Super Case Study

3

Eyjafjallajökull eruption in 2010

Online Version

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1 Introduction

The effects of an eruption can depend more on the vulnerability of the man-made infrastructures and systems affected than on its geophysical size.

Iceland is a volcanic island in the North Atlantic Ocean, located on the ridge between the Eurasian and American tectonic plates. The area contains more than 30 active volcanic systems that generate relatively frequent eruptions. Many volcanoes are located under ice caps and can produce highly explosive eruptions when water interacts with magma, with plumes exceeding 12 km in height and fine-grained ash that can traverse great distances in the atmosphere. Eruptions have occurred in Iceland on average once every 3–5 years over the last four centuries (Thordarson and Larsen, 2007). These eruptions are usually moderate in size (VEI 1–3) ([1]) and have generally not caused significant harm beyond the island's borders. The most notable exception was the Laki eruption in 1783, which emitted vast amounts of SO2, which caused a drop in mean temperatures north of the equator, and besides its devastating effects in Iceland is believed to have markedly increased mortality in the United Kingdom and on the European continent (Grattan et al., 2003).

In comparison, the Eyjafjallajökull eruption in 2010 was small but its effects were large. The effects of an eruption can depend more on the vulnerability of the man-made infrastructures, systems and services affected than on the event's geophysical size. While no direct fatalities were attributed to the 2010 eruption, the travels of millions of people were disrupted as well as the transport of goods. Recent research links global warming and deglaciation with the possibility of increased generation of magma under Iceland (Compton et al., 2015), which could mean that an eruption similar, or larger, in size and impact could possibly occur on average once in every 7 years in the future, if all the magma were brought to the surface (Pagli and Sigmundsson, 2008). This super case study discusses local and international effects of the 2010 eruption, the measures taken to mitigate its effects, and recommendations on how to improve responses to future eruptions.

2 The Eyjafjallajökull eruption April – May 2010

Westerly and northerly winds prevailed, carrying ash towards mainland Europe.

Eyjafjallajökull, with its peak at approximately 1 660 m above sea level, is a moderately active ice-capped volcano with eruptive periods separated by hundreds of years of dormancy (Thordarson and Larsen, 2007). After an 18-year period of intermittent volcanic unrest, two eruptions occurred in 2010: first, an effusive lava-producing eruption from 20 March until 12 April 2010 on the eastern, ice-free, flank of the volcano, and, second, an explosive summit eruption taking place from 14 April until 22 May 2010 (Gudmundsson et al., 2012) (Figure 1).

The summit eruption had an initial phase of subglacial activity for a few hours during which cauldrons were melted into the ice by the eruption, creating floods of meltwater, known as *jökulhlaup*, rushing down the slopes of the volcano. *Jökulhlaup* is an Icelandic term that has been adopted in other languages to describe the glaciological phenomenon of a glacial outburst flood, triggered by a subglacial volcanic eruption or geothermal heating.

([1]) The volcanic explosivity index (VEI) is a logarithmic scale from 0 to 8 to describe the magnitude of explosive volcanic eruptions, including observations of volume of products and eruption cloud height (Newhall and Self, 1982). VEI 6 eruptions occur once or twice per millennium (Gudmundsson et al., 2008).

A catastrophic explosive eruption began when the magma had melted its way through the overlying ice cap. The VEI 3 eruption emitted a 5–10 km-high eruption plume of unusually fine-grained ash. The amount of erupted material has been estimated as the equivalent of 0.18 ± 0.05 km^3 of dense rock (Gudmundsson et al., 2012). Intense ash fallout occurred in inhabited areas in south Iceland, leading to total darkness during the periods of most intense tephra fall. Westerly and northerly winds prevailed during most of the eruption, carrying ash towards mainland Europe (Stohl et al., 2011; Woodhouse et al., 2013).

Figure 1. *Eyjafjallajökull volcano erupting on April 18, 2010.* ***Source****: photos courtesy of Gunnar Gestur.*

3 Local crisis

3.1 Crisis management

A trustful relationship has been built between scientists, officials, and the public.

An important factor in the management of natural hazards in Iceland is that one agency, the Icelandic Meteorological Office (IMO), leads the monitoring of all natural hazards, be it weather, floods, landslides and avalanches, earthquakes or volcanic eruptions. The IMO takes part in Iceland's emergency management both by giving advice to the Icelandic Department of Civil Protection and Emergency Management (ICP), which manages the response to all natural hazards, and by participating in the Civil Protection Scientific Advisory Board, which meets twice a year when no eruption is occurring but more often during eruptions. The board communicates its findings in a transparent and open way, reaching out to the public through the media. A trustful relationship has been built between scientists, officials, and the public (Bird et al., 2018).

