project, Enhancing Risk Management Partnerships for Catastrophic Natural Disasters in Europe (Reichardt et al., 2015b).

In the following section, the selection of the scenario parameters is explained. Then the graphical outcome of the scenario modelling is presented and the potential impact of the modelled ash distribution are discussed. The focus of this paper is the development of the extreme-case scenarios, the visual demonstration of the potential impact of the selected scenarios, and the resulting weaknesses that could be identified in current volcanic ash response exercises. The presentation and discussion of these scenarios in a workshop with various air traffic stakeholders have been described (Reichardt et al., 2017b).

4.3 Methods

This study was performed in three steps. First, interviews were conducted to determine the scenarios and their characteristics. Second, the data were fed into a volcanic ash dispersion model to simulate the ash distribution. In the third step, the outcome of the scenario modelling was presented and discussed with the experts consulted before as well as representatives from European air traffic management and a jet engine manufacturer.

4.3.1 Volcano Selection

Experts from the Earth Science Institute at the University of Iceland, as well as from the Icelandic Meteorological Office (IMO) and the VAAC London, were consulted to discuss the probability and extent of potential volcanic eruptions. According to the interviews and the literature, the risk of volcanic eruptions is a given (Gudmundsson et al., 2008; Thordarsson and Höskuldsson, 2008). Furthermore, recent research indicates that it may be increasing due to climate change (Compton et al., 2015), rendering an event like E2010 possible up to every 7 years in the future (Schmidt et al., 2013). Discussion about the probability of the proposed volcanic eruptions is outside the scope of this study.

Based on the assumption that a new eruption will take place, the scenarios focus on attributes of the eruptions. Two main volcanic eruption attributes define the impact that volcanic ash has on air traffic: duration and intensity. The longer an eruption emits volcanic ash into the air, the greater the potential ash distribution and hence the possible jet engine exposure to ash. The more intense the eruption, the denser the ash cloud and more severe the impact on the aviation industry. The study developed two scenarios that focus on these two attributes. Figure 4.1 shows the locations of the volcanoes used in the scenarios.

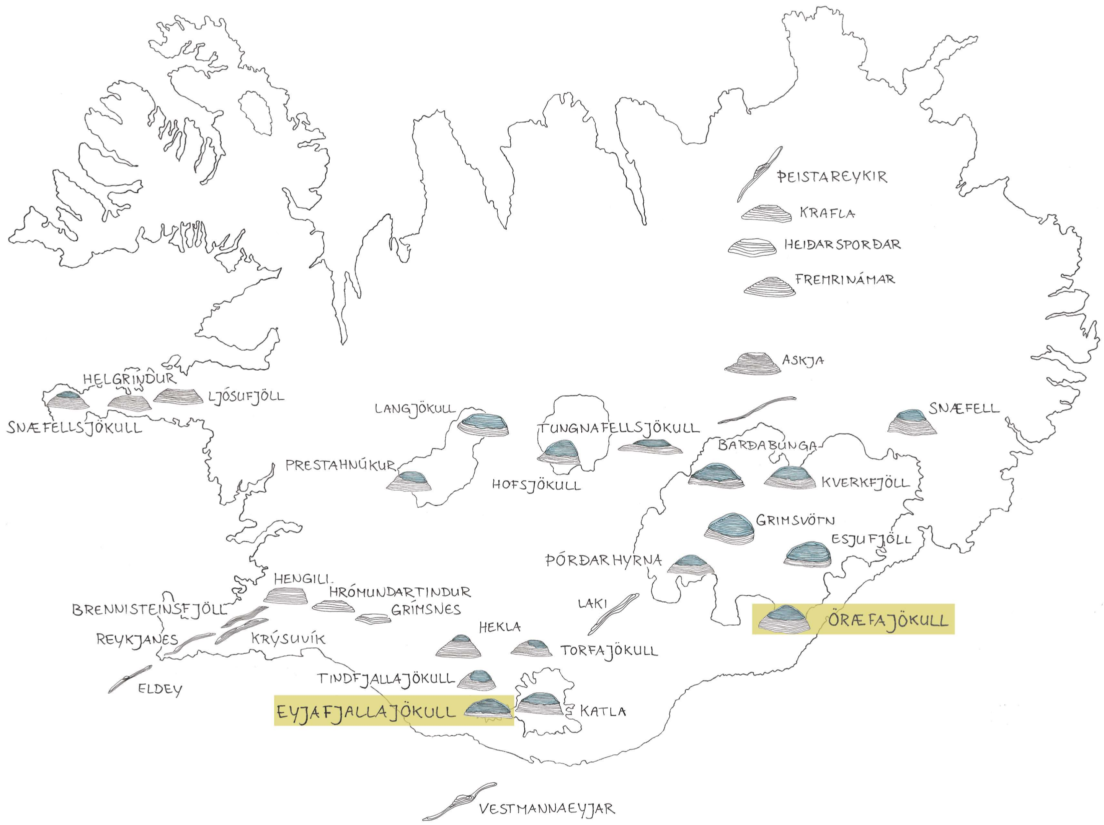


Figure 4.1 Location of volcanoes in Iceland with scenario volcanoes highlighted.

Eyjafjallajökull 4x Scenario

The first scenario investigates operations in the event of an eruption that releases low to medium concentrations of ash over a prolonged period of time. The first scenario is a new eruption of the Eyjafjallajökull volcano, located under the Eyjafjallajökull glacier in the southwest of Iceland. The volcano is situated south of the intersection of the South Iceland Seismic Zone and the Eastern Volcanic Zone (Arnadottir, 2012). The estimated duration of the eruption is roughly 24 weeks, four times longer than the eruption in 2010, hence the title of this scenario is Eyjafjallajökull 4x. The ash volume and ash distribution from the E2010 event is used, based on information and models from the IMO. It assumes a 24-week bout of recurring eruptions with an initial column height of 10 km and erupted tephra volume of 1 km^3 for each discharge. These parameters were suggested by an expert volcanologist from the FutureVolc research group (interview in August, 2014) and are based on historic data of the volcano's behavior. The last eruption of Eyjafjallajökull lasted three months and included a period of three consecutive weeks of ash emission.

Öræfajökull Scenario

While E2010 was highly disturbing for the air industry and the public at large, it was not an extreme volcanic event in terms of intensity. Other volcanic systems in Iceland are potentially able to cause far greater and more widespread travel disruptions (Gudmundsson, 1987).

The second scenario will investigate operations in the event of an eruption that leads to a nearly complete shutdown of air traffic in affected airspace due to very high concentrations of ash. The scenario describes an eruption of the Öræfajökull volcano which could give rise to a severe volcanic event (Gudmundsson, 2008). The volcano is part of an intraplate volcanic system in the southeast of Iceland that is assumed to be above the mantle plume located beneath Iceland (Arnadottir, 2012).

As Öræfajökull is located under the glacier Vatnajökull, the interaction of the magma with ice would lead to a dense and voluminous ash plume. In the last 1000 years, two Öræfajökull eruptions have been documented, the latest being in 1727. An eruption in 1362 was the largest eruption recorded in Iceland since the settlement, with a Volcanic Explosivity Index (VEI) of 6 that is referred to as 'Plinian'. A Plinian eruption is characterized by columns of gas and volcanic ash that reach far into the stratosphere, an atmospheric layer at an altitude of 15–50 km (Newhall and Self, 1982). The scenario estimates a 25 km high column and the duration of the eruption is set to be 2–3 weeks, emitting 10 km^3 of tephra, with the main emission within the first 24 hours. Table 4.1 provides an overview of the parameters used for the volcanic eruption scenarios.

Table 4.1 Overview of scenario parameters

Scenario description	Eyjafjallajökull 4x	Öræfajökull
Column height	10 km	25 km
Total erupted tephra volume	1 km^3	10 km^3
Time scale	24 weeks	2–3 weeks

4.3.2 Meteorological Patterns

Choosing meteorological patterns for the volcanic ash scenarios is of crucial importance as the wind direction heavily influences the volcanic eruption impact on the North Atlantic and European airspace. With Iceland's location to the northwest of the European mainland, northwesterly winds would carry the ash directly into the airspace over Europe.

There are different means to choose the meteorological pattern for the scenarios. A simplistic approach could be to use 1) the average Icelandic weather conditions throughout the scenario. Another approach would be to use 2) the most frequent weather conditions in Iceland. For the purpose of investigating resilience, it is especially interesting to use 3) unfavorable weather conditions, meaning wind directions that would disperse the ash south and over mainland Europe, which would lead to a more disruptive scenario. It is also possible to 4) randomly choose weather conditions based on weather observations. Finally, it is possible to investigate 5) a variety of weather conditions.

What is most interesting for the scenario development is a meteorological pattern that affects busy airspace significantly, a lower probability but a high impact event, i.e., weather scenario 3). The weather data were set up in cooperation with meteorologists from the IMO and consist of patterns observed during E2010 that happened to be among the most unfavorable wind patterns possible (Petersen, 2010) with an occurrence of around 6% of the time (Sammonds et al., 2010).

4.3.3 Scenario Modelling Environment

To produce data for the ash dispersion maps of the scenarios, the study uses the atmospheric pollution dispersion model NAME (Jones et al., 2007; UK Met Office, 2014b). The NAME model is used by the London VAAC for volcanic ash modelling and forecasting of the location and concentration of volcanic ash (Devenish et al., 2012; Webster et al., 2012; Beckett et al., 2015). The tool was developed in 1986 after the Chernobyl incident as a device to predict dispersion and deposition of material, at that time radioactive gases, released in the atmosphere. The model's application has been extended since and it is used for various dispersion events such as nuclear accidents, airborne animal diseases or smoke from fires (Leadbetter et al., 2015; Hertwig et al., 2015; Meyer et al., 2017).

The input files for the scenarios in this study were set up in cooperation with the Atmospheric Dispersion and Air Quality Group (ADAQ) of the London VAAC. The input data to run the model contain the geographical location of the volcano and its estimated plume height. The plume height of the erupting volcano means the distance between the volcano's summit and the highest point of the eruption plume. In the case of an eruption, first estimations about the plume height would be derived from photographic observations. Satellite observations, radar and LIDAR installations in Iceland, the UK and other European countries help to adjust first estimations and make the data input more accurate and add more information on the particle size and composition. The plume height in the scenarios is based on data of historical eruptions of the volcanoes in question.

The plume height is used to make assumptions about the mass eruption rate to estimate the amount of ash emitted into the atmosphere. The mass eruption rate is calculated as a function of plume height using the Mastin et al. (2009) relationship (Witham et al., 2016). The model runs with the current and forecasted meteorological data. Both scenarios were set up to illustrate the forecast of ash distribution within 5 days after a 24-hour one-off eruption, assuming the meteorological conditions described above.

The raw data of NAME are produced in a so-called fields_grid format, which are text files and contain air concentration, deposition rates, etc. In a next step, a Python script was used to create plots of the ash distribution. Similar to the London VAAC forecasts, the plots show three different concentrations of ash, in three different flight levels.

4.4 Scenarios and Impacts

Aviation safety rules ensure the avoidance of airspace that is contaminated with ash concentrations that threaten immediate loss of engine power. Birtchnell and Büscher (2011) call the Eyjafjallajokull incident an "eruption of disruptions." This illustrates the biggest risk being financial through business losses in the cascading effects of the "systems within systems" (Birtchnell and Büscher, 2011).

The ash from an Icelandic eruption has the potential to interfere with several intercontinental flight corridors for goods and passengers, impacting economies worldwide. Adaptive behavior of actors as well as the diversity of offsetting factors for the airlines and other industries, such as use of alternative modes of transport (Mazzocchi et al., 2010), make prediction of the potential financial impact very complicated.

However, useful approximation can be achieved by drawing on the losses witnessed during E2010 and combine them with expert judgements on the potential impact on flights in the proposed scenarios. The following estimations are based on this combination. During E2010, the biggest effect of loss was on passenger flights, but there was also a significant impact on cargo (around 40%). Throughout the crisis, around 48% of flights were cancelled, with 80% of European flights being cancelled on the day with the greatest impact (EUROCONTROL, 2010). The overall global loss for the 6-day interruption was estimated at 4.7 billion euros, with the loss for European economy estimated at 2.5 billion euros (Oxford-Economics, 2010).

The financial impact can be further approximated through the experience of the first days of the events in 2010. Though not an unknown risk (Scarone, 1987), the threat of volcanic ash to aviation was not included in the states' emergency responses across Europe and made the response reactive, as Alexander (2013) examines in his article on the management of the 2010 crisis. He describes the delay of action by the UK's national policy and strategy committee as a "lack of visible leadership". This also seems to have been the case on a continental scale (Brannigan, 2010). A representative of EUROCONTROL, the European Organization for the Safety of Air Navigation, drew the comparison concerning the financial impact with the creation of the European Aviation Crisis Coordination Cell (EACCC). "It is difficult to make a statement about the mitigation of loss. But during the crisis there were 5 days in which we were involved, it took us two days to organize ourselves and three days to unlock the crisis. If you divide the total financial damage of [2.5 billion euros GDP for Europe] through 6, then two days less would have saved around 800 million euros. But now the crisis sector is getting more and more attention so that helps the development" (interview with representatives of EUROCONTROL, February 2015).

Following are illustrations and detailed descriptions of the scenario plots. The display of the ash clouds as a discrete area is due to the modelling input. The duration of the eruption was set to 24 hours, during which the main ash emission is expected to occur but repeated bouts of ash eruption phases are possible. Once the pressure of the eruption declines, the plume height changes and the model needs to be adjusted (discussion with the IMO, 2015). The design was chosen to illustrate the distribution of the main first 24-hour emission within a period of 5 days. The modelling is based on the assumption that, depending on meteorological conditions, ash particles can remain in the atmosphere for up to 5 days. Depending on the length of the eruption, the ash cloud would continue to contaminate the airspace for several days into the forecast. As the meteorological data sets are taken from the events in April 2010, those dates have been adopted for the plots in this report. The plots are marked with the dates, with the evening of April 14 being the onset of the eruption and midday of April 19 being the end of the forecast. The colors indicate low (blue, under 2000 $\mu g/m^3$), medium (grey, 2000–4000 $\mu g/m^3$) and high (red, greater than 4000 $\mu g/m^3$) ash concentrations.

4.5 Ash Dispersion and Impact of the Eyjafjallajökull 4x Scenario

The Eyjafjallajökull scenario includes recurring eruptions, similar to the one in April 2010, over the course of several months. Figure 4.2 illustrates the forecasted ash distribution up to 5 days into one of these eruptions. The overview of the complete sequences of the 6 hourly forecast plots for all three flight level bands are to be found in the Appendix.

Twenty-four hours into the scenario eruption, high ash concentrations are forecasted to have reached the UK, including the London area airports which are the busiest in Europe, as well as parts of Norway, Sweden and Denmark. Over the course of the following days, the air masses travel further south, spanning from Western to Eastern Europe. While high ash concentrations slowly decrease, a broad band of air with low ash concentration is forecasted 5 days into the eruption up to flight level 200. Flight level (FL) describes the measure of altitude in hundreds of feet, and FL 200 denotes 20,000 feet.

This scenario would mostly impact air traffic at low altitudes, affecting take-offs and landings. Figure 4.3 shows plots of the same date and time in the three different flight level bands issued by the model after 24 *h*, 48 *h*, and 72 *h*. Low, medium and high ash concentrations are forecasted up to FL 350, while there is no ash contamination forecasted for the level above.

To make a statement on the impact of such an ash forecast, the research draws on expert opinions voiced during an interview. Based on experience with airlines' operational behavior in case of volcanic ash-contaminated airspace, the representative of Rolls-Royce estimated that "even under the new [EU] regulations, by day two, flights would be limited, approximately up to 50%—a significant reduction in air traffic" (Rolls-Royce interview, May 2015).

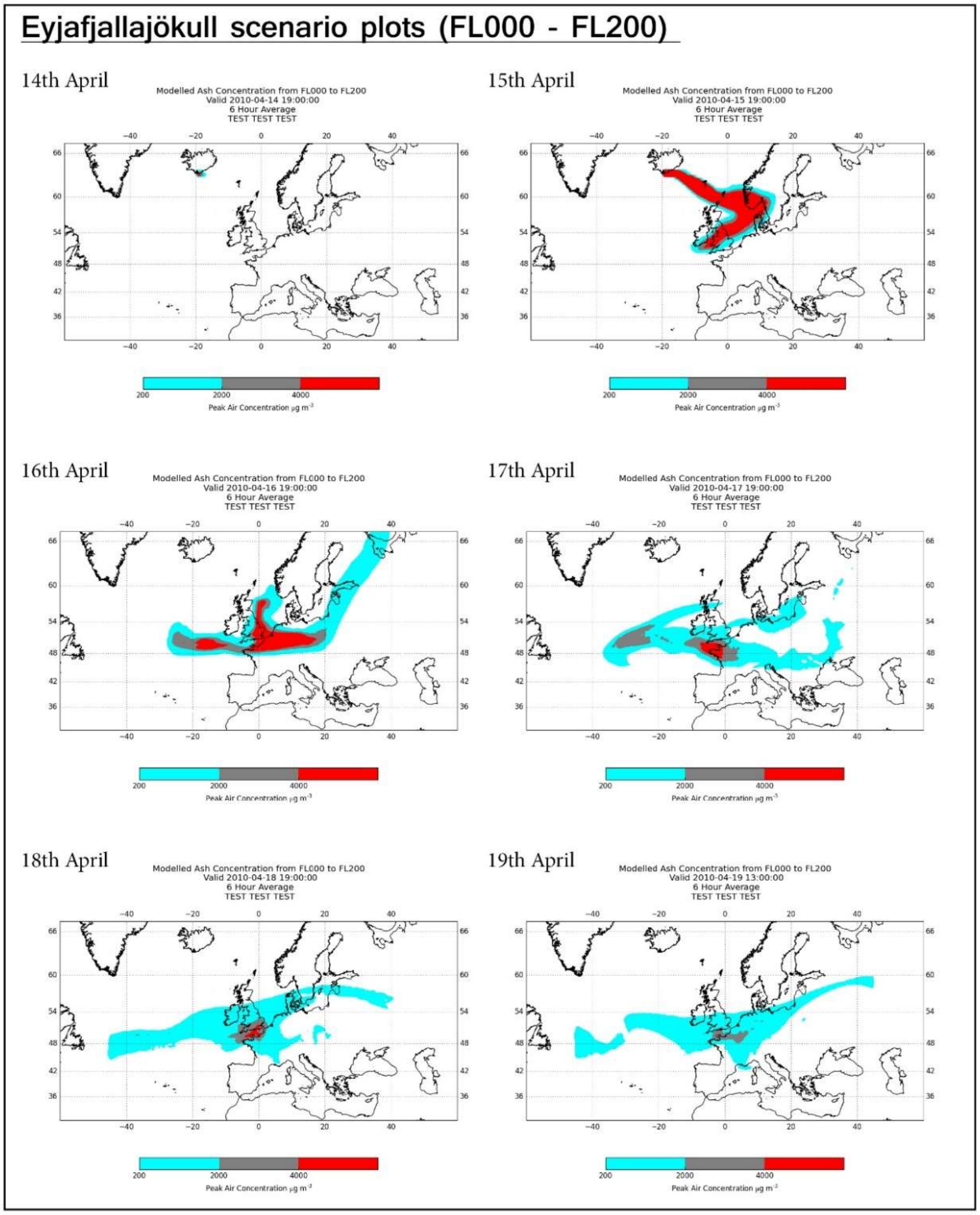


Figure 4.2 Ash distribution for the Eyjafjallajökull scenario plotted for 5 days into the eruption for flight levels (FL) up to FL200.