Following signs of renewed activity in the beginning of 2010, authorities had been preparing for a potential eruption of the Eyjafjallajökull volcano. The National Commissioner of the Icelandic Police along with the ICP are responsible for disaster risk management at the national level and operate a National Crisis and Coordination Centre for emergency situations (Act on Civil Protection 82, 2008). In collaboration with local civil protection authorities the ICP had prepared contingency plans based on a hazard assessment for Eyjafjallajökull (Gudmundsson and Gylfason, 2005). These had been tested in a full-scale live evacuation exercise in 2006 (Almannavarnir, 2006)
.
When the summit eruption of Eyjafjallajökull started, the ICP had only just finished responding to a relatively ash-free eruption in a mountain pass on the eastern flank of Eyjafjallajökull. The ICP system had been fully activated from March 20th until April 12th, 2010, but mainly remaining on the *Alert Phase* ([2]). The response involved support and protection of thousands of travellers, who wanted to witness the small but spectacular eruption. The sudden and much larger explosive eruption in the Eyjafjallajökull summit crater on April 14th, 2010 called for an immediate activation of the ICP system only a day and a half after the flank eruption ended. An Emergency Phase was declared shortly after midnight and the ICP issued the highest priority evacuation orders for the immediate surroundings of Eyjafjallajökull. The Red Cross opened emergency shelters for evacuees in nearby villages. In the early morning, a glacial outburst flood started on the slopes of Eyjafjallajökull, roads were closed and access restrictions enforced around the eruption site. The dense ash made things difficult and the use of protection masks and safety goggles when outdoors was strongly recommended.

The ICP opened temporary service centres that served as one stop shops for locals that needed assistance. In the coming spring and early summer weeks, the local communities required much assistance due to copious amounts of ash and lack of pasture and hay for the livestock. It was vital to offer psychological, social, and economic support to those suffering, in an effort to secure their wellbeing. The National Crisis and Coordination Centre coordinated the disaster response dealing with not only national, but also global crisis communication, allocating resources and assisting the various stakeholders and government institutions (Bird et al., 2018). Even though the ICP was well prepared for the eruption, the large amount of airborne ash caused challenging international pressures that called for an exceptional disaster response. Because of the flight restrictions, the eruption developed into an international crisis that needed reactions that had not been anticipated in the contingency plans.

([2]) The levels, or phases, of the Icelandic Civil Protection activation are uncertainty, alert and emergency/distress (Regulation No 650/2009).

3.2 Community effects

Access roads and tracks should have been closed to all traffic to prevent sightseers risking their own lives and those of first responders..

At the time of the eruption, approximately 2 700 people were registered as living in the municipalities potentially affected by an eruption in Eyjafjallajökull. Sheep, cattle and horse farming were the most important livelihoods in the region, while many residents were also involved in tourism activities. When ordered to evacuate because of the potential risk from *jökulhlaup,* many residents were concerned about leaving their livestock unattended. Nevertheless, many people complied and, overall, officials considered the evacuations a success (Bird and Gísladóttir, 2018). A note is warranted here on the cooperation between locals and officials during evacuations in rural areas. When evacuating their homes, people put up a sign (coloured cardboard) in a window or other easily visible place, to be noted by their neighbours or other passers-by. The police monitor the main road junctions leaving the area and ask drivers what farms have put up the sign. This spares police the effort of having to visit every farm.

There were no fatalities or serious injuries caused by the jökulhlaup or the eruption. From a tourism perspective, many residents and rescue workers believed access roads and tracks should have been closed to all traffic to prevent sightseers risking their own lives and those of first responders, because many sightseers were ill prepared for the conditions. In fact, two people lost their lives to hypothermia after getting lost during a trip to view the earlier flank eruption.

It should be noted that, while the majority of residents evacuated, Bird and Gísladóttir (2018) found that almost half (47 %) did not, many because they needed to care for elderly family members or livestock or because they felt it was safer to shelter within their own homes. Some considered the evacuation orders irrelevant to them. Despite these issues, the community trusted those responsible for public safety. This trust stemmed from the ongoing and perceived honest communication between officials and residents well before the eruption commenced, during the initial small eruption in the mountain's flank, as well as during the more severe summit eruption. Officials also earned community trust by relaxing evacuation protocols and allowing farmers to re-enter the hazard zone for 2-hour periods each day so they could attend to their livestock.

While many people coped well with the eruption, their farming and tourism businesses did not fare as well. Farmland and livestock of roughly 120 farms were affected by the volcanic ashfall and glacial outburst floods (Thorvaldsdottir and Sigbjörnsson, 2015). A sharp drop in the number of inbound tourists to Iceland was observed in April and May 2010, which affected the local hospitality sector during that period. In the following years, however, the publicity received through the infamous eruption seems to have contributed to the start of an unprecedented tourism rise in Iceland, with a yearly increase of 16 % in 2011 and with the growth peaking at a 39 % year-on-year increase in 2016 (Icelandic Tourism Board, 2011, 2019).

3.3 Health effects

Residents who had been exposed to the eruption, and to the ongoing resuspension of ash in the period that followed, reported worsening of several health impacts

Natural-hazard-related disasters can have serious consequences at both individual and community levels, damaging the infrastructure of societies and causing suffering or death among those affected (Hansell et al., 2006). Previous research shows that individuals exposed to volcanic eruptions are at a greater risk of psychological (Araki et al., 1998; Warsini et al., 2014) and physical (Higuchi et al., 2012) morbidity than unexposed individuals in the short term, particularly those living in close proximity to the eruption. Studies assessing the long-term health effects of volcanic eruptions have been rare and the results inconclusive (Horwell et al., 2006, 2015). A series of studies were undertaken following the Eyjafjallajökull eruption to add to the understanding of the short- and long-term effects of a volcanic eruption on the local population.

A few weeks after the onset of the Eyjafjallajökull eruption, findings from a cross-sectional study, including 207 individuals living close to the volcano, indicated that short-term exposure was associated with upper airway irritation symptoms and exacerbation of pre-existing asthma, but it did not seem to contribute to serious physical health problems (Carlsen et al., 2012a). However, 39 % of individuals showed symptoms of mental distress, and parents reported respiratory symptoms and increased worry and anxiety among their children. Six to nine months following the eruption, a larger population-based questionnaire study, sent to 1 615 residents exposed to the eruption and a matching sample of 697 unexposed individuals, indicated that those living in the exposed area had markedly increased prevalence of physical symptoms, such as tightness in the chest, cough, phlegm and eye irritation, as well as psychological morbidity symptoms, compared with those unexposed (Carlsen et al., 2012b). This was more evident among those living closer to the eruption than further away. Another part of the study revealed that having suffered material damages or intense insecurity, having had a view of the eruption from their home or having had to stay outside during ashfall was highly associated with increased likelihood of adverse mental health outcomes, such as post-traumatic stress disorder (PTSD) or stress symptoms (Gissurardottir et al., 2018). A quarter of the inhabitants (26 %) reported having used the psychosocial support offered, and the vast majority (82 %) were satisfied with the support received (Thordardottir et al., 2018).

Three years after the Eyjafjallajökull eruption, the same individuals took part in a follow-up study. At this time, residents who had been exposed to the eruption, and to the ongoing resuspension of ash in the period that followed, reported worsening of several symptoms such as morning phlegm in winter, skin rash/eczema, back pain and insomnia. PTSD symptoms decreased during the 3-year follow-up, while levels of psychological distress and perceived stress remained similar (Hlodversdottir et al., 2016). In both surveys, in 2010 and 2013, parents were asked to answer questions about their children's health. According to their answers, children exposed to the eruption were more likely than non-exposed children to experience respiratory symptoms and anxiety/worries 6 to 9 months after the eruption (Hlodversdottir et al., 2018). Children whose homes were damaged in the eruption were more likely to be reported as having psychological symptoms, such as anxiety/worry and depressed mood, than children whose homes were not damaged. Alarmingly, parents did not report a significant decrease in their children's symptoms between 2010 and 2013.

3.4 Lessons learned

There is a need for an all-hazards approach to disaster risk reduction of volcanic eruptions, incorporating plans for medium to long-term recovery.

Locally, the 2010 Eyjafjallajökull eruption showed that, although physical and psychological effects of an eruption may seem relatively benign, health symptoms may still be prevalent years after the event. The Eyjafjallajökull eruption highlighted the need for an all-hazards approach to disaster risk reduction, incorporating plans for medium- to long-term recovery as well as the immediate response and early recovery phases (Bird et al., 2018). The findings on adverse health effects in the aftermath of the Eyjafjallajökull eruption in 2010 emphasise the importance of future research on the long-term health of those who are exposed to volcanic eruptions. This includes long-term studies, health monitoring, and development of efficient and accessible psychosocial treatment and support, especially for children and other vulnerable groups.