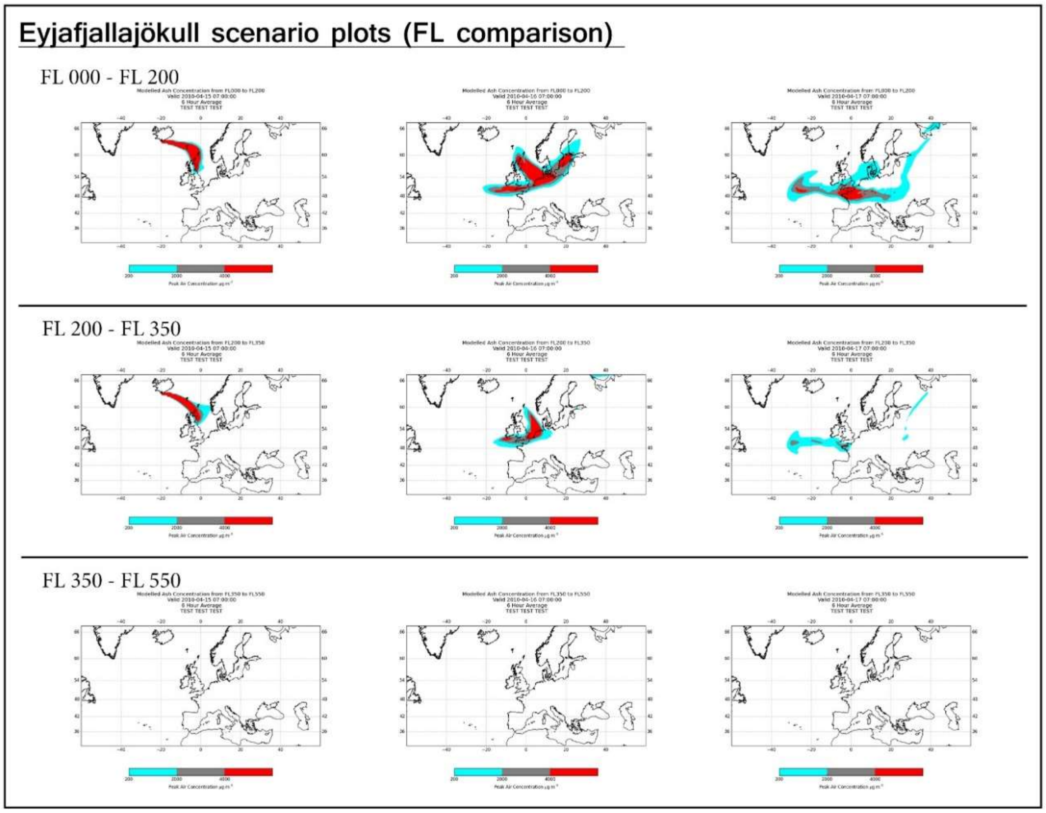


Figure 4.3 Comparison of the ash distribution forecast at different flight levels (FL) 24h, 48h and 72h into the Eyjafjallajökull eruption

The uncertainties regarding estimated financial impacts of the scenarios have been mentioned. Since, however, the expected impact on flights would resemble those at the onset of the eruption in 2010, a rough estimate is possible. The estimate of a 400 million euro total loss per day in E2010 is taken as a baseline. This is estimated on days 2 and 3 with large areas of high ash concentration. How the event progressed is uncertain, but 50% of the average loss/day is assumed for days 4 and 5 with prevailing medium and low ash concentrations. The estimated accumulated loss in Europe during just one eruption sequence within the 24-week span of the scenario would exceed one billion euros. The scenario assumes that sequences, like the one described above recur every few weeks. According to the Rolls-Royce representative, every eruption event would have a similar impact on the air traffic (Rolls-Royce interview, May 2015). While business continuity plans might take effect and mitigate some of the impact, the loss caused by an event similar to the scenario is still likely to be on the order of several billion euros worldwide over the course of the whole scenario.

4.6 Ash Dispersion and Impact of the Öræfajökull Scenario

The Öræfajökull scenario assumes a one-off eruption. Though the eruption can last several days, the main emission is expected within the first 24 hours. Since the ash particles are assumed to have left the atmosphere within 5 days after their emission, the plots account for the maximum travel distance given certain meteorological conditions. Depending on the progress of the eruption, the forecasted ash cloud could remain connected to Iceland during the whole period and prolong the conditions of ash contamination. Figure 4.4 illustrates the forecasted ash distribution up to 5 days into the eruption. The overview of the complete sequences of the 6 hourly forecast plots for all three flight level bands are found in the Appendix.

Twenty-four hours into the scenario eruption, high ash concentrations are forecasted to have reached Northern European countries. In the consecutive days, a large, broad band is forecasted over Europe reaching far west over the Atlantic and far east toward parts of Russia. High ash concentrations of more than 4000 $\mu g/m^3$ are predominant throughout the forecast period.

This scenario is likely to impact air traffic at all flight altitudes. Figure 4.5 shows the comparison of plots of the same date and time in the three flight level bands issued by the model after 24 *h*, 48 *h* and 72 *h*. High ash concentrations are forecasted at all flight levels.

A representative from EUROCONTROL stated that even though the airspace would most likely not be closed by national authorities there would be no flying within one or two days of the eruption onset. “I do not believe that any aircraft operator would fly through areas of high ash concentration unless they are convinced that the ash concentration forecast is incorrect and their SRA [Safety Risk Assessment] allows them to operate in such areas” (personal communication with EUROCONTROL, November 2015). The forecast shows large parts of the North Atlantic and European airspace contaminated with high ash concentrations, including the cities with the four busiest airports in Europe in terms of both passengers and freight revenue: London, Paris, Frankfurt and Amsterdam (Port Authority of New York and New Jersey, 2014). Assuming an eruption of several days, the impact may last for 2–3 weeks. We use the assumption of 50% flight cancellation equals around 400 million euros/day as described for E2010. The cost estimation considers a 5-day period without flights (loss of 800 million euros/day), 5 days with 50% flights cancelled (loss of 400 million euros/day) and 4–11 days with 25% decreased air traffic (loss of 200 million euros/day). This amounts to 7–8 billion euros’ worth of damage for the European economy during the scenario event.

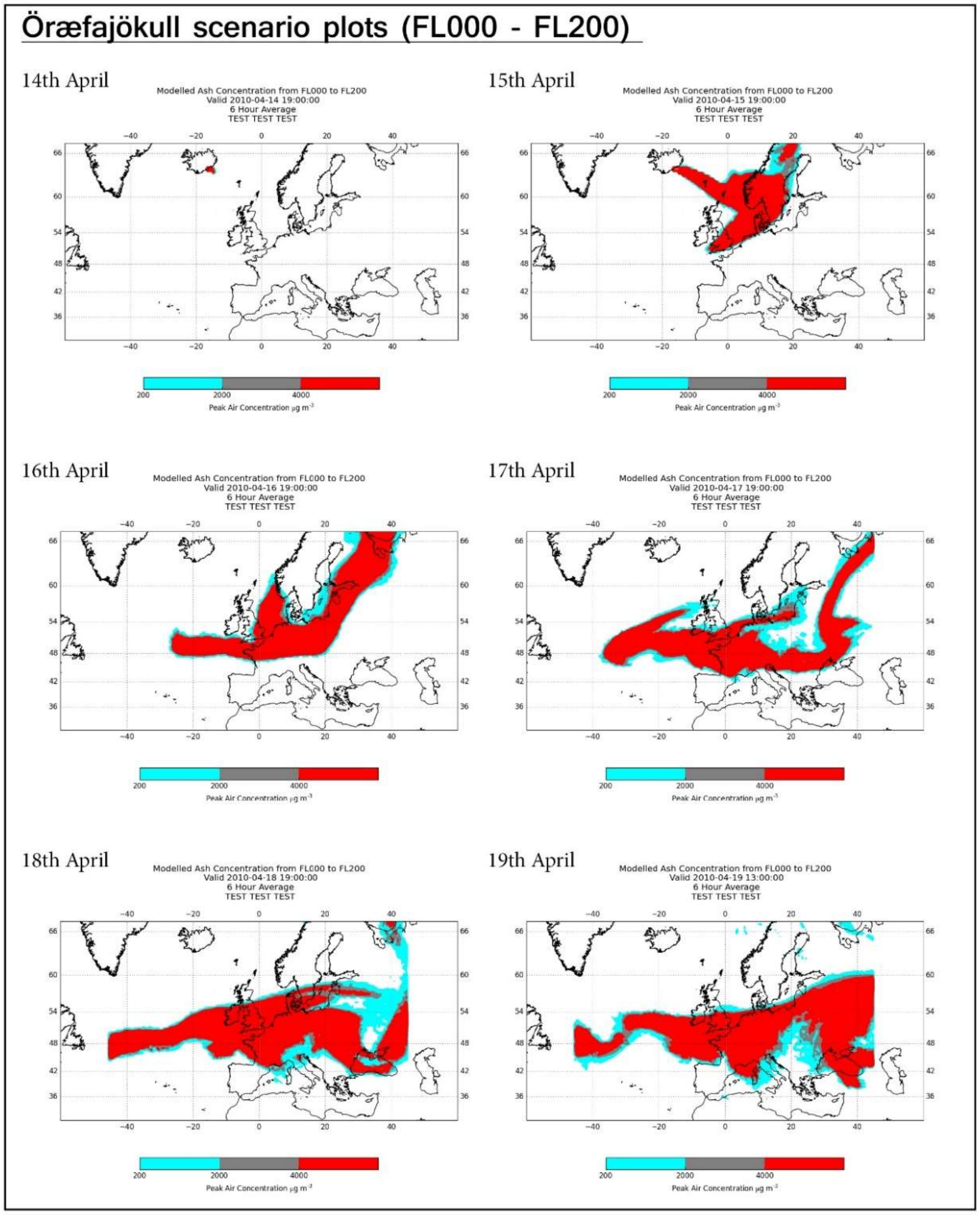


Figure 4.4 Ash distribution for the Öræfajökull scenario plotted for 5 days into the eruption for FL000–FL200.

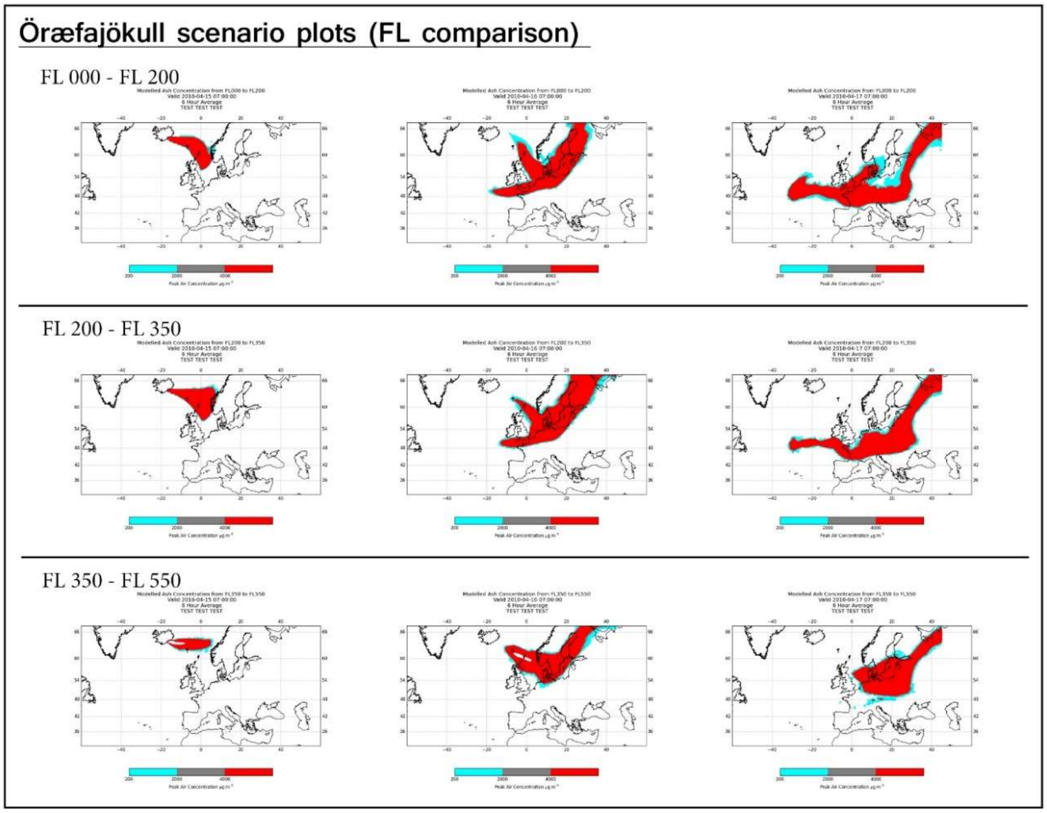


Figure 4.5 Comparison of the ash distribution forecast at different flight levels (FL) 24h, 48h and 72h into the Öræfajökull eruption.

4.7 Conclusions

Aviation experts recognize volcanic ash as probable high-impact threats (Linz, 2012) to both the growing stream of passenger and dedicated freighter aircraft (Budd and Ison, 2017).

This paper developed scenarios of extreme volcanic ash eruptions to explore potential impacts and weaknesses in aviation response exercises. The results provide general recommendations based on the experience with scenario analysis and specific recommendations derived from the case study.

Scenario analysis provides a relatively low-cost method to explore different futures. The research found that the scenario analysis can be used productively to expand the boundary of normal experience to identify weaknesses in exercises and preparedness. For this case study it was clear that both scenarios brought a new understanding to the stakeholders.

The analysis of the Eyjafjallajökull 4x scenario suggests it would mostly impact air traffic at low altitudes, affecting take-offs and landings. A representative of Rolls-Royce estimated that "even under the new regulations, by day two flights would be limited, approximately up to 50%—a significant reduction in air traffic." This is notable in light of the long duration of the scenario. It suggests aviation stakeholders need at some point to exercise their response beyond the first two days in order to reveal system weaknesses under a long duration event.

A highly intensive scenario like Öræfajökull is likely to impact air traffic in all flight altitudes. A representative from EUROCONTROL stated that even though the airspace would most likely not be closed by national authorities there would be no flying within one or two days of the eruption onset. This scenario in particular showed that current exercises are too heavily based on recently occurring events, which so far have not been very intense. Current exercises are not looking back in time far enough to find quite possible but much more extreme scenarios than those that have occurred in the last 50 years or so.

It is concluded, based on this research, that an exercise is needed to test the aviation response system beyond the onset (first two days) of a volcanic eruption. It is suggested that a more extensive and especially longer-duration exercise be performed regularly but less frequently, for example at 10-year intervals, since such an exercise will be costly and taxing for staff members. However, it could greatly facilitate testing procedures under a long-lasting eruption. The method employed in this study served as an example to assess effects of possible impacts of volcanic eruptions on aviation and could be applied to other parts of the world.

Further, scenarios of higher intensity are important for exercises to truly challenge the execution of current procedures. This is also supported by results from the latest VOLCEX exercise, where participants voiced concern over the exercises not being challenging enough; this can lead to a false sense of security (observation at VOLCEX debrief meeting in Reykjavik, November 2016). The scenarios presented in this study demonstrate the potential impact on North Atlantic and European air traffic and beyond, given adverse combinations of parameters.

These recommendations, taken together with those of Reichardt et al. (2017b) calling for a more comprehensive contingency plan to include stakeholders from alternative modes of transport, give a more comprehensive set of recommendations to improve the aviation community's resilience to volcanic ash eruptions.

5 Increasing Resilience through Interaction: Stakeholder Workshop on Aviation and Volcanic Ash

Material from this chapter has been presented at the 8^{th} *Conference of the International Society for Integrated Disaster Risk Management*. The chapter is being submitted to a journal for publication.

5.1 Abstract

The Eyjafjallajökull volcanic eruption in 2010 illustrated the threat that Icelandic volcanoes can pose to global air transportation and the connected economy. It highlighted the necessity for crisis management and contingency planning that crosses borders. This research obtained insights into how the European aviation volcanic risk management has progressed since 2010. It developed extreme volcanic scenarios to investigate the robustness of the aviation sector and to identify improved mitigation measures.

This paper presents a multi-level methodology to build a lasting relationship with, and between, stakeholders and to obtain relevant data. The first step consisted of establishing a face-to-face interaction with stakeholder representatives on an individual basis. Subsequently the group was invited to a one-day participatory stakeholder workshop where extreme volcanic events and their effects on aviation were investigated using scenario narratives.

The workshop's set-up proved successful in enabling discussions and obtaining information. The stakeholders' positive responses to the invitation, as well as their feedback after the workshop, illustrate their interest in this type of workshop. The feedback showed that the stakeholders appreciated the opportunity to meet and specifically to discuss aviation contingency issues. The workshop raised awareness and facilitated information flow between the stakeholders.

The paper describes this case, provides generalized guidance on how to build fruitful interaction between interviewees in a study, sheds light on the resulting impact, and presents opportunities to create value beyond the study.

Keywords: risk management, aviation, volcanic eruption, participatory workshop

5.2 Introduction

Iceland contains 32 volcanic systems that are considered active (Gudmundsson, 1987). Historic records (see Gudmundsson, 1987; Haraldsson, 2012; Höskuldsson et al., 2013) suggest a volcanic eruption in Iceland approximately once every five years. Recent studies point to the possibility of increased eruption frequency due to less pressure from melting glaciers (Pearce, 2012; Schmidt et al., 2013; Compton et al., 2015), posing a greater threat to the local population. The particles in volcanic ash vary in size and weight. Volcanic ash can, if light enough, be lifted to great elevations in the atmosphere and can remain there for significant amounts of time.

A number of historic volcanic eruptions in Iceland have had an impact beyond the island's borders. A widely known example is the ash of the Lakagígar eruption in 1783–1784, which is speculated to have led to weather changes that subsequently impaired harvests in Western Europe and is thus considered to have possibly contributed to triggering the French Revolution (Wood, 1992). Again, the potency of Iceland's volcanism aroused global attention in spring 2010, when Eyjafjallajökull erupted with severe consequences for aviation (Ulfarsson and Unger, 2011).