Furthermore, the event showed the importance of systematic and interdisciplinary preparations by civil protection and other responders such as the ICP. Open and transparent communication with multiple stakeholders is of prime importance. This needs to be organised and prepared, not least when the natural hazard turns out to gain international attention, as was the case with the Eyjafjallajökull eruption in 2010.

4. International aviation disruption

4.1 Regulation of volcanic ash and air traffic in europe prior to 2010

Volcanic ash risk was known and met with precautionary approach that did not match current air traffic and economic developments.

The 2010 Eyjafjallajökull eruption aroused international attention not because of its size as such, but because of an interplay of ash volume, winds and regulations that did not match air traffic developments and the interconnectedness of global supply chains. Although scientific findings indicating the risk posed to European airspace were available (IAVWOPSG, 2008), they were not used for risk characterisation in Europe. The European risk management approach to aviation and volcanic ash was not updated despite increasing air traffic volume, which turned the 2010 eruption of Eyjafjallajökull into an emerging systemic risk (Castellano, 2011). The lack of preparedness was further reflected in the lack of a coordinated approach between different transport sectors to absorb the shock caused to one mode of transport.

The impact of volcanic ash on jet engines has been recognised since the 1980s (Smith, 1983). 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 Mount 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 from ash to aircraft, especially the observed immediate harmful impact of ash on jet engines, with resulting high maintenance costs and shortened lifespan of the engines, Casadevall (1993) states that the only way to manage the risk is a precautionary approach whereby aeroplanes avoid clouds of volcanic ash completely

Until 2010 the general guidance in Europe was, as it still is today in most parts of the world, to completely avoid airspace contaminated with volcanic ash (ICAO, 2007). It is assumed that potential personal, societal and economic losses of ash encounters (USGS, 2004) always outweigh the costs of rerouting or cancelling flights. In fact, little is yet known about the effects of different ash compositions and concentrations on aircraft. Although aircraft may manage to traverse ash-contaminated airspace, jet engines exposed to ash can suffer long-term damage that shortens their lifespan at considerable cost. Advice on the predicted ash contamination of airspace is issued by the Volcanic Ash Advisory Centres (VAACs) worldwide (Met Office, 2017). At present, VAAC forecast graphics indicate airspace with ash at selected densities or no ash, so that air traffic can be diverted to avoid encountering ash.

According to the regulations prior to the eruption in 2010, airspace in Europe could be closed by national authorities individually if conditions were deemed unsafe. At the onset of the Eyjafjallajökull eruption, the instructions of the International Civil Aviation Organization (ICAO) were zero ash tolerance (ash volumes < 0.2 mg/m^3). The decisions for air traffic are based on the ash dispersal modelling by the VAAC, which is further informed by ground-based monitoring measurements. When the London VAAC forecast the ash being blown towards Ireland and the United Kingdom, Irish and British aviation authorities started reducing air traffic and closing airspace, followed by similar actions by aviation authorities on the European continent (CAA, 2010).

4.2 Eruption impact on international air traffic and decision-making

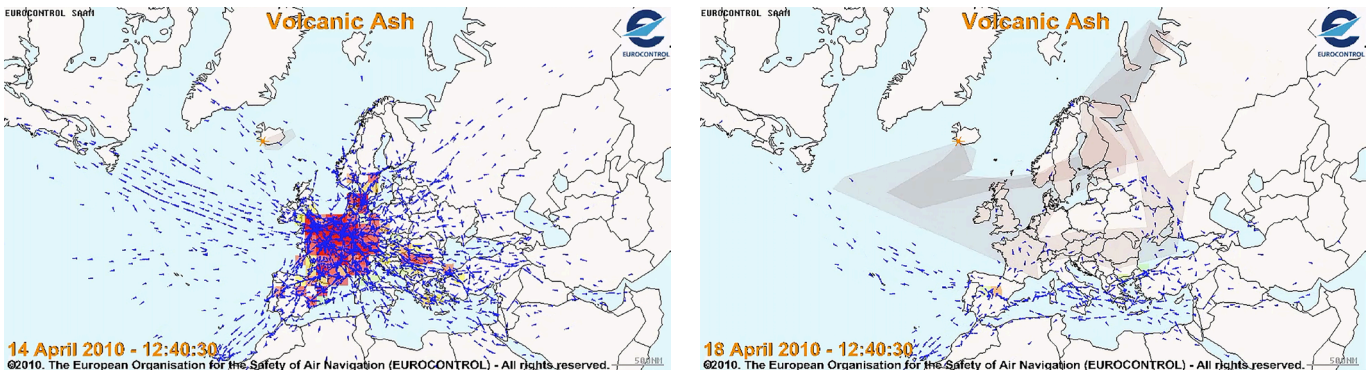
Amid individual national efforts, the crisis called for a coordinated European approach.

In April 2010, about 48 % of Europe's total air traffic was grounded during an 8-day period (Bye, 2011). In its cascading effects, the 'eruption of disruption', as it was called by Birtchell and Büscher (2011), affected individuals, businesses and institutions worldwide. The disruption drove African flower producers out of business, threatened lives through the delay of organ and bone marrow air transport in North America and northern Europe (CBS News, 2010; Alexander, 2013), and delayed industrial supplies between continents. From 14 to 21 April 2010 more than 100 000 flights were cancelled, with an estimated EUR 1.3 billion loss of revenue for the airlines (Bolić and Sivčev, 2011) and an 11.7 % decrease in air travel throughout the month for European air carriers (IATA, 2010). The event disrupted the travels of 10 million passengers and 40 % of cargo transport in Europe (Eurocontrol, 2010).

The amount of ash emitted by the eruption and its dispersion in the atmosphere, both actual and predicted, severely affected international aviation for weeks. The ash reached up to 10 km in the atmosphere and was carried by northerly winds towards Ireland, the United Kingdom and mainland Europe, where it impacted one of the most densely populated airspaces in the world. Airspace in Europe was closed on several additional occasions until the eruption ended in May 2010. The eruption is claimed to have caused the greatest disruption of air traffic since the Second World War, with an estimated worldwide loss of EUR 3.75 billion (Oxford Economics, 2010).

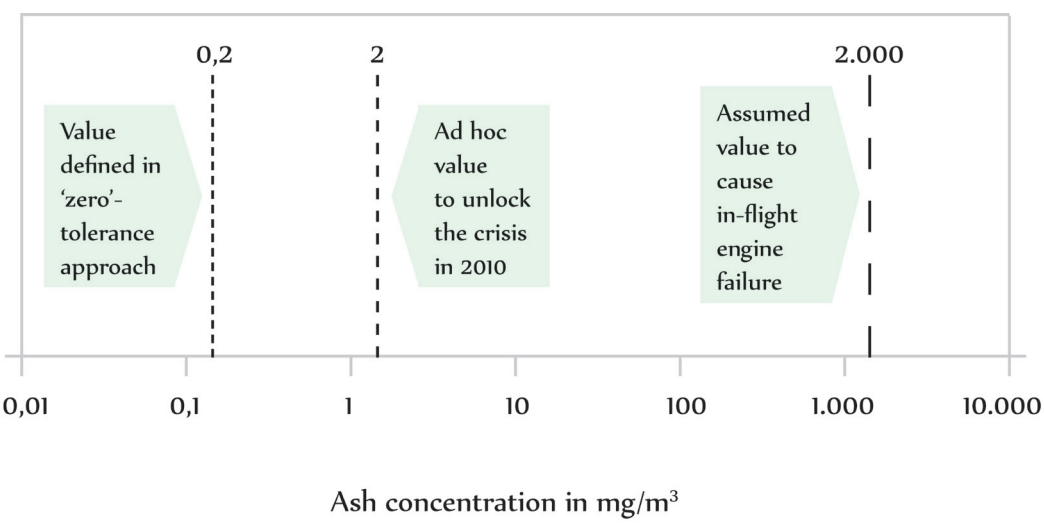
This unprecedented disruption led to a paradigm shift in European regulation and risk management regarding volcanic ash. Figure 2 illustrates the impact of the volcanic ash cloud on air traffic in Europe.

Figure 2. *Effects of the volcanic ash cloud on aviation in Europe in April 2010: stills from a Eurocontrol video simulating air traffic in real time.* ***Source****: IVATF, 2010.*
Notes: *The image on the left is from the onset of the eruption on 14 April, and the image on the right is from 18 April 2010. Blue dots indicate individual aeroplanes, while coloured squares represent space too densely populated with aeroplanes for individual representation. The grey area refers to the modelled ash dispersion issued by the London VAAC. Grey shades reflect different heights of the ash plume: light grey, up to 6 100 m; dark grey, up to 10 700 m.*



Three days into the airspace closures, the financial implications of the zero-tolerance response led to pressures for revision and a search for a safe solution that would allow airports to open again (Mazzocchi, 2010). In an effort to reopen British airspace, the UK Civil Aviation Authority sought to determine safe ash concentration thresholds. Scientists, air traffic managers, airlines and engine manufacturers were consulted to revise the ash thresholds while ensuring flight safety (Reichardt et al., 2017). Figure 3 presents a comparison of how the safe-to-fly threshold was changed in spring 2010 from 0.2 mg/m^3 to 2 mg/m^3. This value was later revised to 2–4 mg/m^3.