Depending on the density of the ash surrounding a flying jet aircraft, the threat to the jet engines ranges from shortening their lifetime to complete failure (Dunn and Wade, 1991; Guffanti and Miller, 2002). The eruption of the Eyjafjallajökull volcano in April 2010 (hereafter abbreviated as E2010) was modest in comparison to the magnitude of other eruptions (Gudmundsson et al., 2012), yet unprecedented in the impact it had on global aviation and the economy. E2010 prevented millions of passengers, as well as goods, from reaching their destination, as air traffic was halted in Europe for several days (Ulfarsson and Unger, 2011). It led to what is known to be the greatest disruption of air traffic since World War II and caused an estimated worldwide loss of 5 billion USD with more than 100,000 flights cancelled (Oxford-Economics, 2010).

The event illustrated the vulnerability of the increasing interconnectedness of global infrastructure and the lack of coordination between institutions at the time. It highlighted the necessity for crisis management and contingency planning that crosses borders, both on a physical and institutional level (Alexander, 2013).

As part of the EU project ENHANCE on stakeholder partnerships, this study obtained insights into how the European aviation sector's risk management regarding volcanic ash has progressed since E2010. This research focused on cooperation and information exchange between Icelandic and other European stakeholders. It aspired to enable interaction and enhanced discussion between the stakeholders. The study conducted expert interviews and used the method of scenario narratives and visualization in a stakeholder workshop to facilitate the discussion and for the stakeholders to jointly develop improvement measures.

This paper describes the multi-level method the research study used to build a relationship with the stakeholders and gain a deeper understanding, both at an individual level and through group dynamics. The purpose of the paper is to share the study's methodology with a focus on the stakeholder workshop as a practical example when working with stakeholders from diverse institutions and backgrounds. The article aims to underline the importance of providing a physical opportunity for stakeholders to meet and discuss scenario ideas for the risk management of transboundary and multi-spectral hazards.

Following the introduction, the third section of the paper gives a brief schematic overview of the institutions represented in the case study and their roles in the management of volcanic ash. The fourth section provides an overview of the methods that were used in obtaining the data. This is followed by a description of the composition and process of the stakeholder workshop in detail. It is followed by the stakeholders' feedback, which was collected throughout the course of the study. Finally, there are concluding remarks and recommendations.

5.3 Stakeholder Overview

A volcanic eruption calls for various stakeholders to form an alliance and cooperate on different levels to mitigate the adverse impacts of this natural hazard on people, infrastructure, and machines. Bearing the importance of each of them in mind, the study focuses on the stakeholders that exist around the aviation response while leaving out primarily land-based response actors, e.g., direct on-the-ground emergency management.

According to their position in the process, the stakeholders can be grouped into information providers, crisis coordination and network management, air navigation service providers, global/international and national regulators, and aircraft operators. An overview of the sectors, roles, and associated institutions can be found in Table 5.1.

Table 5.1 Overview of sectors, roles, and example of institutions

Sector	Role in volcanic ash management	Institutions
Global air regulator	Development of global standards and recommended practices	ICAO (International Civil Aviation Organization)
International regulator	Limit-setting for shared air transportation zones	EU Directorate General for Mobility and Transport
International facilitator	Representative of airline industry, formulates industry policy on critical aviation issues	IATA (International Air Transport Association)
National regulator	Responsible for the state's Volcanic Ash Contingency Plan, approval of Safety Risk Assessment procedures, airspace closure	ICETRA (Icelandic Transport Authority)
National regulator	Supervision of ISAVIA and ICETRA, resource allocation to fund extra costs, policies regarding risk management (e.g., transportation plans)	Icelandic Ministry of the Interior
Crisis coordination and network management	Network management and crisis-coordination response	EUROCONTROL (European Organisation for the Safety of Air Navigation)
Information provider	Issue weather observations and forecasting. Monitoring of volcanic eruption, detection of seismic activity, ash measurements, issue warnings	IMO (Icelandic Meteorological Office)
Information provider	Forecasts expected location of the volcanic ash cloud, issued as VAG and VAA	London VAAC (Volcanic Ash Advisory Centre)
Information provider	Engine manufacturer, guidance on engines for airlines and information for national governments, European Aviation Safety Agency	Rolls-Royce
Air navigation service provider	Management of airport operations and air traffic in control area	ISAVIA (Icelandic Air Traffic Management)
Aircraft operators	Air transportation and service providers to passengers and cargo	Icelandair (Icelandic aircraft operator)

(*Based on: Reichardt et al., 2015b*)

Global and national regulators provide the legal framework for aircraft operations. In case of a volcanic eruption, the information providers collect information on the eruption and create forecast maps of predicted ash concentrations. These maps facilitate the decision-making process of the aircraft operators on whether to proceed, divert or cancel flights. Air navigation service providers coordinate the air traffic. To ensure a smooth transition of flight plans, the network manager facilitates on a European level and acts as crisis coordinator if needed.

Since the European airspace is a composition of multiple national and international airspaces, the disruption of air traffic due to E2010 was managed and coordinated both on national and international levels. The effective decision-makers were mainly at the national level, following regulations, contingency plans, and recommendations from international and global regulatory bodies while using information provided by national and international institutions.

To trace briefly the response being studied, as it happened during E2010, the Icelandic Meteorological Office (IMO) initially informed the London Volcanic Ash Advisory Centre (VAAC) and the Central Flow Management Unit of EUROCONTROL about the new eruption and the emerging ash plume of E2010. The VAAC issued Volcanic Ash Graphics (VAGs) and Volcanic Ash Advisories (VAAs). Based on the forecasted distribution maps and following the recommendations of the International Civil Aviation Organization (ICAO) contingency plan to avoid ash-contaminated airspace (ICAO, 2009), as well as the EU recommendations of ash density limits, EUROCONTROL recommended closure of the airspace predicted to be contaminated based on the VAAC forecast. This closure recommendation was submitted to the various air navigation service providers operating under national civil aviation administration oversight, who initiated the closures in their respective airspaces. Questioning the rationale behind the regulation-specified ash-density limits and in light of increasing economic losses, EUROCONTROL, national civil aviation administrations, and aircraft operators called for a coordinated European approach and review of the existing guidelines. The European Commission's Directorate General for Mobility and Transport, with the agreement of the national ministries of transport, reviewed the guidelines on the limits of ash density and developed changes to EU regulations, which changed the no-flight zone and partially reopened airspace.

The study recognizes the limitations that come with the choice of stakeholders. The aviation industry is a broad field with stakeholders on the national, international and global level. A comprehensive study of all stakeholders involved goes beyond the temporal and financial limitations of this project. The research group thus worked with the main global and European stakeholders. On the national level, the project's focus was on Icelandic institutions due to project relevance and access. While this case was successfully analyzed, the analysis does not comprehensively represent all stakeholders, since several remain outside this research.

5.4 Method Overview

The study researches human interaction, collaboration, partnership and communication of stakeholders. The stakeholder groups' opinions and assessments thus formed the core part of the research outcome. For this, the aim was to build trust and a close relationship with the stakeholders. The process was divided into two sets of data-gathering cycles: Individual meetings with the stakeholders and the participatory stakeholder workshop with the stakeholders together in a group.

After the initial literature and policy review, the study developed a multi-level method for repeated interaction with the stakeholders. The emphasis was placed on meeting the stakeholders face-to-face in the first place to lay grounds for a lasting interaction. This proved to be a successful approach as all stakeholders were open for further discussion and information exchange through email, phone, and online meetings. In this section, the different steps are briefly described. The stakeholder workshop is described in the subsequent section.

5.4.1 Preliminary Discussions

In the beginning of the research, face-to-face meetings were conducted at a national level. The study group consulted experts of potential stakeholders such as the Civil Aviation Authority in Iceland, IMO, the Earth Science Institute at the University of Iceland, and ISAVIA to gather information about the field of study. A member of the research group facilitated as a note taker. The discussions helped to establish a general idea of the problem, the process, and potential stakeholders in question. The interview partners were asked to suggest institutions and contacts that they considered to be of value to the project.

5.4.2 Face-to-Face Interviews

Once the stakeholder group was identified, the study conducted individual interviews. Interviews were held with representatives and field experts from the London VAAC, EUROCONTROL, ICAO, ISAVIA, Icelandair, the University of Geneva, the University of Iceland, Reykjavik University, and Rolls-Royce about their experience, the decision-making processes at the time, and the impact E2010 had on them and their organizations. The interviews were set up as face-to-face interviews, with guideline questionnaires, at the site of the institution and lasted between 70 minutes and 3 hours. The visit to the institution facilitated the understanding of the process and was often combined with meeting further representatives who provided valuable insights to the research. All interviews were held in English, recorded and transcribed verbatim. They were partly complemented through additional communication with the interviewees via email and phone. The interviews further facilitated the trustful relationship between the research and the stakeholder. This greatly helped all further information requests and exchange and supported the successful turnout of the workshop.

5.4.3 Participation in Internal Stakeholder Meetings

Having established a personal relationship with the stakeholders through frequent interaction and the face-to-face interviews, the study group was allowed to participate as observers in internal stakeholder group meetings, such as the Volcanic Ash Exercise (VOLCEX) planning meeting, exercise and debrief meetings, as well as best practice VAAC workshops and other ICAO meetings. This not only strengthened the connection with established contacts but also provided access to other representatives from the aviation sector. It facilitated the gain of more information toward a comprehensive understanding of the whole process.

5.4.4 Scenario Development

The researchers developed two scenarios that exceeded E2010 in a) duration and b) magnitude to facilitate the discussion with the stakeholders about the current procedures and what is needed to improve preparedness for more extreme cases than E2010.

The first scenario describes a new Eyjafjallajökull eruption of medium ash concentration over the course of 24 weeks (about four times longer than E2010) of recurring eruptions. This long duration scenario helped the researchers to collect information on the stakeholders' decision-making when facing a long period of continuous risk assessment and maintenance. The second scenario is based on the historic eruption of the Öræfajökull volcano in 1362 with a large ash emission but in a rather short period of time (2–3 weeks). This scenario helped to capture the reaction of the stakeholders to a large-scale severe interruption of air traffic. Both scenarios are modelled under the meteorological conditions that were prevailing during E2010, with predominantly N-NW winds (Peterson 2010), which are especially unfavorable with respect to the European airspace. Although the uncertainties are considered too numerous to perform a detailed economic risk assessment, the financial consequences in both scenarios are expected to be on the order of billions of euros. The scenarios are described in detail in Reichardt et al. (2018a).

The parameters of the volcanic eruptions were developed based on discussions with expert volcanologists from the FutureVolc research group at the University of Iceland. To model the extreme-case scenarios, the research group was in close cooperation with the Atmospheric Dispersion and Air Quality (ADAQ) Group at the UK Met Office which provided the NAME model as well as a training course and staff hours to facilitate the model set-up. The interaction included face-to-face and online meetings as well as email exchange.

5.5 Stakeholder Workshop

5.5.1 Workshop Preparation

The aim of the workshop was to get the experts' opinion on how cooperation to manage the risk of volcanic ash can be improved. Therefore, the workshop was designed to require as little mediation or steering by the researchers as possible. It was intended to serve as a platform for stakeholders to talk and interact, steered only to make sure that every party was being heard and to help move the discussion further.

The majority of the stakeholders had been contacted and interviewed face-to-face in an earlier stage of the project, which facilitated the gain of first-hand information and the establishment of personal relationships with the stakeholders. This helped the preparation for the workshop. Since the workshop also served the purpose of further connecting the other European stakeholders with the Icelandic representatives, these institutions were addressed first and their availability on the suggested date confirmed.

Invitations were sent by email or telephone and received a positive response from the stakeholders. The attendance of the international stakeholders served as a pull factor. The word spread to a broader audience than initially targeted, which led to requests to be allowed to join the workshop.

The workshop was hosted by the research group and the participants were reimbursed for transportation and accommodation costs, where applicable.

Prior to the workshop, the stakeholders received a questionnaire regarding their institutions' processes in case of volcanic eruptions and their experience during E2010. Thus some additional, comparable information could be collected and it was ensured that representatives at the workshop were up-to-date in their role and ready to discuss on the spot even if they had not been in this position during the E2010 event.

The workshop design was inspired by the scenario workshop tool-kit developed under the EC project TRAMS: Training and Mentoring of Science Shops (Gnaiger and Schroffenegger, 2008). The TRAMS document was especially helpful in assembling and bridging the separate parts of the workshop and defining the scenario run.

The workshop day was set up as an alternation between short presentations from research team mediators and the stakeholders, plenum discussions, scenario group discussions, and opportunities for the participants to discuss in smaller groups.

While the general process was discussed in plenum, the subgroup setting for the scenario runs allowed for in-depth discussions. A number of focus points, aspects and questions were developed as orientation for discussion in all the sessions. The discussion topics were supported by visualization tasks and intermittent change of locations to open up communication dynamics through changing positions and discussion partners. To ensure that the participants were aware of the research team's focus areas and questions, these were visually emphasized using printouts and flip charts. Furthermore, a color code of differently colored Post-it note blocks was applied to structure the outcome of the individual tasks for further analysis.

Breaks were an important issue to be considered during the set-up of the workshop agenda. The day started with a welcome coffee to provide an environment for casual interaction between the participants. In addition to lunch and coffee breaks, different locations within the building were used for different sessions to ensure physical movement and diversions during the workshop day. This was also meant to give the participants an added opportunity to engage with each other during the workshop.

The researchers had developed a detailed agenda, which listed the content, aim and tools needed for every part of the meeting. This helped to establish a clear focus for each part of the workshop, ensured all points were covered, and kept track of the timing of the workshop. For every subsection, one of the two researchers was appointed as a speaker to facilitate the preparation for the different parts of the workshop. The researcher who was not mediating would keep track of the time and help to facilitate, e.g., in discussion rounds. Two assistants helped the mediators capture the process of the workshop by taking notes, later used to develop the meeting minutes.

5.5.2 Progress During the Workshop Day

The workshop was attended by representatives from EUROCONTROL, IATA, Icelandair, ICETRA, ISAVIA, IMO, the Icelandic Ministry of the Interior, and Rolls-Royce.

After a brief welcome and introduction round, the aim of the first task was to create a common idea about the processes and connections between the institutions, as well as to collect first insights about potential improvements to current processes. This also facilitated an open discussion environment, making the participants comfortable to speak. Figure 5.1 demonstrates the outcome of the first task pinned to a whiteboard. The participants were handed a sheet of paper with their institution's name and asked to pinpoint their institution's main tasks and visualize the stakeholders' connections (drawn arrows) between each other in the general response to a volcanic eruption. Then the participants were asked to write down potential obstacles that could prevent the process from running efficiently (orange Post-its). At the end of this first part, a representative from each institution presented their position in the process and possible obstacles. Time was included for open discussion. This exercise also served to openly illustrate the stakeholders' position in the process. Further, this created a first discussion environment in preparation for the discussion in the scenario run.

Figure 5.1 Stakeholder workshop, Task 1 outcome: Stakeholder main tasks and connections.

The second part of the workshop contained the scenario run. The stakeholders were divided into two groups and were presented with one scenario each. The information about the scenarios was presented in the form of artificial newspaper articles, graphically designed to be realistic in order to create a feeling of a real-life situation.

Group 1 (with representatives from IATA, IMO, ISAVIA, Icelandair and Rolls-Royce) was presented with the scenario of a long-lasting eruption with low concentrations of ash in the atmosphere over several months, which was presented with the following narrative:

> "50 shades of grey [Title]
>
> Iceland's Eyjafjallajokull volcano continues to emit ash into the European Airspace for the 4th month in a row – air traffic industry on continuous alert.
>
> With almost constant ash concentration levels between 500-3000 μg/m³ in areas ranging from the Northern parts of Scotland to the Western tip of the Black sea in Europe's airspace, the Eyjafjallajokull volcano has kept the air traffic industry on its toes since late February. The initial eruption at the start of this year had

a remarkable column height of 10 km and total erupted tephra volume of 1 km³. Subsequently new craters opened up beneath the Eyjafjalla glacier emitting ash columns of similar height and volume repeatedly. The new eruption yesterday was the 4th one within four months. Iceland's meteorological office said a change of wind direction in the past few days had sent the ash cloud again south and south-east towards Europe. Furthermore, uncommonly dry weather makes it likely for the ash to remain in the atmosphere for a few more days. "Eyjafjallajokull's warning shot in 2010 brought attention to the vulnerability of the European air traffic to the force of Icelandic volcanoes" the spokesman from Rolls-Royce, a major manufacturer of jet engines. "With the summer holidays starting all over Europe soon and no end of the eruption in sight, the continuous presence of ash … [Continue reading]"

Group 2 (with representatives from EUROCONTROL, Icelandair, ICETRA, ISAVIA, and the Ministry of the Interior) discussed a scenario of an intense eruption with high concentrations of ash over the course of 2–3 weeks, presented in the following narrative:

"Ashpocalypse now [Title]

Iceland's Oræfajokull volcano outdoes its own historic performance from 1362 and covers the European airspace in ash – a doom for the air traffic industry?

"Eyjafjallajokull's warning shot in 2010 brought attention to the vulnerability of the European air traffic to Icelandic volcanoes and led to significant changes across the industry to increase resilience" says the spokesman from EUROCONTROL, the European Organization for the Safety of Air Navigation. "Yet, the Öræfajökull eruption from five days ago is on an entirely different scale."

With a column height of 35 km and a total erupted volume of more than 10 km³, Iceland's tallest volcano exceeded its own historic magnitude from 1362. Back then, most of the emitted ash was transported North, Northwest from the volcano and thus threatened the Icelandic population, flora and fauna. This time, however, North-Northwesterly winds carry large amounts of ash straight into Europe's airspace. From the Northern parts of Scotland to the Western tip of the Black sea, ash concentration levels are still far above 4000 μg/m³, the threshold declared as high ash contamination. Uncommonly dry weather makes it likely for the ash to remain in the atmosphere throughout the week.

EUROCONTROL’s spokesman continues “This time, we … [Continue reading]”

The mediators left the room during the group work to minimize the researchers’ influence on the discussions. In order to follow the build-up of ideas, separate minute takers captured the process of the discussions. A number of focus questions were prepared on a flip chart beforehand to provide the groups with some guidance during the discussions. Focus areas were printed out and distributed on the group tables to keep the diverse topics in the stakeholders’ view during the discussion. They were encouraged to add further areas that they considered important. The groups were asked to discuss how the scenario in question would affect the stakeholders and what obstacles (Figure 5.2, red Post-its) would be expected.

Following this, the stakeholders were directed to discuss possible solutions (Figure 5.2, yellow Post-its) to the expected obstacles. In the following plenum session, the groups moved together to one room. Both groups presented their results to all workshop participants and the floor was opened to further discussion.

In the last part of the workshop, the participants were asked to vote for what they considered the most important obstacles/solutions. For this exercise, 6 sticky dots were handed out to every institution present, with up to three dots to vote for the most important obstacle to manage and up to three dots for the most important solution (Figure 5.2). For the voting, the stakeholders were encouraged to interact with each other and discuss their reasoning before making their final choices.