Figure 3 *Comparison of the ash threshold change during the 2010 Eyjafjallajökull eruption in Europe, in relation to ash concentration values assumed to lead to engine failure..* ***Source****: Reichardt et al., 2017.*



Amid individual national efforts, the crisis called for a coordinated European approach. Without a designated regulatory body to manage such a move at an international level, committees had to be formed during the crisis. Days into the event, the European Commission asked Eurocontrol, the aviation network manager and organisation for the safety of air navigation, to provide regulators with suggestions on how to solve the crisis (Alemanno, 2010). Eurocontrol proposed to introduce areas of different ash concentration levels in which the operation of air traffic is possible, provided that specific inspection and maintenance requirements are fulfilled. The decision to fly through these designated zones was left to the aircraft operators (European Commission, 2010).

4.3 Crisis management: regulatory actions and scientific support

The event emphasised the need to build broader frameworks for scientific cooperation to coordinate knowledge and support decision making regarding ash and aviation.

The risk to aviation from volcanic eruptions in Iceland has been known by different entities within the scientific community for many years (Thorarinsson, 1981; Oppenheimer, 2010) but was not included in states' emergency plans across Europe. The Joint Research Centre (JRC) in Brussels similarly had not previously worked on the threat of volcanic ash and had little internal expertise on this issue (Donovan, 2019). An overarching structure to connect different voices in the scientific community with each other and with members of the aviation community and policy-makers was missing. Internal government exercises, such as the United Kingdom's horizon-scanning exercises to identify potential future threats, did not typically include academics (Miles, 2005). Thus, although authorities had been made aware of the threat, the event was not anticipated by the industry as a whole and this made the response reactive (Alexander, 2013).

During the crisis, scientific advice was requested on two fronts. On the one hand, modellers and experts in space- and ground-based monitoring from the fields of volcanology, meteorology and atmospheric dispersion were consulted regarding volcanological input parameters and the accuracy of the European 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. Scientific input from different fields and countries significantly helped to unlock the crisis (Reichardt et al., 2017), yet the event emphasised the need to build broader frameworks for scientific cooperation to coordinate knowledge and to support decision-making regarding ash and aviation.

The Secretary General of the ICAO formed the International Volcanic Ash Task Force (IVATF) in May 2010. The IVATF reviewed the response to the Eyjafjallajökull 2010 eruption, assessed areas of improvement regarding volcanic ash and aviation, and defined actions needed to address aviation risks (WMO, 2012). The group consisted of a multidisciplinary team of experts working in subgroups on atmospheric sciences, airworthiness, air traffic management and international airways volcano watch coordination (WMO, 2012). The aim was to establish guidance for further research, issue recommendations for risk management and deliver 'new tools to counter future volcanic ash events' (ICAO, 2012b). The group delivered a final report in 2012, and further work is being carried out by the International Airways Volcano Watch Operations Group as well as other ICAO groups (WMO, 2012). Information provisions include developments in scientific research and modelling, and inclusion in the system of decision-making, as stated in the IVATF report (ICAO, 2012b).

Following the Eyjafjallajökull 2010 eruption, the European Aviation Crisis Coordination Cell (EACCC), with Eurocontrol as chair, was created to facilitate a coordinated European approach to aviation crises in the future (Bolić

and Sivčev, 2011). The function of the EACCC is to manage and coordinate actions when circumstances disturb normal aviation operations. It provides a platform to collect and distribute information, suggests solutions to support regulators and decision-makers, and implements decisions made. The coordinating body consists of a variety 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, national militaries, national air traffic managers, airports and airspace users, and national agencies with connections to national crisis management as well as experts on the nature of the crisis (Eurocontrol, 2020).

Since 2010, much work has been done to improve the inclusion of science in policy-making and to strengthen links between volcanologists in key institutions across Europe. Since the Eyjafjallajökull 2010 eruption, scientists have built a new connection with operation service providers from the VAACs to join forces in advancing knowledge of ash characterisation and modelling of volcanic ash plumes (Reichardt et al., 2017).

The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and the World Meteorological Organization (WMO) organised the IAVCEI–WMO workshop in 2010, the first to bring scientists from various fields together with experts from the London VAAC. Specialists in modelling and space- and ground-based monitoring from the fields of volcanology, meteorology and atmospheric dispersion met to discuss ash grain-size distribution, volcanic mass eruption rates and plume height, uncertainties of prediction models, and the ash particle aggregation to be taken into account in models (Bonadonna et al., 2012). Whereas 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 institutionalise the cooperation and strategies for operational implementation of scientific findings (Bonadonna et al., 2014). The WMO SCOPE Pilot Project 2, 'Advanced Nowcasting for Aviation', organises meetings to foster exchange between institutions to keep track of the international state-of-the-art developments in volcanic ash cloud detection and monitoring equipment (WMO, 2019).

Within a few days of the eruption in 2010, scientific advice helped revise ash thresholds that had been in effect globally for more than a decade (Bolić and Sivčev, 2011). Such cooperation between policymakers and (regulatory) scientists can, however, cause problems. It may lead to loss of credibility, as the public tends to fear that short-term political agendas may reduce the integrity and quality of experts' advice. Similarly, the shift of decision-making from aviation authorities to aircraft operators based on scientific advice during a crisis could have a negative impact on the public's trust.

A study of UK residents in 2012 showed that airlines were better trusted than the media, social networks, or friends and family concerning the risk from ash and believed to have a similar level of accuracy in their judgements to that of the UK government (Eiser et al., 2015). However, it was also found that the airlines were regarded as much more likely to underestimate the risk. This might reflect the effect of comments given by impatient airline chief executives during the crisis, as well as an awareness of the cost issues facing airlines with grounded flights (Eiser et al., 2015). It suggests that the public may not fully trust aircraft operators to be the sole decision-makers. Transparency in safety risk assessment procedures, prior to an eruption, may be necessary to ensure trust in decision-making. It may be pointed out that aircraft operators are already trusted to make similar fly or no-fly decisions regarding several other safety factors, such as inclement weather. Research has also shown that the high repair and maintenance costs of engines congested with volcanic ash can lead airlines to take a rather conservative stand when it comes to volcanic ash (Reichardt, 2018).

Although procedures have been greatly improved since 2010, much needs to be done to better understand the relationships between policy, public trust and risk management.

4.4 Lessons learned

Trust needs to be built between advisors and policymakers prior to crises.

Although the 2010 eruption in Eyjafjallajökull was geophysically moderate in size and local consequences, it had a major effect on international aviation, disrupted the travels of approximately 10 million people and delayed the transportation of goods. Yet airspace closures only lasted for a few days. Larger volcanic events, up to VEI 6, may occur, and volcanic events may possibly occur with greater frequency in the coming decades, as studies suggest (Compton et al., 2015). Thus, the most important aspect of the Eyjafjallajökull eruption may be to serve as a wake-up call.

Internationally, the Eyjafjallajökull 2010 eruption led to increased awareness of the threat of volcanic ash to air traffic in Europe. Since then, numerous advances have taken place in research, regulation, and cooperation (Bolić and Sivčev, 2011; Ulfarsson and Unger, 2011; Reichardt et al., 2016, 2017). Research cooperation was established between airlines and private businesses to test on-board measuring devices for volcanic ash, such as AVOID (Prata et al., 2016) or ZEUS (Clark, 2014), to avoid ash-contaminated airspace.

According to the updated regulations and procedures, most of the European airspace now remains open and the relevant aircraft operators decide whether to fly or not (Reichardt et al., 2017). For aircraft operators to decide whether or not to fly in ash-contaminated airspace, a safety risk assessment (SRA) must be in place, stipulating safety procedures when encountering volcanic ash in flight. The SRA must be approved by the operator's national aviation administration for the operator. As of November 2016, the majority of European nations mutually recognise the SRA.

A number of studies have been conducted to improve the understanding of ash characterisation, modelling of the volcanic ash plume and the atmospheric environment (see e.g. the special issue in the Journal of Geophysical Research: Atmospheres in JGR, 2012; Langmann et al., 2012). The cooperation within the scientific network has been expanded through workshops that facilitated exchange between neighbouring research fields (Bonadonna et al., 2012, 2014). The level of communication, e.g. between information providers in Iceland and the United Kingdom, has been elevated, and institutional staff exchange supports a trustful environment for effective interaction (Reichardt et al., 2017).

To practise and adapt volcanic ash contingency plans and procedures, an annual volcanic ash exercise has been introduced and is run by ICAO. A volcanic ash scenario is simulated to practise the emergency with the EACCC, service providers, regulators and aircraft operators during a 2-day exercise (Easa, 2011). The exercise focuses on the air traffic response to the onset of a volcanic eruption with ash emission. Since the 2010 eruption in Eyjafjallajökull, the ICP has prepared contingency plans for different types of volcanic eruptions to deal with the response to ash, toxic gas, lava and *jökulhlaup*.