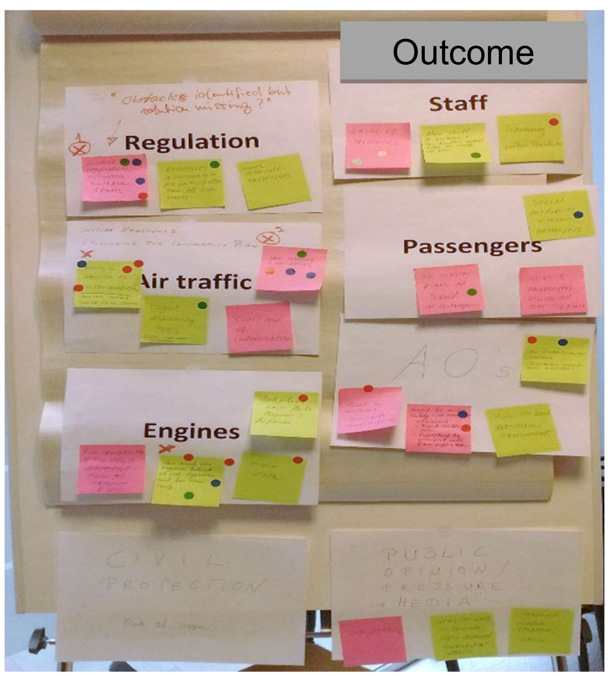


Figure 5.2 Stakeholder workshop: Outcome of scenario runs.

The workshop was concluded by thanking the participants for their engagement, a presentation summary of the tasks, an overview of the next steps within the project, and a feedback round with the stakeholders. They were encouraged to also provide written personal feedback.

During the course of the day the representative of Rolls-Royce offered to give a brief update presentation after the workshop about the company's undertakings with regards to volcanic ash. This was welcomed by the participants and followed after the formal closure of the workshop. The workshop concluded with a dinner to thank the participants and provide additional time for interaction.

5.5.3 Post-Workshop Processing

A grouped model approach was used to capture the workshop results. The visual arrangement of the input during the workshop followed the intended outline of the result presentation to facilitate the post-workshop processing. Obstacles in the general process, during the exploration of the extreme scenarios as well as possible solutions to these obstacles were grouped around the main focus areas. The recommendations derived from the workshop are discussed in further detail in Reichardt et al. (2018b) (see chapter 6).

Within a week after the workshop, the participants received the transcript of the meeting minutes and a two-page summary of the workshop including the results of the workshop, agenda and contact list of the attendees. They were asked to comment on the accuracy of the content and to provide suggestions for changes if needed.

5.6 Feedback

The stakeholder feedback was collected in two steps. A first feedback session was held at the end of the stakeholder workshop to capture the participants' impression of the workshop in detail. In a second round, feedback was collected through telephone interviews.

5.6.1 Feedback Round within the Workshop

The feedback round revealed that prior to the workshop, the majority of the participants had not realized the dimensions of potential volcanic eruptions, and the uncertainty of the impact of ash on jet engines was not fully known to all of them either. The workshop raised their collective awareness to these issues. One representative concluded, "After this workshop, it would be crazy to say we have done everything we can and are fully prepared. The next exercise will be a big one, for sure."

One of the main feedback issues concerned the novelty of the meeting, bringing this group together for the first time. As one participant said, "The workshop was a fantastic opportunity as this was the first time that experts from all parts of the process chain sat around one table and discussed and listened to each other." The effort spent to prepare and set up the workshop and create scenarios was appreciated. "When working in the [agency omitted], having only so many resources, you never have time to give a creative subject a full day, so this was very fruitful."

Another stakeholder highlighted the knowledge collection during the workshop: "Amazing to see your own contributions as part of the bigger picture, as a piece in a puzzle. This overview is very welcome. Through this approach, it is much easier to see the requests (from other stakeholders) vs. the potential solutions, and to try to move together toward a better response next time." The representative from ISAVIA suggested that the outcome of the workshop be presented at the next VOLCEX planning meeting. If other stakeholders at the planning meeting agree, one of the scenarios could be used for a future VOLCEX exercise.

5.6.2 Feedback 6 Months after the Workshop

Six months after the workshop, the participants were interviewed by telephone to capture feedback on their long-term impressions of the workshop and its effects. All stakeholders reiterated the uniqueness of the workshop in combining the whole chain of actors in the process, and echoed the feedback that was given directly after the workshop.

The scenario run and the initiated discussions had affected the stakeholders' view on the situation and their work after the workshop. "It definitely has affected the way I am thinking about these issues, also during the work on the EUR/NAT contingency plan." Another representative stated, "It made me think about re-suspended ash as a particular problem in Iceland. The discussion at the workshop showed a different perspective and I digested what I learned and acted on it in the process of updating guidance."

A majority of the participants had established a contact with institutions that they were not in touch with before. In one case, this initiated collaboration between stakeholders that had not worked together before. While not everyone has made use of the new contacts since the workshop, all stated that they now know better than before whom to talk to. One participant stated, "It was very useful to meet a representative from Rolls-Royce face-to-face. We were looking for detailed information concerning the engine tolerances beforehand but could not really get hold of any, so this was very useful."

All stakeholders were interested in the outcome of the research. The feedback showed support for further cooperation and interest in taking the outcome of the workshop further. Regarding ideas for further steps, one participant summarized it as follows: "It would now need smaller groups (e.g., ISAVIA–IMO) on the national as well as on the European level to discuss. Exercises that focus on testing a specific part of a long chain (e.g., IMO, ISAVIA, Icelandair) and further help to identify obstacles and improve them would be very valuable."

Another one voiced the use of a comprehensive flow chart to illustrate "which institution is doing what and how everyone is placed in the process and what they are triggering."

Overall, the stakeholders had a positive view on the potential implementation of the measures that were developed during the workshop. However, some interviewees who were present at the workshop indicated that they were not in a position to directly implement the changes. This is an important insight and should be taken into account when planning future workshops.

The research helped identify obstacles and build a platform for the stakeholders' interaction in the future. This is captured in a participant's comment summarizing the long-term effect of the workshop: “The long-term benefits might not be visible yet but will show eventually. The workshop will become useful when entering a new ash situation. It definitely goes into the experiences and helped to be mentally prepared.”

5.7 Conclusion

After E2010, efforts were undertaken to increase coordination between institutions (Reichardt et al., 2017a). In order to advance crisis preparedness for Icelandic volcanic eruptions, scenarios are needed that reach further in impact and intensity than E2010 to drive strategic emergency planning forward and help to mitigate future impacts of volcanic eruptions (Alexander, 2013).

This paper presents a multi-level approach to prepare and facilitate interaction between key stakeholders in aviation response to volcanic crises. The approach is based on solid individual preparation of the discussants followed by group discussions with the help of scenario narratives in a participatory stakeholder workshop.

The workshop set-up proved to be successful in enabling discussions and obtaining information. Its timeliness was illustrated by both the stakeholders’ positive response to the invitation as well as the participants’ feedback after the workshop. As the feedback showed, the meeting was appreciated as an opportunity to meet and discuss contingency issues beyond the day-to-day business. It raised awareness among the participants and enabled information flow between stakeholders. The main outcome of the workshop was threefold: First, the workshop helped to facilitate discussions between stakeholders and allowed them to exchange perceptions, interests and knowledge. Secondly, it raised the stakeholders’ awareness of the complexity of potential risk situations and the multitude of actors involved. Thirdly, it enhanced understanding of the risk management cycle and offered the potential to jointly identify potential gaps in the process.

The value of a stakeholder workshop goes beyond the collection of data. It can be important for practical reasons as well. Valuable insight may be gained through understanding why the participants chose to attend the workshop. The incentive may be to gain knowledge, contribute to improvements, or extend one’s networking. Making sure these incentives can be met will help ensure the participants’ attendance. In this case, the study group ensured opportunities for the participants to understand holistically the aviation sector’s response to volcanic ash, make their own institution’s role known, create new contacts, and enlarge their network.

A practical point is to rank participants in order of necessity for the workshop and to start with the most necessary participants when setting a date for the workshop to ensure their ability to attend. The confirmation of attendance from key stakeholders can serve as an incentive for other participants to attend.

It is important to consider the costs that participants face when attending the workshop. While institutions may be willing to contribute the hours spent on the workshop, reimbursing transportation and accommodation costs is important to guarantee representation at the workshop. The time spent at the workshop should be limited. Preliminary interviews and discussions, as well as questionnaires and necessary information handed to the participants before the workshop, increase the likelihood that the time can be used effectively at the workshop itself to obtain the required results.

The experience from this research provides practical insight on how to successfully implement participatory stakeholder workshops, at least in the context of risk management of natural hazards. The authors have since successfully shared the experience acquired with other researchers of natural hazard risk management (NORDRESS, 2016).

6 Volcanic Ash and Aviation: Recommendations to Improve Preparedness for Extreme Events

This chapter contains the peer-reviewed journal article:

Reichardt, U., G. F. Ulfarsson, and G. Pétursdóttir, 2018. Volcanic Ash and Aviation: Recommendations to Improve Preparedness for Extreme Events. *Transportation Research Part A: Policy and Practice*, Vol. 113, pp. 101–113.

6.1 Abstract

The eruption of the Eyjafjallajökull volcano in 2010 was an unprecedented event for European aviation and emphasized the need for advancements in the corresponding risk management of the stakeholders involved. This study researches progress since 2010, as significant regulatory changes have been introduced to improve European and North Atlantic aviation risk management with regards to volcanic ash. A participatory stakeholder workshop with scenario narratives was set up in which stakeholders discussed obstacles in the general management of aviation during volcanic ash eruptions as well as under extreme eruption scenarios. This paper presents recommendations developed from the workshop.

The research found that a better understanding is needed of the impacts that long-lasting ash episodes may have on aviation. Events of long duration require improved availability of staff, e.g., with staff exchange between related agencies. Furthermore, it is recommended that staff be trained to meet accelerated demands and restructured tasks during a crisis that may last for months. It is also suggested that more challenging response exercises be used to drive stakeholders out of their comfort zone.

The study provides recommendations on information exchange between the stakeholders. During an event, the large amounts of information received from scattered sources may be quite challenging. A single point of information for stakeholders could be set up to structure the information and reduce confusion. Communication products, such as maps, must be better aligned with end-user needs. Ensuring the comprehensibility of difficult features, such as the representation of uncertainty in ash distribution modelling and resultant data, requires discussion with end-users prior to an event.

The study stresses the need for further funding of research on the impact of ash on jet engines since lack of knowledge in this area limits the benefits of advances in ash forecasting. The application of the Safety Risk Assessment approach needs to be coordinated across nations. Strengthening society's resilience as a whole to such events, calls for a comprehensive long-term contingency plan, including alternative transportation if aircrafts are grounded.

Keywords: risk governance; volcanic ash; aviation; multi-sector partnerships, contingency plan

6.2 Introduction

During eruptions, volcanoes can emit a diverse range of material such as lava, tephra, and gas. The matter of greatest concern to aviation is volcanic ash. Its chemical and physical composition makes volcanic ash a highly abrasive material that can harm the surface of an aircraft as well as the jet engines (Casadevall, 1993). Volcanic ash consists of small, light particles that can travel several thousand kilometers from the source volcano and, depending on the initial height of the ash column produced by the volcano, can be found in all flight levels (Casadevall, 1994).

After the first aviation incidents with engine failure caused by volcanic ash, the International Civil Aviation Organization (ICAO) developed precautionary guidelines to mitigate exposure to the hazard. Aviation safety rules ensure the avoidance of airspace that is contaminated with volcanic ash concentrations that threaten loss of engine power (ICAO, 2012a).

While the precautionary approach ensures aviation safety, avoidance of airspace can cause immense economic damage through rerouting or cancellation of flights if rerouting is not an option. The ash from a volcanic eruption in Iceland has the potential to interfere with heavily used intercontinental flight corridors for goods and passengers, impacting economies worldwide. A case in point is the Eyjafjallajökull eruption in April 2010 (hereafter termed E2010). More than 100,000 flights were cancelled, more than 10 million passengers were affected, and there was an estimated 5 billion USD in global economic damage (Bye, 2011). E2010 revealed the vulnerability of global interconnectedness through air traffic as described by Birtchnell and Büscher (2011).

E2010 further highlighted the need for coordination in the air transportation sector in Europe. With no preexisting central response coordination structure in place, EUROCONTROL, the European Organisation for the Safety of Air Navigation, took a coordinating role in the crisis (Bolić and Sivčev, 2011). It facilitated discussions to replace the precautionary approach of general airspace closure and to introduce a more refined risk approach.

In agreement with jet engine experts, the lower threshold for ash concentration was raised and new ranges of ash concentration levels were determined to divide airspace into low, medium and high levels of ash contamination. This allowed airspace to be reopened in areas contaminated with low levels of ash concentration and partly reopened in medium level ash concentrations (Bolić and Sivčev, 2011).

Subsequently, the European Aviation Crisis Coordination Cell (EACCC), with representatives from the European aviation network, was created under EUROCONTROL to formalize a coordination body during crisis situations.

E2010 further prompted a paradigm shift in the management of volcanic ash and aviation in Europe. In the aftermath of E2010, a regulatory change was initiated to shift the decision-making from state aviation authorities to airline operators. Prior to E2010, European states would close airspace that was forecasted to be contaminated with volcanic ash (Bolić and Sivčev, 2011). Under the new procedure, European airspace would, with exceptions, remain open. The decision on whether to fly would be made by the aircraft operators, conditional on a Safety Risk Assessment (SRA) of the airline having been accepted (ICAO, 2012a).

The SRA describes the procedures which an aircraft operator follows when operating in airspace forecasted or known to be contaminated with volcanic ash. The SRA has to be completed and evaluated by the operator's State Civil Aviation Authority prior to the operation (ICAO, 2012a).

The hazard posed by volcanic eruptions in Iceland has been well documented (Guðmundsson et al., 2008; Thordarsson and Höskuldsson, 2008), and research indicates that it may be increasing due to climate change (Compton et al., 2015) with an event like E2010 even possible up to every 7 years (Schmidt et al., 2013) in the future. Since such an event cannot be prevented from happening, cooperation and preparation are key in mitigating impacts.

The management of volcanic ash risk to aviation is complex and requires the efforts of a number of stakeholders from different sectors to cooperate, referred to here as a multi-sector partnership. According to their position in the process, the stakeholders can be grouped into information providers, crisis coordination and network management, air navigation service providers, global/international and national regulators, and aircraft operators. Table 6.1 provides an overview of the sectors, roles, and associated institutions that were identified by the study.

Table 6.1 Aviation stakeholders – Overview of Sectors, Roles, and Example of Institutions in the Study.

Sector	Role in volcanic ash management	Institutions
Global air regulator	Development of global standards and recommended practices	ICAO (International Civil Aviation Organization)
International regulator	Limit-setting for shared air transportation zones	EU Directorate General for Mobility and Transport
International facilitator	Representative of airline industry, formulates industry policy on critical aviation issues	IATA (International Air Transport Association)
National regulator	Responsible for state's Volcanic Ash Contingency Plan, approval of Safety Risk Assessment procedures, airspace closure	ICETRA (Icelandic Transport Authority)
National regulator	Supervision of ISAVIA and ICETRA, resource allocation to fund extra costs, policies regarding risk management (e.g., transportation plans)	IRR (Icelandic Ministry of the Interior)
Crisis coordination and network management	Network management and crisis-coordination response	EUROCONTROL (European Organisation for the Safety of Air Navigation)
Information provider	Issues weather observations and forecasting. Monitoring of volcanic eruption, detection of seismic activity, ash measurements, issues warnings	IMO (Icelandic Meteorological Office)
Information provider	Forecasts expected location of the volcanic ash cloud, issued as VAG and VAA	London VAAC (Volcanic Ash Advisory Centre)
Information provider	Engine manufacturer, guidance on engines for airlines and information for national governments, European Aviation Safety Agency	Rolls-Royce
Air navigation service provider	Management of airport operations and air traffic in control area	ISAVIA (Icelandic Air Traffic Management)
Aircraft operators	Air transportation and service providers to passengers and cargo	Icelandair (Icelandic aircraft operator)

(*Based on: Reichardt et al., 2015b*)

Global and national regulators provide the legal framework for aircraft operations. During a volcanic eruption, the information providers collect information on the eruption and create forecast maps with predicted ash density. These maps facilitate the decision-making process of the aircraft operators on whether to proceed, divert or cancel flights (UK Met Office, 2017).

Air navigation service providers coordinate the air traffic (ICAO, 2016). To ensure a smooth transition of flight plans, the network manager facilitates on a European level and acts as crisis coordinator if needed (EUROCONTROL, 2017b).

While both proactive and reactive stakeholder approaches are essential components of disaster risk management, research emphasis should be placed on proactive engagement to mitigate effects (Mojtahedi and Oo, 2017). This study identified proactive measures in the management of volcanic ash events in Europe. The study was conducted within the ENHANCE project on enhancing Risk Management Partnerships for Catastrophic Natural Disasters in Europe (Ulfarsson et al., 2013, 2014; Reichardt et al. 2015a, 2015b, 2016a, 2016b).

Stakeholders were invited to a participatory workshop to work with extreme but realistic volcanic eruption scenarios in July 2015 to discuss and determine obstacles in the general management of aviation during an eruption, as well as under extreme-case scenario narratives. The purpose was to provide policy recommendations for improved response in the future. The term 'extreme-case scenarios' refers to above average spatio-temporal dimensions of ash distribution that go beyond the typical scenarios that have been used for ash exercises in the aviation sector. It has been described in further detail in Reichardt et al. (2018a).

The following section briefly introduces the extreme volcanic eruption scenarios and the setup of the participatory workshop, which was used to obtain the data. The subsequent section provides an overview of the themes discussed in the workshop. It leads to improvement measures that are suggested in order to strengthen resilience in a future volcanic ash event.

6.3 Methods

The research developed two extreme but realistic volcanic eruption scenarios using expert judgement and historic data. The stakeholder group was identified through literature, policy review, and interviews with local stakeholders. In preparation for the workshop, the researchers conducted individual face-to-face expert interviews with the stakeholders introduced above. The personal introduction through the interviews helped to establish a trustful bond between the researchers and the individual stakeholders and eased further communication and collaboration.

The interviews were set up as face-to-face guideline interviews at the respective institutions and lasted between 70 minutes and 3 hours. They facilitated learning about the stakeholders' experience during E2010, their decision-making processes at the time, and their individual progress since. The interviews offered an understanding of the individual function of each stakeholder and provided necessary background information to the dynamics within the group. This allowed a focus on the stakeholders as a group on the day of the workshop.

Both eruption scenarios are based on previous eruptions and were chosen due to the significance they held in terms of impact. The first one describes a volcanic eruption of low and medium ash concentration (up to 4000 $\mu g/m^3$) over 3–4 months (Eyjafjallajökull times four scenario). It enabled discussion of the obstacles that stakeholders face during a long period of continuous risk assessment. The second scenario (Öræfajökull volcano) consists of a volcanic eruption with a large ash emission and high ash densities (>4000 $\mu g/m^3$) continuing over the course of 2–3 weeks. This scenario tests the reactions of the stakeholders to a large-magnitude and short-duration interruption of air traffic.