Thus, the Eyjafjallajökull eruption in 2010 led to several advances in the management of volcanic ash and air traffic. While the regulatory framework has been well established formally, and exercises and coordination have improved, there is potential for further lessons to be learned (Reichardt et al., 2018).

Volcanic eruptions can affect air traffic beyond the initial phase, as the 2010 Eyjafjallajökull event demonstrated. Eruptions of greater volume and duration than in 2010 can have a severe and long-lasting impact on European air traffic, as a scenario analysis of a hypothetical VEI 6 eruption of the Öræfajökull volcano in south-east Iceland

showed (Reichardt et al., 2019). Potential responses still need to be determined and practised (Alexander, 2013; Reichardt, 2018).

A smooth transfer between transportation modes benefits from preparation and coordination in advance to determine the additional resources needed. This means timely information flow to and from 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 execution of the response to impactful eruptions will simultaneously strengthen trust in decision-making, because such exercises can improve preparedness and leadership (Reichardt et al., 2018, 2019).

To save time and effort, governments and academics need to become better at engaging with each other, particularly in anticipation of future potential risks. Trust needs to be built between expert advisors and policymakers prior to crises. Governments and other responders need established connections with the right experts to communicate effectively in times of crisis. A platform is necessary to enable information exchange between the different sectors involved. Multi-stakeholder workshops using worst-case scenarios of volcanic eruptions have proven to be successful in bridging the knowledge gap between information providers, operators and decision-makers and in creating connections for them to interact in a timely manner in times of crisis (Reichardt et al., 2019).

5 Conclusions

The ash from an Icelandic eruption has the potential to interfere with several intercontinental flight corridors for goods and passengers, affecting economies worldwide. In the light of a potentially much larger eruption in the future, the case study of the 2010 Eyjafjallajökull eruption emphasises the need for national and international efforts to be strengthened. Locally, the importance of trust and cooperation between the public and various sectors of civil protection cannot be overestimated. Systematic exercises, planning and consultation of different stakeholders must be maintained in times when no eruption is occurring. Long-term support and follow-up of potential health effects, both physical and psychological, need to be built into the response system. On a cross-border scale, international agreements and protocols are urgently needed to manage volcanic eruptions with widespread ashfall.
The following recommendations should be taken into consideration to better prepare for future eruptions, at both local and international scales (Reichardt et al., 2018).

- Research funding: To support informed decision-making on how to mitigate the adverse effects of volcanic eruptions, more research is needed on all fronts. Regarding aircraft operators, further research on volcanic ash and jet engines is particularly necessary to improve understanding of the limits for safe operation of jet engines in ash-contaminated air.

- Operational experience and research. Involving potential users in exercises helps when evaluating their needs, as well as the need for further research. To better accommodate user needs through research, the capacity for research work within operational work should be increased or closely linked to external research institutions.

- Long-term contingency planning: Effects of longer-lasting eruptions need to be considered and prepared for, locally and internationally, within and beyond the aviation network.

- Improved exercises. New response exercises must avoid training for a previous event. 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 datasets and forecasts. Crisis management would benefit from a designated single point of information. It has yet to be discussed whether or not this single point of information should serve for public information as well.

- Staff funding. The staff capacity of agencies under accelerated demands creates a bottleneck for adequate responses. To mitigate work overload, the staff must be sufficiently trained, and provisions made to access additional staff if needed.

- Involve other modes of transportation. A framework is needed to coordinate information exchange between different transportation networks, i.e. air-, land-, and sea-based transportation.

- Regulatory alignment. Alignment of regulations, and not least the application of the SRA, would improve coordination between stakeholders and allow a smoother response.

The most important measure to strengthen societies' resilience to volcanic ash is to think further. This means developing contingency plans that can handle events of truly long duration, when air traffic is effectively halted for months, not merely a few days. An important part of such preparations is to expand the network of stakeholders managing the threat of volcanic ash, to include other modes of transport, on land and sea. Other transport systems can mitigate the systemic risk, economic loss and inconvenience due to delayed or cancelled flights for passengers and goods. They should be included in risk management processes.

Lastly, a key improvement is to strengthen the exercises and prepare for more unexpected events. The exercises need to be based on larger events and designed to surprise and stress-test the response systems. When time passes and the last event becomes an increasingly distant memory, it is harder to draw stakeholders to the table to participate in possibly costly exercises and contingency planning. It is crucial to maintain stakeholder interest in the topic. For that to occur, it is imperative that stakeholders see realistic benefits from taking part in exercises and planning efforts.

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