The study used modelled ash distributions and developed newspaper article narratives describing the course of the scenarios. They were handed to the stakeholders in the participatory stakeholder workshop to facilitate their discussion and the joint development of improvement measures.

6.3.1 Extreme-Case Scenario Development

To simulate the ash dispersion for both scenarios, the study worked with the NAME model. NAME is the atmospheric pollution dispersion model used by VAAC London to produce volcanic ash dispersion graphics for Icelandic volcanoes (UK Met Office, 2014b). Both scenarios are modelled under the meteorological conditions that were prevalent during the Eyjafjallajökull eruption during April 15–19, 2010 (Petersen, 2010). The scenarios include the assumption of a similar meteorological pattern for the duration of the event.

The ash cloud's display as a discrete area, separate from Iceland, is due to the modelling input (e.g., Figure 1 and Figure 2). The duration of the modelled eruption was set to 24 hours, but repeated bouts of ash eruption phases are assumed during the overall event. Hence the ash density figures are based on a 24-hour eruption only. Once the pressure of the eruption declines, the plume height changes and the model needs to be adjusted (discussion with the IMO, 2015). The maps display different density concentrations of ash, low (blue, 200–2000 $\mu g/m^3$), medium (grey, 2000–4000 $\mu g/m^3$) and high (red, above 4000 $\mu g/m^3$) over a period of up to 5 days into the eruption. The maps of ash densities are issued at three different flight levels. A flight level (FL) describes the measure of altitude in hundreds of feet. FL 200 denotes 20,000 feet.

Eyjafjallajökull x4 Scenario

To facilitate a discussion on how processes have improved since 2010, the first scenario is based on E2010. The scenario presents a set of recurring eruptions with volumes of around 1 km^3, similar to the ones in April 2010 (Gudmundsson et al., 2012). While the eruption source and volumes are similar to E2010, the scenario is four times longer in duration. This choice is made to discuss actions during a long lasting event, spanning the course of several months. This duration was selected based on a discussion with volcanologists at the Earth Science Institute at the University of Iceland about possible durations for this specific volcanic system (discussion in summer 2014).

Twenty-four hours into each of the scenario eruptions, high ash densities are forecasted to have reached the UK, including the London area, as well as parts of Norway, Sweden and Denmark. Over the course of the following days, the ash-contaminated air masses travel further south, spanning from Western to Eastern Europe.

The scenario would mostly impact air traffic at low altitudes, affecting take-offs and landings. Figure 6.1 depicts a sample of the scenario's ash density 24 hours, 48 hours, and 72 hours into the eruption at the three different FLs. Low, medium, and high ash densities are forecasted up to FL 350, while there is no ash contamination forecasted at the next higher level. Whereas high ash concentrations slowly decrease, a broad band of air with low ash density is forecasted 5 days into the eruption up to FL 200.

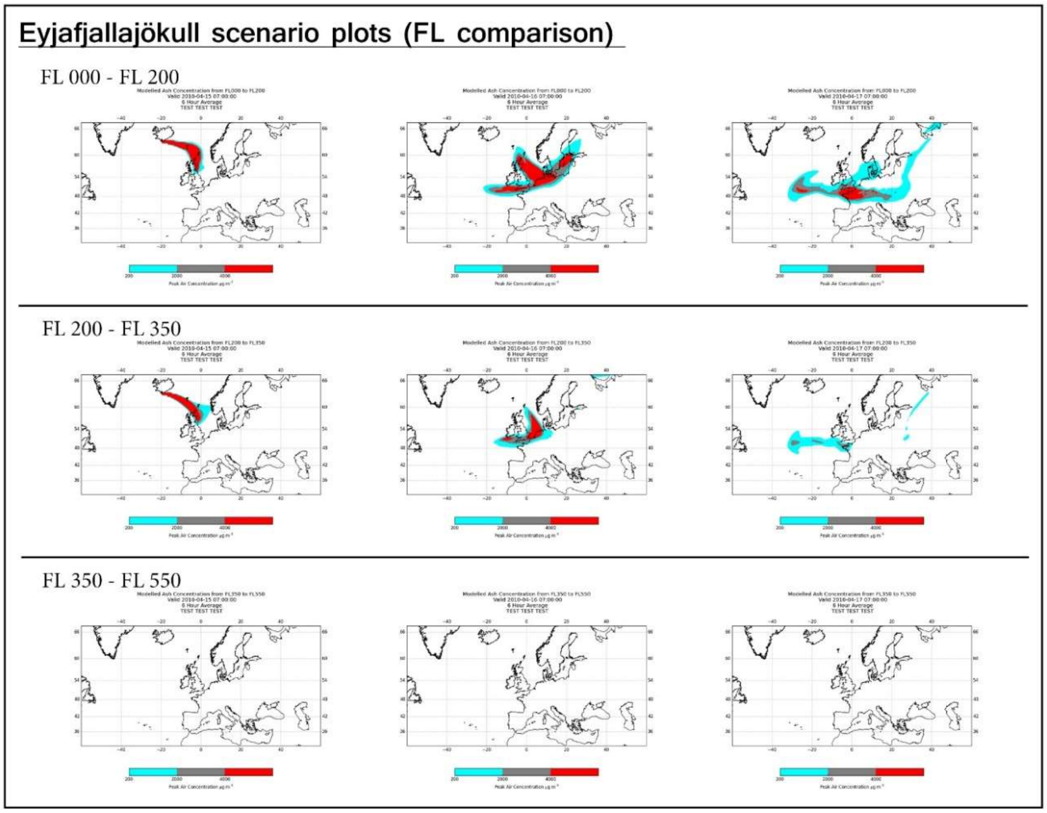


Figure 6.1 Eyjafjallajökull 4x scenario. Example of modelled ash distribution for one of the eruptions in the scenario, at 24 h, 48 h, and 72 h into the eruption. A broad band of air with low ash density between 200–2000 µg/m^3 is forecasted up to FL 200.

Öræfajökull Scenario

The second scenario is based on the Öræfajökull volcano's eruption in 1362. It is recorded as the largest eruption in Iceland after the island's settlement with an eruption volume of 10 km^3 (Newhall and Self, 1982). The scenario contains a volcanic eruption with a large ash emission but in a rather short period of time to test the response and management of the stakeholders to a large-scale severe interruption of air traffic (Figure 6.2).

Within 24 hours after the start of the scenario's eruption, high ash densities are forecasted to have reached Northern European countries, including the UK, Norway, Sweden, and Denmark. In the consecutive days, a large broad band is forecasted over Europe reaching far west towards North America and far east including parts of Russia. High ash densities of more than 4000 µg/m^3 are predominant throughout the forecast period. This scenario is likely to impact air traffic in all flight altitudes, as depicted in Figure 6.2. The forecast shows large parts of the European airspace contaminated with high ash densities, including the cities with the four busiest airports in Europe in terms of both passengers and freight revenue: London, Paris, Frankfurt, and Amsterdam (Port Authority, 2014). Assuming an eruption over several days, the impact may last for 2–3 weeks.

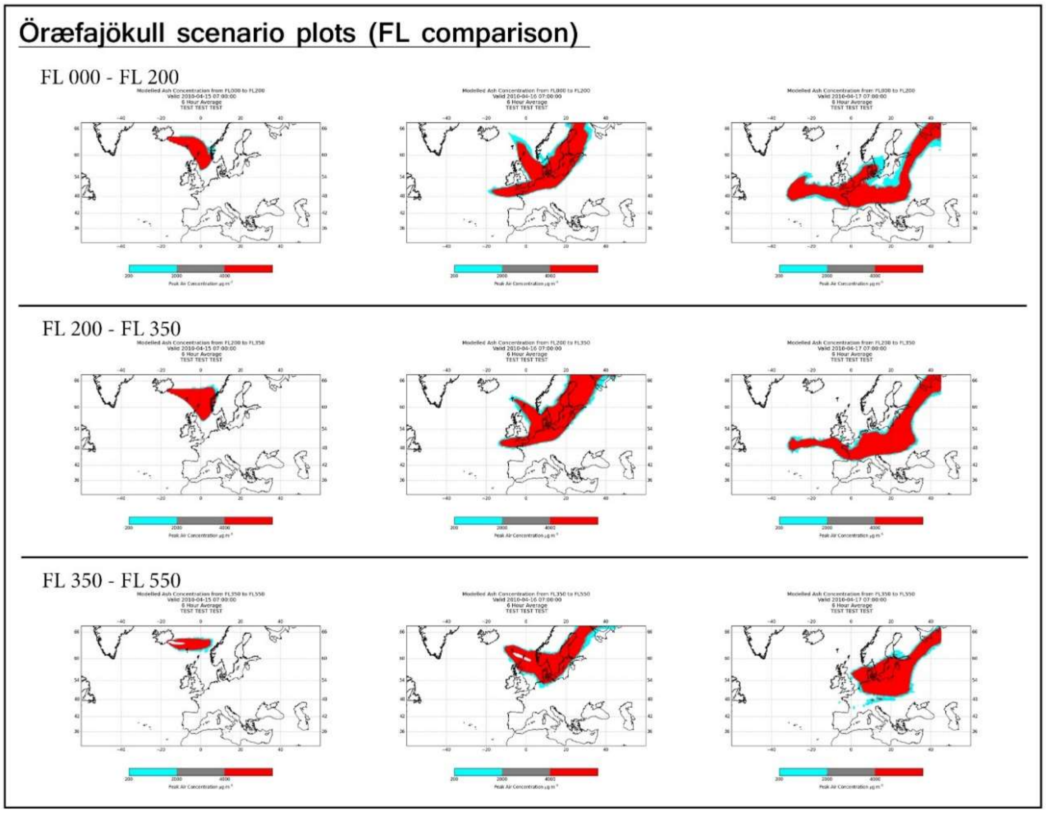


Figure 6.2 Öræfajökull scenario. Example of modelled ash distribution for one of the eruptions in the scenario, at 24 h, 48 h, and 72 h into the eruption. High ash densities of more than 4000 µg/m^3 are predominant throughout the entire forecast period and exist at all flight levels.

6.3.2 Stakeholder Workshop

The workshop was organized by the research group from the University of Iceland and was attended by representatives from the European Organisation for the Safety of Air Navigation (EUROCONTROL), the International Air Transport Association (IATA), Icelandair, the Icelandic Transport Authority (ICETRA, the Icelandic Civil Aviation Authority), ISAVIA (the Icelandic air navigation service provider and airport management corporation), the Icelandic Meteorological Office (IMO), the Icelandic Ministry of the Interior (IRR), and Rolls-Royce.

The workshop served as a platform to discuss the management processes in the aviation industry in the case of an Icelandic volcanic eruption with ash emission into the North Atlantic and European airspaces. The workshop facilitated communication among the stakeholders to discuss obstacles in the procedures to handle volcanic ash events. It helped to identify measures to improve the response and increase resilience to these types of events. The workshop design was inspired by the scenario workshop tool-kit developed under the EC project TRAMS: Training and Mentoring of Science Shops (Gnaiger and Schroffenberger, 2008).

The one-day workshop contained research and stakeholder presentations and plenum discussions covering the overall process. To facilitate a stronger individual discussion of the scenario run, the stakeholders were divided into smaller groups.

The scenarios were presented as narratives in fictitious newspaper articles with maps to assist the group in imagining the events and discussing real-life implications. A number of focus points, aspects and questions were developed by the researchers in advance as orientation for discussion in all the sessions and were on display for orientation during the workshop. Furthermore, an intermittent change of rooms for different parts of the workshop throughout the day helped to open up communication dynamics through changing positions and discussion partners. For an extensive description of the workshop set-up see Reichardt et al. (2015b).

6.4 Stakeholder Workshop Outcomes

The outcomes of the workshop were threefold. First, joint discussions at the beginning of the workshop helped to identify obstacles in the general process following air space interruptions due to volcanic ash. Second, the stakeholders identified challenges in the handling of events similar to the extreme-case scenarios. Third, a final joint debate discussed potential solutions to mitigate the issues identified. All obstacles and solutions were ranked by the participants at the end of the workshop.

6.4.1 General Obstacles to Improved Risk Management

Obstacles in the general processes mostly revolve around work capacity limitations, as well as difficulties in applying the new air traffic regulations in terms of the SRAs, the accuracy of parameter input, and modelling.

Concerns were raised by the aircraft operators on the usability of the VAAC products. As an airline representative stated, the airline “might not agree with the forecast of the ash distribution” when comparing it to the aircraft operator’s in-house modelling. Furthermore, the temporal resolution of the VAAC forecast has been questioned for being too low for the needs of aircraft operators.

Every airline has to seek the approval of the national Civil Aviation Authority for its SRA. It was brought up in the discussion that conditions for approval are not transparent and can differ widely between different sovereignties. In the heat of a crisis, the lack of SRA coordination between different states increases the risk of time-consuming disagreements and demands for regulatory clarification. Coordination across Europe calls for an implementation tool from the EU, as this task is “impossible without this legal instrument,” according to EURCONTROL (statement by a EUROCONTROL representative during the workshop, 2015).

The concerns mentioned in the first part of the workshop were discussed in more detail in two scenario groups when confronted with accelerated demands.

6.4.2 Eyjafjallajökull 4x Scenario Run

According to the stakeholder group in the workshop, the Eyjafjallajökull 4x scenario would lead to the grounding of up to 50% of the aircraft fleet in Europe within 3–4 days after the eruption onset, with associated impact on the global economy. Flight capacity may remain limited due to new eruptive phases, even months into the event. Airspace closure in states that have not yet fully approved the SRA approach means increased load on other territories, like the Icelandic airspace. That could lead to air traffic reaching the capacity limits of the air traffic controllers, which might cause a bottleneck situation where air traffic would need to be phased through the remaining open airspace, causing further delays. While around 80% of flights are planned by computers, more human modification is needed in anomalous situations. More staff would be needed by the stakeholders and across the aviation industry to cover added labor demands.

The discussion in the group facing a new and much longer-lasting Eyjafjallajökull eruption revolved around the threshold of discernible ash around 2000 $\mu g/m^3$, which defines the upper safety limit for flying (ICAO, 2014b). However, discernible ash is difficult to define and the question is passed on from the forecasters to surveillance aircrafts and jet engine manufacturers.

The models used to describe the ash dispersion (e.g., NAME or HYSPLIT) have error margins due to the simplified assumption that the ash is evenly distributed, and there was a vivid discussion within the stakeholder community about the ash density charts and their benefits (WMO, 2015). Satellite images are increasingly used to adjust the model outputs and give further information about the thickness of top and bottom heights of contamination levels, but they can only be used if available for the airspace in question.

Research cooperation was established between airlines and private businesses to test on-board measuring devices like AVOID (Airbus, 2013) or ZEUS (British Airways, 2014) to avoid ash-contaminated airspace. Also, research on the effects of ash on jet engines has advanced after E2010 (Reichardt et al., 2017a). In the aftermath of E2010, the International Volcanic Ash Task Force was formed and developed recommendations about the testing of the effects of ash on jet engines (ICAO, 2012b). This was taken into account by the engine testing conducted by the U.S. National Aeronautics and Space Administration (NASA, 2012) in 2015.

However, information is still lacking on the long-term effects of ash on jet engines, even in low concentrations over a given time. In an extended scenario like the one discussed, such data would accumulate fast, allowing jet engine manufacturers to give more precise guidance on engine tolerance a month or two into the situation.

6.4.3 Öræfajökull Scenario Run

The discussion in the group dealing with the scenario of an Öræfajökull eruption commenced with the immense impact the eruption would have on the local population. According to the representative of the Icelandic Ministry of the Interior, approximately 40,000 inhabitants would need to be evacuated. Sea routes might be cut off due to a thick layer of pumice (a porous and floating volcanic rock) which would build up on the ocean along the south shore of Iceland. This would heavily impact the Icelandic economy as it would be likely to hinder fishing vessels as well as export of fish and food imports, at least with Europe.

According to the stakeholders, the event would greatly impact the local population, institutions, and infrastructure and call for a large-scale operation by the Icelandic stakeholders. International aviation concerns would rank as secondary problems in the short term. Although national crisis management is not a part of this project, it is important to consider the constraints that the Icelandic stakeholders like the IMO, ISAVIA, ICETRA, and the Ministry of the Interior would potentially face when developing international contingency processes and alternative plans.

While Iceland's Keflavík International Airport might remain open, the immediate airspace around the volcano would be closed. Though airspace in general would remain open under the new laws, air territory over the North Atlantic and major parts of Europe would be contaminated with ash in the following days. Regarding the susceptibility of jet engines to volcanic ash, the group emphasizes the specific geological compositions of this scenario, which can lead to about 30% lower melting temperatures of the emitted ash from Öræfajökull compared to the ash from the Eyjafjallajökull eruption. Only a few airlines have issued SRAs for flying in high contamination, but the ash concentrations of this scenario might force all aircraft operators in Europe to ground their fleets in the short term.

Large impacts would be expected in terms of transportation of passengers and goods, dwarfing the impacts of E2010. The coordination of stranded passengers is viewed as especially challenging, as so far no overarching contingency plan for passenger management exists for an event of this size.

Differences between the European states regarding the implementation of the SRA approach can impact coordination. While the SRA approach has been recognized by all European countries, the same does not apply to all other countries. If an eruption were to occur now, a few countries, including Germany, would not allow flight operations in areas of high ash concentrations and would close the respective airspace (EUROCONTROL, 2018).

6.4.4 Potential Mitigating Solutions

The representative from EUROCONTROL initiated the discussion on the issue of diverse regulations and suggested regular exercises and more active participation than have been seen to date. The representative suggested more challenging scenarios to attract stakeholders' attention and keep them on guard. The same accounts for preparation and training of staff for extreme situations. Clear, written procedures would shorten the staff's response time.

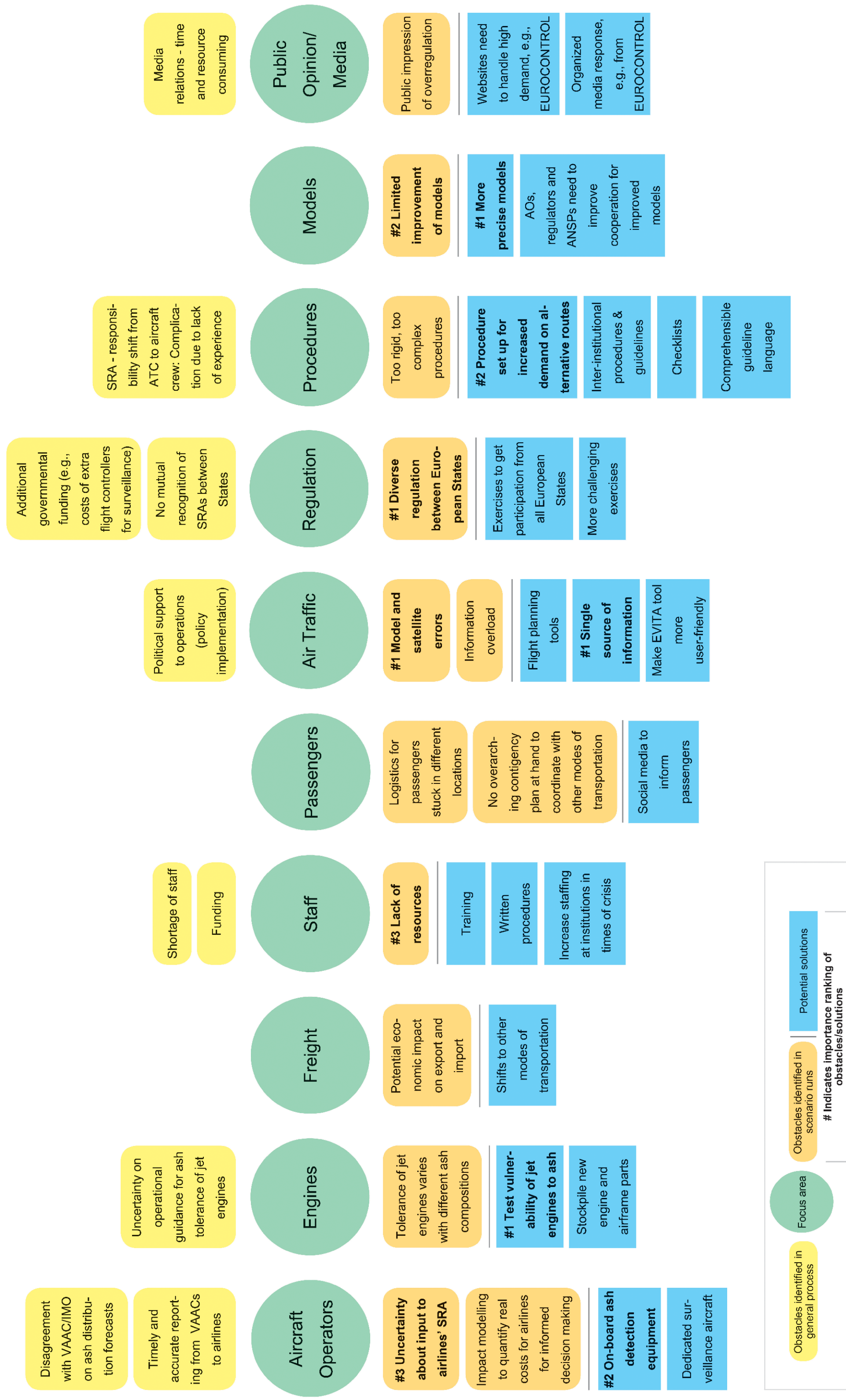
A request for more precise models and applications was voiced. At the moment, the VAAC forecast does not seem to fully meet the aircraft operators' needs as they have been looking for better forecasts from other providers. On-board ash detection tools were mentioned as a way to support pilots' decision-making.

A single trustworthy source of information for the stakeholders was suggested. Plans to extend the visualization tool by EUROCONTROL, EVITA, to this kind of information platform, were mentioned. However, the tool is currently being developed to suffice for flight planning and was not user friendly enough to be used in a crisis at the time of writing. EVITA’s development is costly, but other applications are being developed in parallel; a synergy of efforts and resources would be valuable in this area. EUROCONTROL stresses a closer cooperation of the stakeholders (VAAC, regulators, controllers, etc.) on modelling and flight planning tools.

Given effective media communication about the extent of the eruption, the stakeholders would expect understanding from the public, but they emphasize the need for a clear platform to inform both stakeholders and the public. Such a platform must be strong and efficient enough to work under high pressure and demand. Furthermore, a system of two-way communication, as provided by social media, is stressed to allow passengers to make their voices heard.

Jet engine tests are also emphasized in this group, as risk management rests on knowing how the engines respond to ash. All further efforts of modelling will suffer if the question of jet engine susceptibility remains unclear.

Figure 6.3 presents the outcomes of the stakeholder workshop arranged around the focus areas of concern (green circles). Obstacles identified by the stakeholders in both the general risk management process and when facing more severe ash eruptions are shown as yellow and orange boxes respectively. The blue boxes display identified solutions to the obstacles. The stakeholders were asked to prioritize the obstacles and solutions by ranking them. The highlighted orange and blue boxes display the items identified as most important. The stakeholders added “public opinion” to the focus areas represented in the process. Civil protection was listed but not discussed in detail because the local direct response mechanisms are outside the scope of the study.



(Based on: Reichardt et al., 2015b)

Figure 6.3 Stakeholder workshop outcomes: Obstacles and solutions in the process.

6.5 Improvement Measures and Policy Recommendations

The improvement of the multi-sector partnership and its preparation for air traffic interruptions, such as the scenarios discussed in the workshop, is crucial. The mishandling of the response to a volcanic eruption threatens entire economies (Sammonds et al., 2010), can send companies to bankruptcy (Alexander, 2013), and can seriously affect lives, for example, in the case of medical emergencies such as delays in air transportation of organs (CBS, 2010). One estimate of the possible future frequency of the occurrence of an event similar to E2010 in Iceland is on average once every 7 years given climate change and related deglaciation (Schmidt et al., 2013). This puts additional economic value on the profound importance of the development of crisis management infrastructure and the successful work of the multi-sector partnership. To create noteworthy mitigation of the financial and social impacts of a more intense volcanic eruption, enhanced communication and cooperation are key (Alexander, 2013).

This section presents the improvement measures and policy recommendations that emerged and were developed from the stakeholder discussions in the workshop. The study identified improvement measures along the lines of:

- Contingency planning,
- Improved exercises,
- Staff funding,
- Communication,
- Research funding, and
- Regulatory alignment.

6.5.1 Long-Term Contingency Planning

Currently, there are two major regular eruption exercises in Europe to exercise procedures in response to a volcanic ash eruption in Iceland. The international volcanic ash exercise VOLCEX is organized by ICAO and held every 1–2 years with stakeholders from across the aviation sector. A simulated eruption of a European volcano is used to exercise the procedures up to two days into the event. The exercise is attended by stakeholders from across the aviation sector. The bi-national VOLCICE is a monthly one-day exercise to practice emergency response procedures between the Icelandic stakeholders ISAVIA and IMO and the London VAAC to a simulated volcanic eruption in Iceland or Jan Mayen (Witham et al., 2015).

The scope of both exercises is the immediate response to an eruption. They do not take longer durations into account. This was discussed in the workshop and partly attributed to the uniqueness of events. Eventually each scenario would take on its own characteristics, calling for a tailor-made response. However, time for reorganization is costly, as stated by an expert in aviation traffic management who was involved in the creation of the EACCC framework during E2010. He estimated the financial loss due to the delay of action caused by the non-existence of the framework to be around 800 million euros (interview with representatives from EUROCONTROL, February 2015).

A framework can be established beforehand, flexible enough to be adjusted to the situation and would save time and financial resources in a crisis situation. In the workshop scenario run, the stakeholders debated the potential impact of longer-lasting eruptions. The discussion emphasized a lack of strategic emergency planning to prepare for an event that would cause disruptions to air traffic weeks after the initial eruption.

Transport network resilience requires flexibility (Caschili et al., 2015). When airplanes are grounded for a prolonged time, alternative modes of transportation are needed to transport passengers and goods. This requires additional resources for transportation on land and waterways. As the reorganization during E2010 showed, timely preparation and coordination for such an event can mitigate financial damage considerably.

To facilitate comprehensive coordination between modes of transportation, knowledge must be shared across transportation sectors (rail, road, maritime) about the potential effect that ash eruption events can have on air traffic. An ash scenario exercise, similar to VOLCEX but including all modes of transportation could advance contingency planning further.

First, the quantitative impact on aviation in terms of passengers and goods that need redirection should be estimated. This would allow quantification of required additional resources. It would also enable stakeholders to identify and prepare for interdependencies across other modes of transportation and potential obstacles during volcanic ash events.

A superordinate coordination body similar to the EACCC could help create an information overview and moderate between the networks for information to be carried further within each network. It might be a task for European, and potentially global, regulators to manage due to the interconnectedness of mobility and business connections.

Rail, road and maritime network operators are of course complex groups of stakeholders, which makes coordination within the respective network a challenge in its own right. Aircraft operators and their clients, too, are a conglomerate of stakeholders with different needs and flexibilities. The availability of information is crucial for connecting clients to services and coordinating alternative transportation plans in a timely manner. Information platforms need to be set up and linked so resources can be used efficiently. The funding of such a coordination structure is a challenge that needs to be addressed.

The coordination and planning of alternative transportation solutions will become a necessity, should aircrafts be grounded for an extended period of time. In order to create an environment for a smooth transition and aligned business continuity plans, it is necessary to have an overall awareness of the threat and understanding of the volumes that would need shifting, while every event will pan out in a unique way.

6.5.2 Improved Exercises

The multi-sector partnership recognizes the importance of emergency training to test its processes. VOLCEX are established exercises that invite stakeholders to test their procedures. The VOLCEX program is commonly planned months in advance for stakeholders to agree on the scenario that will be tested and to integrate it in the participants' day-to-day schedule. The pitfall of this set-up was debated in the workshop and summarized by a participant: "People prepare for the disaster that already happened. The exercises make a lot of assumptions that aren't real-life situations and give a false feeling of safety."

The false feeling of safety is possibly manifested in the decreased interest airlines have in participating in the exercise. Shortly after the eruption in 2010, 70 airlines participated in the VOLCEX exercise in 2011. Around 40 airlines were involved in the previous exercise in 2016 (EUROCONTROL, 2016). For the multi-sector partnership to be successful, as many stakeholders as possible should participate in the exercise and use the platform simultaneously to exchange experience, knowledge, views, and opinions.

To increase interest among potential participants and create additional learning value, the exercises should be novel and challenging and drive the stakeholders out of their comfort zones. Flaws in the emergency response of the stakeholders are more likely to be identified if the pressure of real-time situations is recreated in the exercise. Therefore, such exercises should contain elements of surprise and last beyond the onset of a volcanic eruption, as Reichardt et al. (2018a) suggest. Exercise leaders can take inspiration from historic eruption events older than 50 years to design scenarios that go beyond the shared memory of the most recent eruptions and match historic events with current air traffic volume. In addition to two-day exercises, procedure testing beyond the onset of an eruption would require an exercise lasting several days. Since this would be demanding in terms of both staff availability and financial resources, such an exercise could be realized less frequently, e.g., every 10 years (Reichardt et al., 2018a).

6.5.3 Staff Funding

Most stakeholders at the workshop agreed that lack of staff would prevent the multi-sector partnership from working successfully. Below, two examples from stakeholders have been chosen to illustrate the potential for improvement to staff capacity during a crisis and in the long term.

The information providers raised particular concern about work overload that affects their services. For the IMO, the workload of staff during the recent and long-lasting Holuhraun eruption in Iceland in 2014–15 revealed the need for a backup plan for alternating working schedules. Beside core duties, media coverage also increases in crisis times. Staff is required to cover communication with journalists and other media, including social media. Solutions to this problem would involve staff training in preparation for accelerated demands and restructured tasks during a crisis, which indeed is recommended for the whole multi-sector partnership.

Another option might be staff exchange, either within or between institutions, similar to volunteering programs that are activated in times of emergency. Specialized workers from one organization could be trained and encouraged to take over and share shifts at another organization. Rosters could be set up beforehand and participation of the “exchange staff” in exercises would ensure that they are up-to-date. In the case of the IMO, this could, e.g., be established with the Earth Science Institute of the University of Iceland, since the institutions have already established a history of cooperation and are in close physical proximity. This measure could ensure the service quality during prolonged alert times. It would, however, require additional resources for training and an agreement for compensation, and it would only be applicable to a certain range of tasks that do not require in-depth expert knowledge specific to the institution.

Another aspect of staff funding concerns the connection between operational work and research. The staff at the UK Met Office that runs the volcanic ash forecasting during exercises and eruptions work on day-to-day operations within the meteorological team under normal conditions. To better accommodate user needs, it would be beneficial if some VAAC staff could work full time on volcanic ash–related research and tasks to improve the service in times of crisis. This would also facilitate the cooperation between scientific institutions and the various VAACs to include more background science and research into operations.

6.5.4 Communication

Single Point of Information

While information is important in times of crisis, large amounts and scattered sources of information can cause confusion and hinder efficient risk management. The multi-sector partnership would benefit from a designated single point of information during a crisis. Managing the network, EUROCONTROL suggested the establishment of a website platform as an acknowledged single point of information, coordinated by the EACCC during a crisis. The use and content of the website can be discussed, tested, and evaluated during VOLCEX planning exercises, and improved in connection with the EVITA tool (EUROCONTROL, 2015). It is to be discussed whether this single point of information should also serve for public information, similar to the publicly accessible part of the Network Operations Portal managed by EUROCONTROL for operational communication.

Aligning Products with End-User Needs

In this study, Icelandair served as a stakeholder representative for the aircraft operator sector. As an aircraft operator with longstanding experience in volcanic threats, Icelandair has in-house experts for producing volcanic ash forecasts. The involvement and recognition of experts in reacting to the transboundary threat of an Icelandic volcanic eruption appears to be a crucial point in smooth cooperation between organizations (Reichardt, 2011).

The missing direct communication with VAAC London may be reflected in the Icelandic aircraft operators' skepticism of the accuracy of forecasts provided by VAAC London as well as the stated divergence between needs and supply. A similar problem is reflected in the flight level categorization of the ash distribution forecasts, which some air traffic controllers would like to see adapted to their needs (interview with ISAVIA, October 21, 2015). Presently, communication between aircraft operators and VAAC London takes place with IATA as a mediator. While it is helpful to interact with one single point of contact in general, a platform where the information provider and the end-user can interact directly helps to create trust and a common effort to align the product to users' needs.

The call for greater awareness of the public as a stakeholder was strongly voiced during the stakeholder workshop, e.g., aircraft operators giving more detailed and expansive information to passengers. Social media strategies should be improved. The channel for communication and the depth of needed information should, however, be chosen carefully because overly extensive warnings can be an economic blunder, as shown by previous examples. For instance, in 2014, a warning issued about an eruption of the Bárðarbunga volcano caused flight cancellations and led to a decrease of new holiday bookings in Iceland (Juskis, 2014), but the following so-called Holuhraun eruption had little impact on aviation.

Input to Aircraft Operators' Safety Risk Assessment

The process of SRA by aircraft operators in the new regulatory framework appears to be mostly disconnected from the institutions that provide the information on which the SRAs are based. While the significance of the ash concentration charts produced by VAAC London has been debated amongst the information providers and other stakeholders, the charts cannot be easily replaced as they form the basis for the airlines' SRA. Direct and transparent communication as well as the inclusion of both the information providers and the aircraft operators is advised to combine efforts to improve the process.

Uncertainties

A further communication issue concerns uncertainties with regards to the susceptibility of the jet engines to particular types of volcanic ash, the input parameters for the ash modelling, and forecasts. It was discussed during the workshop whether or not to include a level of confidence of forecasts. Although it can be problematic to put a confidence rating to practical use, especially if it indicates considerable uncertainty, transparent communication of detailed information on the uncertainty of data enables airlines to perform informed decision-making. As the stakeholder group varies in professional background and sector experience, caution is required regarding how to frame and communicate uncertainties because this can impact decision-making (Doyle et al., 2014). The uncertainty display must be introduced with sufficient information to the users to avoid confusion and prolonged discussions during a crisis situation.

6.5.5 Research Funding

Various research projects have been initiated to determine appropriate input parameters and to set up models to improve forecasts for volcanic ash dispersion (Bonadonna et al., 2014). This research and associated multidisciplinary collaborations need to be pursued to refine existing models closer to real-life conditions (FutureVolc, 2015) and meet the needs of aircraft operators and other users. The research for on-board detection equipment is to be extended.

The stakeholder workshop and expert interviews stressed the need for a more detailed understanding of the impact of different ash concentrations on jet engines as a basis to better manage a volcanic ash incident. This is in line with the recommendations of the International Volcanic Ash Task Force (IVATF) that was set in place in 2010 to develop recommendations after E2010 (ICAO, 2012a). Given the variety of ash compositions, jet engine types, operating temperatures, air speeds and altitudes, the call for more than one project to conduct tests on this issue appears to be clear.

For reasons of liability, engine manufacturers have been cautious to make concrete statements about engine tolerances (Reichardt et al., 2017a); however, some research has been conducted. The U.S. National Aeronautics and Space Administration (NASA) performed a multi-year research project with "engine to end-of-life" vehicle testing through the ingestion of discrete amounts of ash (NASA, 2015). A more gradual picture of the impact of volcanic ash on jet engines is missing and requires further research to account for different ash concentration and exposure time, which would be of value to the airlines when conducting SRAs (Rolls-Royce, 2013).

This is all the more important as discussions showed that ongoing improvements of the modelling environment and research on the volcanological input parameters seem of limited effect as long as the baseline understanding of effects to the jet engines remains poor. Testing the jet engines' reaction to ash would therefore also strengthen the impact of efforts in other contributing fields.

6.5.6 Regulatory Alignment

The varying application of the SRA approach by European countries caused concern among stakeholders, especially the air traffic managers. While most European states fully apply the SRA approach and would not close the airspace at all, some countries, including Germany, do not allow flight operations in forecasted high ash-density contamination (> 4000 $\mu g/m^3$) as of February 2018 (EUROCONTROL, 2018). These variations may lead to confusion and hindered coordination in a new crisis, in addition to the new regulation regarding the decision-making shift to the aircraft operators. A platform with authorities from all the states seems necessary to create a better understanding of how the regulations can be coordinated across borders. A further step would be a comprehensive alignment of SRA regulation throughout the European states involved in a response to volcanic ash from Iceland.

6.6 Conclusions

The aviation community's approach to E2010 has been predominantly reactive. Since then, the multi-sector partnership has grown and strengthened its cooperation (Reichardt et al., 2017a). However, the partnership requires further proactive engagement to prepare for the next volcanic ash incident to successfully mitigate its economic and societal impacts, especially in the case of a more severe event.

This research applied a multi-level methodology to interact with the aviation network stakeholders. The resulting long-term connection with the stakeholders allowed a comprehensive analysis of the stakeholders' roles and concerns, both individually and as a group. The study provided a platform for the stakeholder group to jointly discuss the preparedness to new, extreme volcanic ash eruption events. This work presents the recommendations identified at the stakeholder workshop with the help of scenario narratives. The recommendations span contingency and exercise planning, staff and information coordination, the alignment of regulations and products to end-user needs, and further research on the impacts of ash to jet engines.

The most important recommendation to strengthen the multi-sector partnership's positive impact on societal resilience is the creation of a comprehensive long-term contingency plan that offers an alternative if aircrafts are grounded for an extended period of time. Alternative transportation modes—road, rail or ship—can play an important role in reducing vulnerability of the aviation transport system (Mattsson and Jenelius, 2015). Other transport systems can mitigate economic loss and inconvenience due to delayed or cancelled flights for passengers and goods.

While ad hoc, and at times lengthy, alternatives were individually put in place during E2010 (Mazzochi et al., 2010), a smooth transfer between transportation modes benefits from preparation and coordination in advance to determine the additional resources needed. This means a timely information flow to other transportation agencies and partners in order to enable them to plan and respond to a crisis in a coordinated fashion. Broadening the partnership and enabling a coordinated practice of the response to impactful eruptions will simultaneously strengthen trust in the multi-sector partnership and in its decisions as it demonstrates preparedness and leadership.

Further research is required to better represent all transportation service providers. This could be achieved by inviting stakeholders representing alternative transportation modes for passengers and goods besides aviation to join the present multi-sector partnership and exercises.

7 Conclusions

Reducing the vulnerability of infrastructure to natural hazards is a complex endeavor and requires the knowledge and cooperation of a range of institutions and experts. This research investigated the advances in risk management of the stakeholder group engaged in European air traffic to a volcanic ash eruption event in Iceland. Based on the Eyjafjallajökull eruption in 2010 and its impact on European aviation and neighboring sectors, the study analyzed the current responsibilities of the stakeholder network. It described the advances in research, regulations and cooperation since the impactful eruption in 2010. In a workshop using scenario narratives, representatives from information and service providers, air traffic managers, and regulators were invited to assess their resilience to extreme ash cloud scenarios. The following sections briefly summarize the progress made by the aviation community and the concluding recommendations of the study.

7.1 Advances in European Risk Management

Prior to the major disruption of air traffic caused by E2010, volcanic ash from Iceland was not officially recognized as a risk to European air traffic and beyond. The emerging systemic risk forced European regulators to differentiate their regulatory approach from the global no-flight guidelines to a policy of regulated operations in ash-contaminated airspace. This led to diverse changes in the European approach to managing the risk of volcanic ash.

- **Ash concentration levels**: To reopen airspace during the eruption, the ash concentration levels were changed. The predicted ash concentration threshold in which aircraft could operate safely was raised from 200 to 2000 $\mu g/m^3$. This threshold, created ad hoc during the crisis, has remained valid. The level between 2000 and 4000 $\mu g/m^3$ was then defined as medium ash concentration. Concentration levels above 4000 $\mu g/m^3$ are considered high ash concentrations.
- **Visualization of ash cloud forecasts**: The London VAAC added the Volcanic Ash Concentration Charts to their published products to visualize areas of predicted low, medium, and high ash concentration.
- **Crisis coordination**: The E2010 crisis revealed a lack of coordination between the European States and led to the establishment of the EACCC, which will harmonize the aviation network's response in future events. During a crisis, the EACCC will be activated to provide a platform to exchange information and propose measures to mitigate impacts.
- **Decision-making**: The main regulatory change is the shift in decision-making from aviation authorities to aircraft operators. Under the new SRA approach, airspace remains open for operation during a volcanic ash event. Aircraft operators must submit an SRA that provides strategies to cope with different ash concentrations. The SRA must be approved by the operator's national regulatory authority. It allows the aircraft operator to decide whether or not to fly in ash-contaminated

airspace, depending on the approved thresholds in the SRA. Most of the European countries have fully accepted the SRA approach.

- **Contingency planning**: In 2011, the ICAO established VOLCEX, a major European crisis exercise for aviation stakeholders to rehearse contingency plans and procedures in response to volcanic ash events. VOLCEX takes place once a year to practice responses to eruption scenarios from Iceland, the Azores or Italy. The VOLCICE exercise is a monthly bi-national practice to rehearse procedures between the Icelandic stakeholders ISAVIA and IMO and the London VAAC at the onset of an eruption.
- **Research on volcanic ash**: Based on recommendations by the IVATF, the scientific community made substantial progress in ash cloud identification and forecasting and contributed to improved accuracy of the VAAC products.
- **Research on jet engines**: With little in-depth research on engine susceptibility to ash, the increase of concentration levels during E2010 was a decision based on expert judgement. Mainly two studies engaged in investigating ash quantities and engine damage: NASA conducted "engine to end-of-life" tests of discrete quantities of ash within a multi-year program on ash susceptibility (NASA, 2012). Rolls-Royce compiled a data set based on historic exposure data and modelling and developed a Duration of Exposure versus Ash Concentration Chart (see Appendix 7). According to Rolls-Royce, a total exposure below 14.4 g s/m^3, equivalent to 1 hour at 4000 $\mu g/m^3$, across multiple flights would keep the engine within flight safety margins and would not require inspections (Clarkson and Simpson, 2017).

7.2 Recommendations

The analysis shows that stakeholder cooperation has been growing since the eruption in 2010. The regulatory framework to manage volcanic ash in Europe has progressed and is formally well established. Annual exercises are set in place to practice procedure compliance, and a joint crisis body oversees coordination between the stakeholders during the crisis. However, the network requires further enhancement and effort to prepare for the next ash incident in order to mitigate its economic and societal impacts even further. Figure 7.1 illustrates the improvement measures developed by the study.

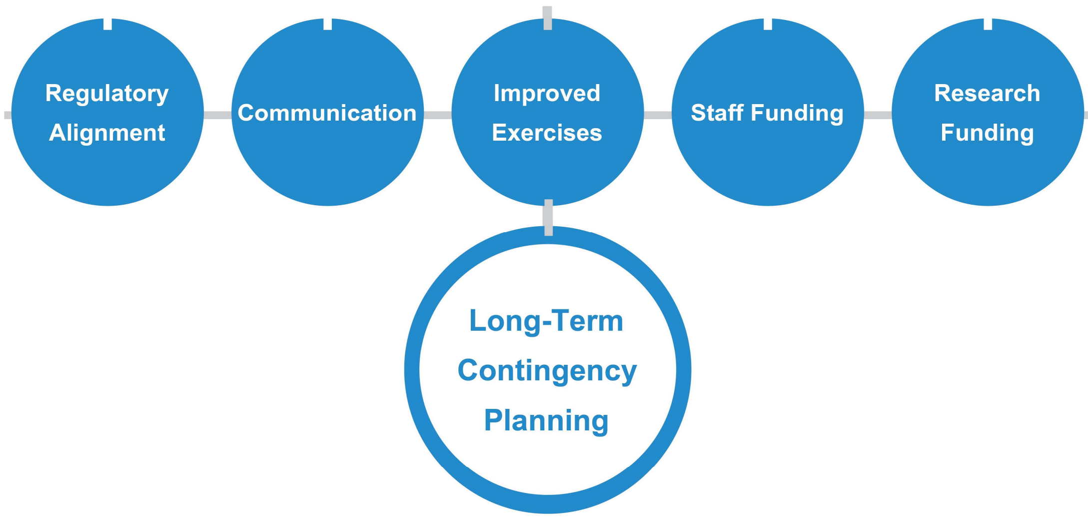


Figure 7.1 Issues and activities to improve risk management of future volcanic ash incidents.

- **Long-term contingency planning**: The impact of longer-lasting eruptions needs to be considered and prepared for, within and beyond the aviation network. A framework is needed to coordinate information exchange between different transportation networks.
- **Improved exercises**: New response exercises must avoid training for a previous event, like E2010. Rather, the exercises should be novel and challenging and drive the stakeholders out of their comfort zone.
- **Communication**: Direct communication between stakeholders should be improved to align products with end-user needs and address uncertainties in data sets and forecasts. The network would benefit from a designated single point of information, e.g., managed by EUROCONTROL. It is to be discussed whether this single point of information should also serve for public information.
- **Staff funding**: The staff capacity in accelerated demands creates a bottleneck for adequate response. To mitigate work overload, the staff must be sufficiently trained, and additional staff in crisis times might be considered. To better accommodate user needs, the capacity for research work within operational work should be increased.

- **Regulatory alignment**: An alignment of the European states' now varying application of the SRA approach would improve coordination between stakeholders and allow for a smoother response.
- **Research funding**: To support informed decision-making of aircraft operators, further research on jet engines is necessary to arrive at a detailed estimation of economic damage, depending on different levels of ash concentrations.

As shown in Chapter 3, knowledge on how much volcanic ash jet engines tolerate is not sufficient for the European aviation community to fully benefit from the regulatory progress. Resources for in-depth risk assessment are required to advance the process. The recent study on exposure time and ash concentrations requires a greater data base and further testing to provide a detailed image of different types of engines and ash. The latest VOLCEX exercise (2017) supports this finding. In the exercise, all airlines opted for rerouting rather than traversing the ash cloud, even if their Safety Risk Assessments had been approved and despite the sometimes high costs of rerouting (EUR/NAT VOLCEX17, 2018). Even though ash avoidance may remain the common response to volcanic ash, responses must be prepared and coordinated for situations where rerouting is not an option.

This research is situated within the context of risk governance of volcanic ash in Europe. It produced guidelines for effective practice to decrease vulnerability to volcanic ash. In order to achieve meaningful communication in interdisciplinary stakeholder involvement, knowledge exchange should be facilitated (Renn et al., 2011). This research used a multi-level approach to prepare and facilitate stakeholder interaction through an analytic-deliberative approach.

The scenario workshop conducted as part of this research placed emphasis on creating a platform that facilitates mutual communication between the stakeholders linked to aviation and volcanic. As shown in Chapter 5, the set-up facilitated exchange of knowledge and perceptions and strengthened the stakeholders' network.

This research focused on the cooperation between stakeholders linked to aviation and volcanic ash. The research concludes that the most important measure to strengthen the networks' positive impact on society's resilience to volcanic ash is to think further. The network needs to expand and prepare a comprehensive long-term contingency plan that includes alternatives if aircrafts are grounded for extended periods of time. The outcome of the scenario discussions show that stakeholders from other modes of transportation need to be included to prevent infrastructure failure. They should be included in risk management processes, both to exercise their right of participation and to add social robustness to the outcome (Roca et al., 2008). To improve risk management, it is crucial to increase interaction with other modes of transportation and facilitate knowledge transfer and mutual planning for severe events. No such activities are currently carried out.

The timeliness of this research is accentuated by the recent seismic activity in Öræfajökull (IMO, 2017), Bárðarbunga (IMO, 2018), and Katla (MBL, 2017). Scientists' and the media's attention was drawn yet again to the potential force with which volcanic eruptions could impact the European air traffic and beyond (e.g., Einarsson, 2018). The study's interaction with the stakeholders contributed to alterations of their framing assumptions, an important prelude to risk assessment and appropriate risk management measures (Millstone et al. 2004; IRGC, 2005).

The ash distribution charts produced by this study show how severe the impact of an eruption similar to the Öræfajökull eruption in 1362 may be and they challenge the stakeholders' perception and framing of the risk. The scenario raised awareness among the stakeholder group to eruptions that may have far greater impacts than recent events. It altered the stakeholders' risk characterization which in turn affects the scope of the annual stakeholders exercise. This year's VOLCEX (2018) exercise will practice the response to an eruption of the Öræfajökull volcano three days into the eruption, which "will be a significant impact to EUR" (EUR/NAT VOLCEX17, 2018).

This study has drawn attention to several means by which the resilience of European air traffic may be increased, in addition to defining and bringing together the key stakeholders in this important transportation sector.

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Appendix A

The overview of the complete sequences of the 6 hourly forecast plots for all three flight level bands for both extreme-case scenarios are included in the Appendix on the following pages in Figures A.1–A.6. The Duration of Exposure versus Ash Concentration Chart produced by Rolls-Royce is displayed in Figure A.7.

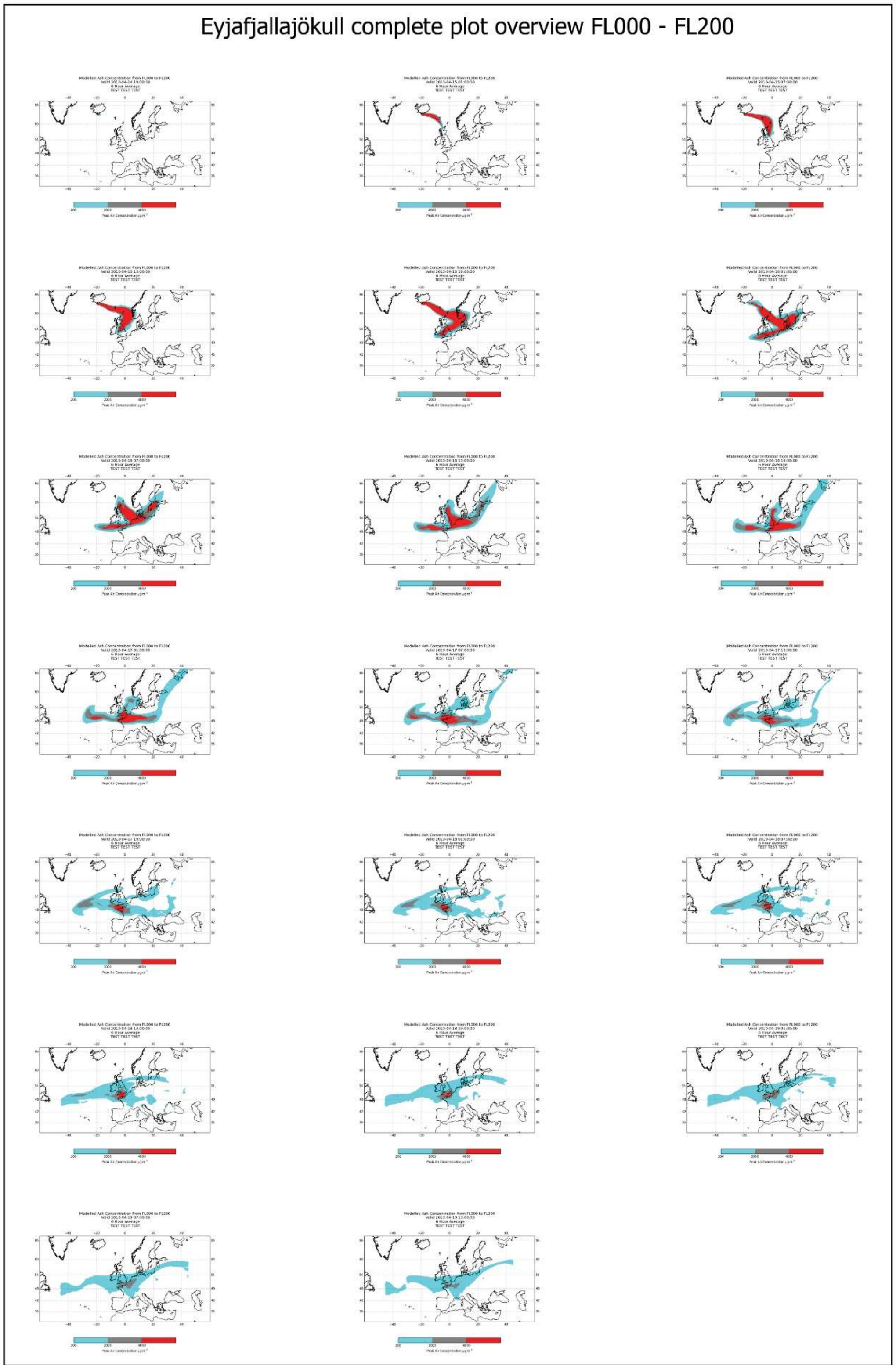


Figure A.1 Eyjafjallajökull scenario run FL000–FL200: Five-day distribution modelling output, complete sequence of 6 hourly plots.

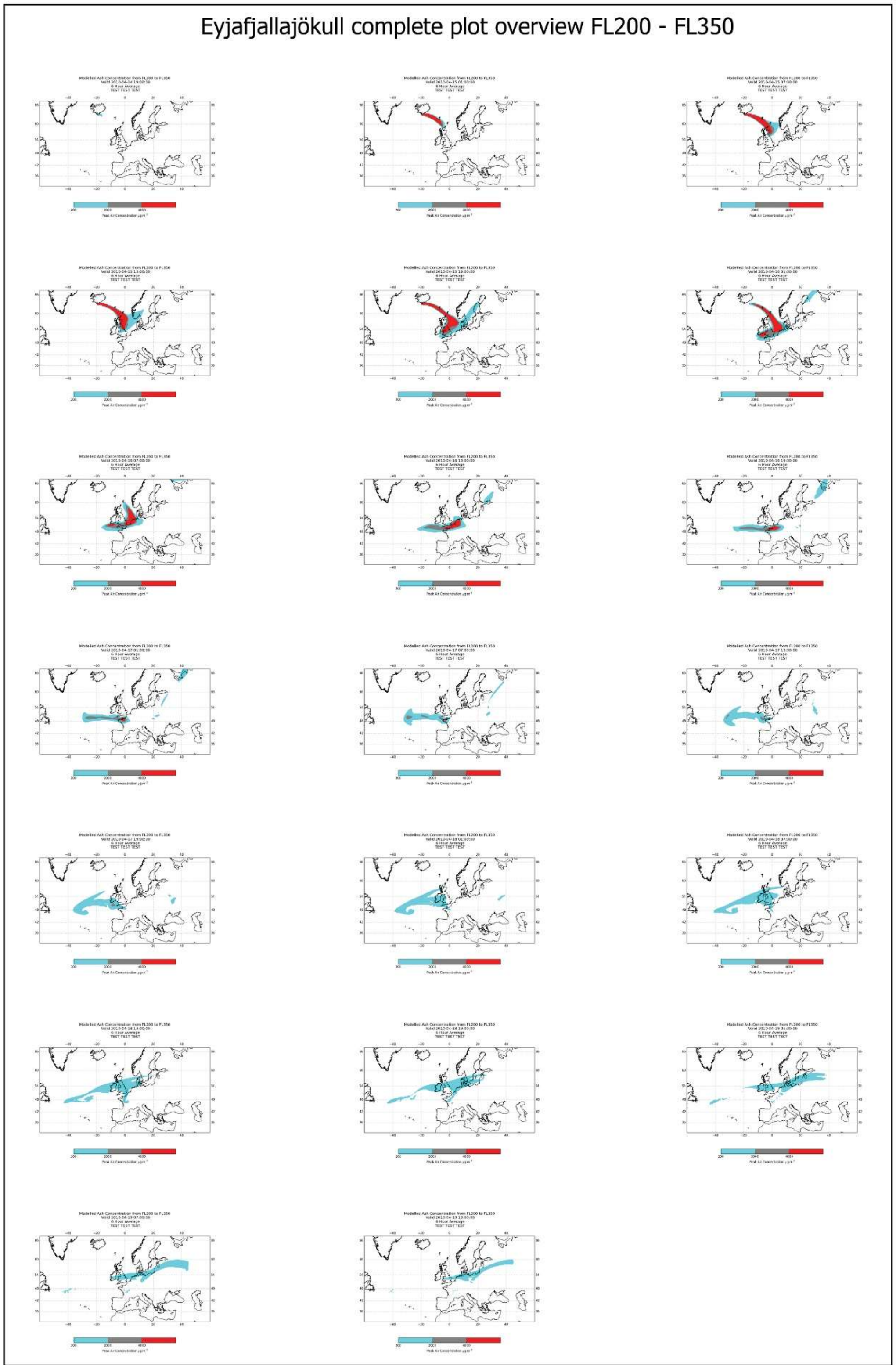


Figure A.2 Eyjafjallajökull scenario run FL200–FL350: Five-day distribution modelling output, complete sequence of 6 hourly plots.

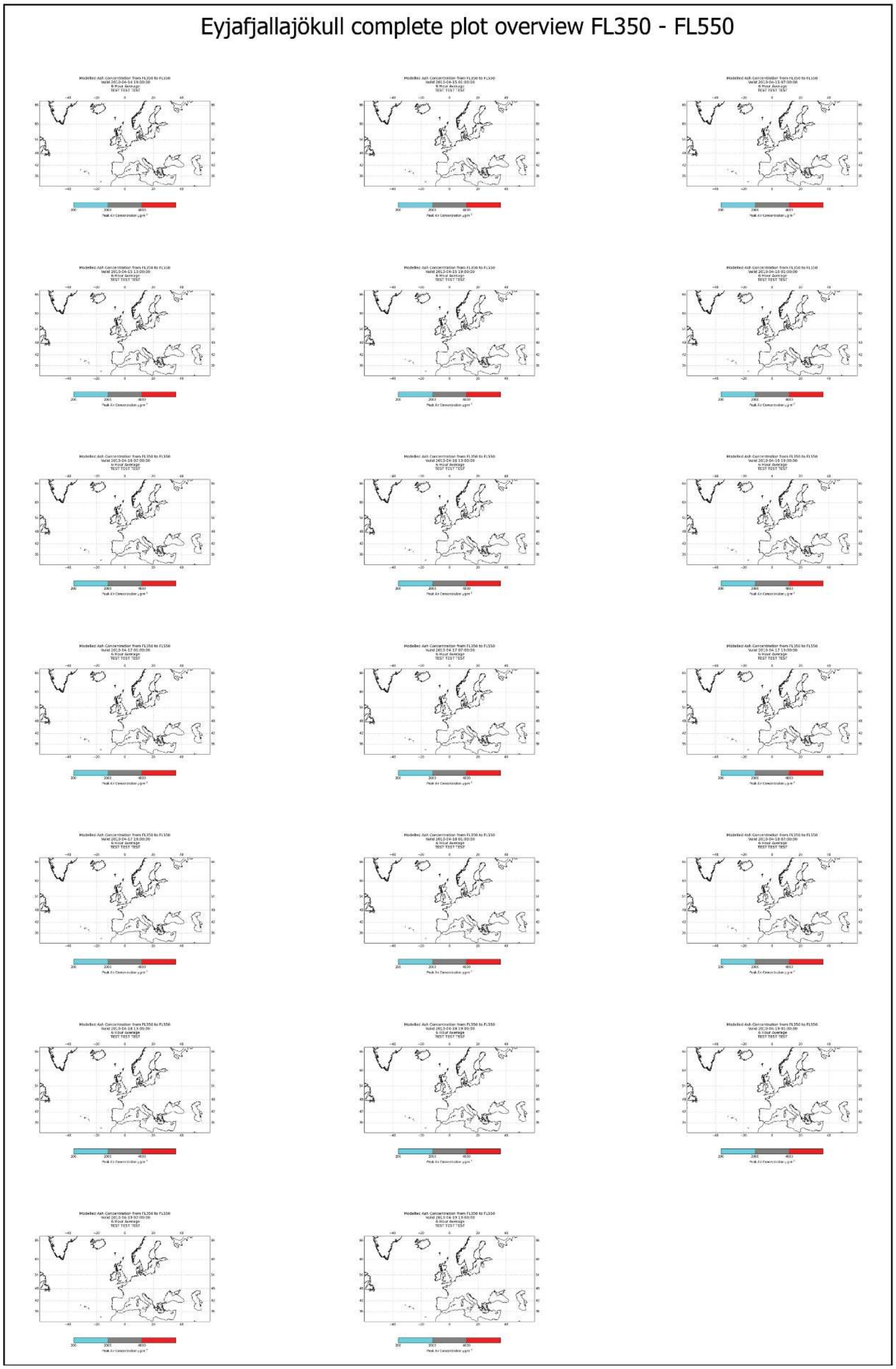


Figure A.3 Eyjafjallajökull scenario run FL350–FL550: Five-day distribution modelling output, complete sequence of 6 hourly plots.

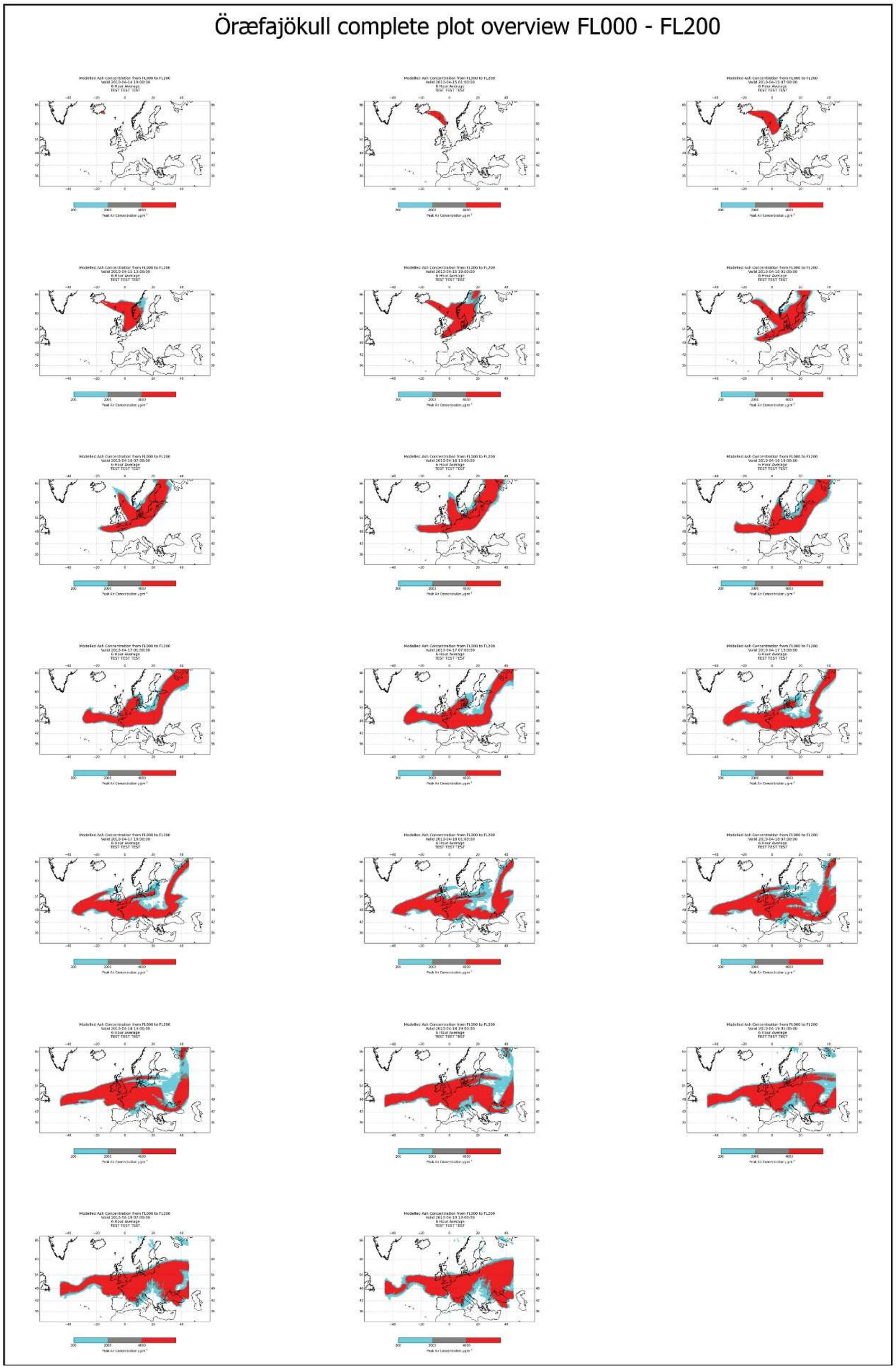


Figure A.4 Öræfajökull scenario run FL000–FL200: Five-day distribution modelling output, complete sequence of 6 hourly plots.

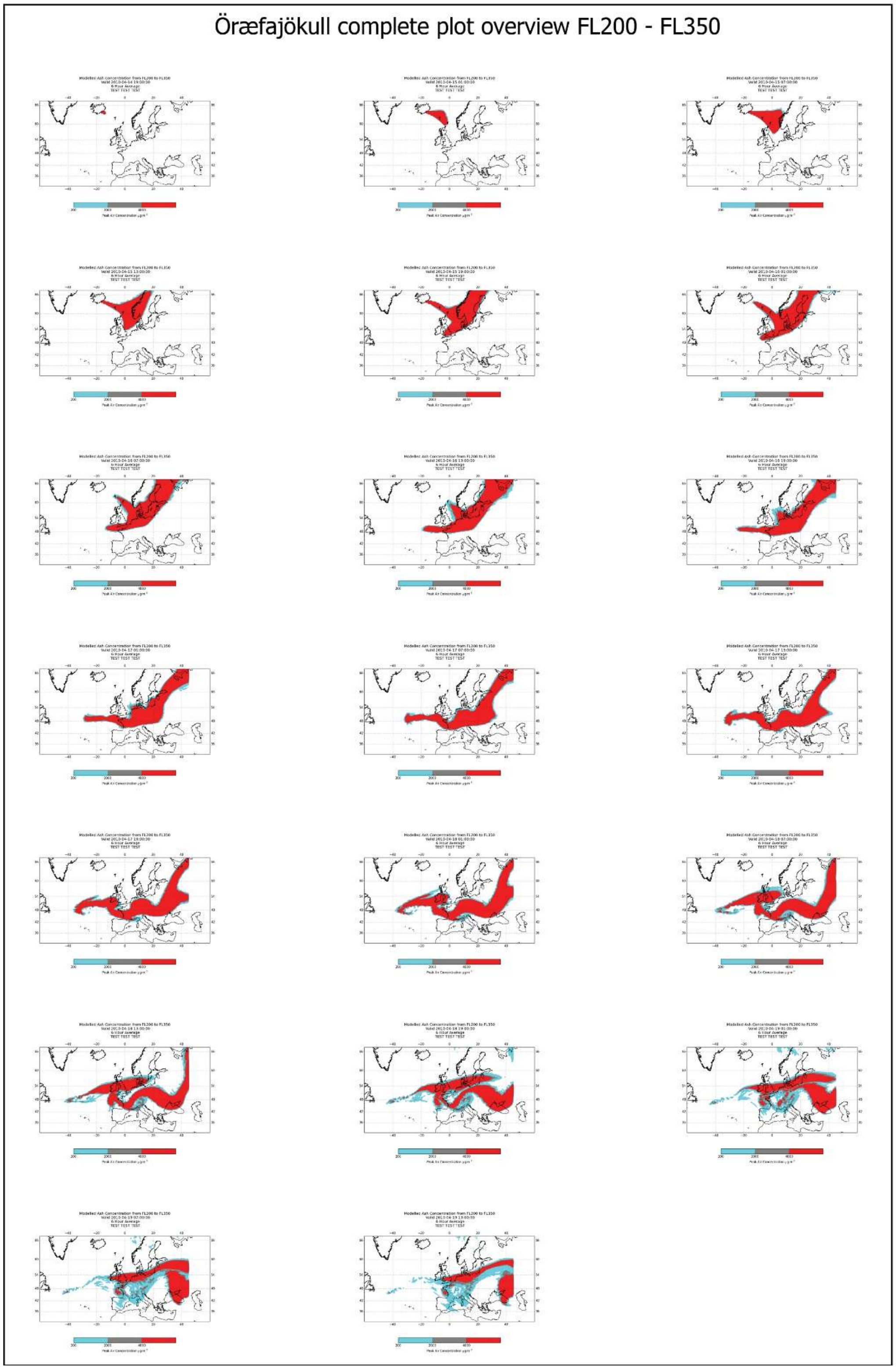


Figure A.5 Öræfajökull scenario run FL200–FL350: Five-day distribution modelling output, complete sequence of 6 hourly plots.

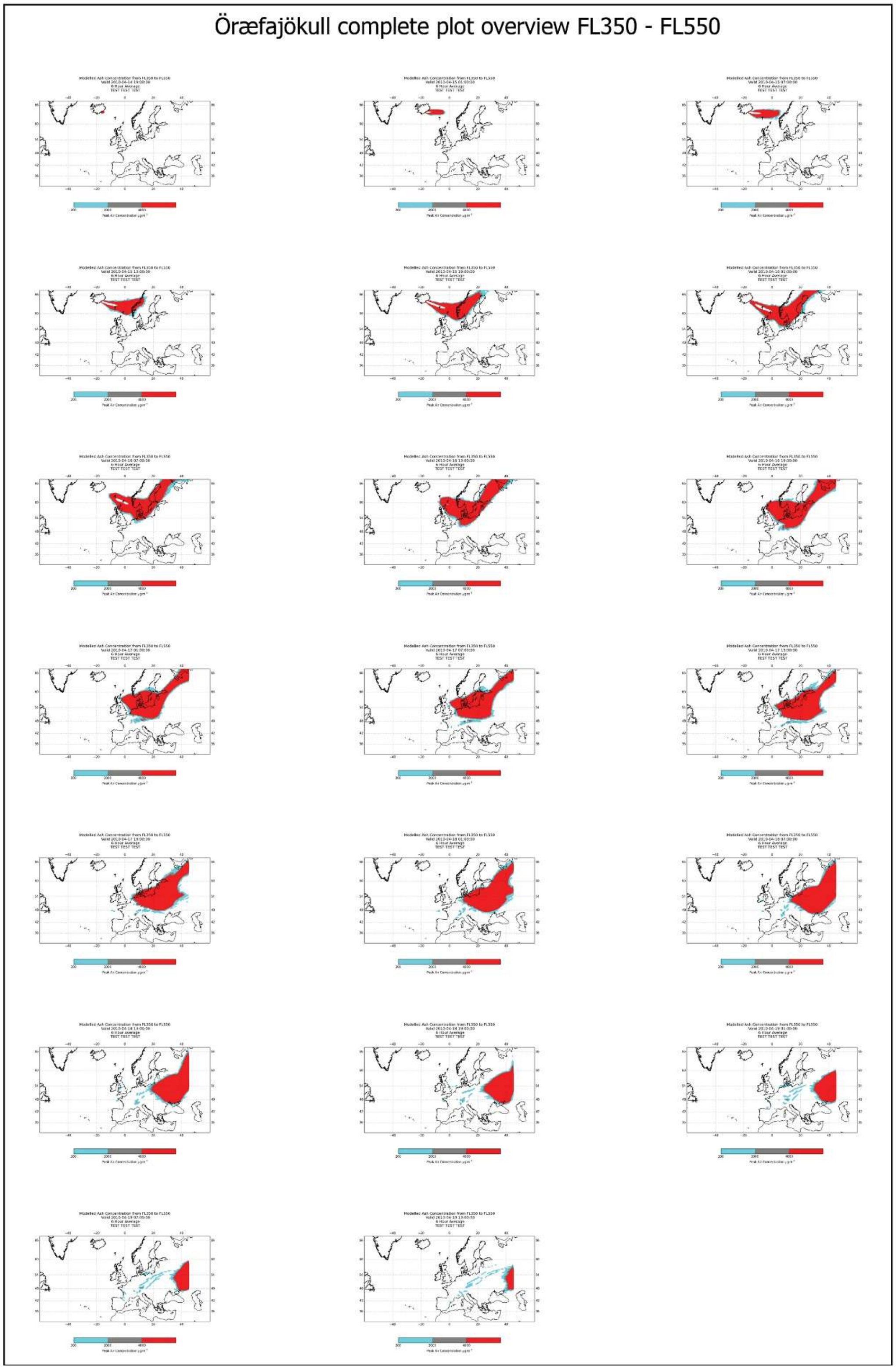
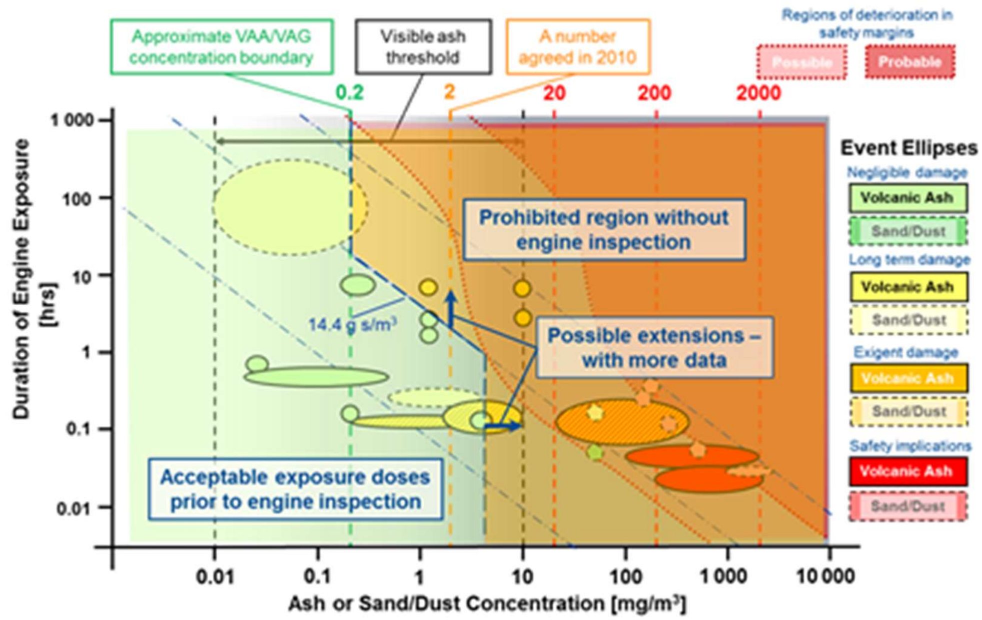


Figure A.6 Öræfajökull scenario FL350–FL550: Five-day distribution modelling output, complete sequence of 6 hourly plots.



(Source: Clarkson and Simpson, 2017)

Figure A.7 Duration of Exposure versus Ash Concentration Chart by Rolls-Royce.

Explanation from Clarkson and Simpson (2017): "Each ellipse or circle represents an engine exposure event. The green background regions are suggestions for where combinations of ash concentration and exposure duration would cause negligible damage. The dark blue broken line defines a 15 g·s/m^3 critical ash dose between the concentrations of 200 and 5000 µg/m^3. Engines can be operated in the pale blue region to the left of the dark blue broken line, but once that line is reached engines need to be inspected and decisions made over whether they can continue to be operated in ash concentrations greater than 200 µg/m^3 or whether some remedial cleaning or repair is needed."