European volcanological supersite in Iceland: a monitoring system and network for the future

Report

D3.2 - Information for EU-MIC and scenarios for major events

Work Package:	*Communications and supporting risk management*
Work Package number:	*3*
Deliverable:	*Information for EU-MIC and scenarios for major events*
Deliverable number:	*3.2*
Type of Activity:	*RTD*
Responsible activity leader:	*Dr. Susan C. Loughlin*
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Type of Deliverable:	*Report*	*[X]*	*Demonstrator*	*[ ]*
	Prototype	*[ ]*	*Other*	*[ ]*
Dissemination level:	*Public*	*[X]*	*Restricted Designated Group*	*[ ]*
	Prog. Participants (FP7)	*[ ]*	*Confidential (consortium)*	*[ ]*

Seventh Framework Programme

EC project number: 308377

Abstract

This report comprises Deliverable 3.2 : 'Information for EU-MIC and scenarios for major events: Development of standardized volcanic information, lexicon and warning messages for the EU-MIC communication hub; delivery of scenarios to Civil Protection for Laki-type and VEI 5+ type events across Europe'. The report describes how scientific research and knowledge gained by research and operational institutions engaged in the Futurevolc project is made available in useful and useable formats to operational and civil protection agencies, who then distribute the information to stakeholders in Iceland, across Europe and internationally. The Bárðarbunga volcano unrest and eruption (2014-15) offered opportunities to test new methods in communication through the FUTUREVOLC network, implement some of the lessons learned from the 2010 eruptions (documented in FUTUREVOLC report D3.1) and implement them in real-time. The focus of the deliverable is primarily on civil protection activities and how scientific evidence is received and distributed by them.

In this report we describe in detail the processes by which scientific information and data is shared between agencies in Iceland, across Europe and internationally (MS21). These processes and the cooperative and collaborative working that they depend upon have been enhanced during the course of the Futurevolc project. In particular, we document the progress in using social media, especially during an eruption. We also document the implementation of the International Aviation Colour Code for Iceland (MS19). This is an optional 'traffic-light' system which reports the status of volcanoes and relies on monitoring and scientific judgement to move between levels. The thresholds for movement between levels are different for each volcano and will be modified as further scientific knowledge and experience is gained. The aviation colour code system is not appropriate for managing proximal hazards and a volcanic alert level system is also in development to facilitate management of proximal hazards and risks.

We also present two scenarios that can facilitate Europe-wide planning by national civil protection agencies for eruptions from Iceland's volcanoes (MS20). These two scenarios have been chosen because between them they include risks to a wide variety of sectors from supply chains and business disruption to agriculture, health and tourism. Planning for these two scenarios should therefore facilitate response to a wide variety of future volcanic eruptions. Joint planning and sharing of knowledge between national civil protection agencies will result in considerable efficiencies. The UK Civil Contingencies Secretariat has made considerable progress in scenario planning and we draw attention to that complementary work. We do not consider impact scenarios arising from eruptions elsewhere in Europe.

Finally we summarise some recommendations arising from this phase of our research and describe the next steps in progressing towards improved volcanic risk communication.

The Futurevolc project aims primarily to ensure that the very best scientific research and evidence is made available and accessible for timely and effective decision-making. This is highly complementary to the goals of the Hyogo Framework for Action (HFA) 2000-2015 and the new Sendai Framework for Action (2015-2030). Members of this Futurevolc work package have also contributed to the process to deliver the Sendai Disaster Risk Reduction framework, drawing on Futurevolc experience and activities.

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List of Abbreviations

Abbreviation	Full name
ACC	Aviation Colour Codes
ACC/FIC	Area Control Centre/Flight Information Centre
ANSP	Air Navigation Service Provider
ATM	Air Traffic Management
BGS	British Geological Survey
CAA	Civil Aviation Authority
CECIS	Common Emergency Communication and Information System, EU
CEO	Chief Executive Officer
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
EEA	European Economic Area
ERCC	Emergency Response Coordination Centre (formerly known as MIC)
EU	European Union
FP7	Seventh Framework Programme, EU
HFA	Hyogo Framework for Action
HILP	High-impact, Low-probability
IAVW	International Airways Volcano Watch
ICAO	International Civil Aviation Organization
ICESAR	Icelandic Search and Rescue Association
IES	Institute of Earth Sciences, University of Iceland
IMO	Icelandic Meteorological Office
ISAVIA	Icelandic Civil Aviation Administration
IVATF	International Volcanic Ash Task Force

Abbreviation	Full name
MIC	Monitoring Information Centre (see ERCC)
MSP	Meteorological Service Provides
MWO	Meteorological Watch Office
NCCC	National Crisis Coordination Centre
NCIP	National Commissioner of the Icelandic Police Department of Civil Protection and Emergency Management
NGO	Non-Governmental Organization
PR	Public Relation
RUV	The Icelandic National Broadcasting Service
RUV	Icelandic National Broadcasting Service
SHS	The Capital Area Fire Brigade
SIGMET	Significant Meteorological Information
UI	University of Iceland
UK Met	United Kingdom Meteorological Office
UKMO	United Kingdom Meteorological Office
UN	United Nations
UNISDR	International Strategy for Disaster Reduction
USGS	US Geological Service
VAAC	Volcanic Ash Advisory Centre
VAR	Volcanic Ash status Report
VO	Volcano Observatory
VOLCEX	Volcanic Ash Exercise
VONA	Volcano Observatory Notice for Aviation
WOVA	World Organization of Volcano Observatories
WP	Work Package

1 Introduction

1.1 Tasks and deliverables

The Futurevolc project aims primarily to ensure that the very best scientific research and evidence is made available and accessible for timely and effective decision-making. This particular deliverable focuses on the critical role of civil protection agencies and partner organisations at national and European level in collating and distributing useful and useable risk information to a wide variety of stakeholders, and in planning for future events.

This report includes a description of work completed for the milestones: M19 'Operational implementation of an Icelandic Volcanic Alert Level', M20 'Scenario report delivery' and M21 'Standards in communication established with EU-MIC'. The EU-MIC is now known as the Emergency Response Coordination Centre (ERCC) and the improved communication standards are relevant to all stakeholders.

The report describes and documents how scientific research and knowledge gained by research and operational institutions engaged in the Futurevolc project are now being used by civil protection agencies, the aviation sector, the public, the media and others in Iceland, across Europe and internationally. The pathways by which scientific evidence is integrated into the process and products are outlined. The focus is primarily on civil protection activities and roles in the communication and management of risks.

This deliverable follows on from Deliverable D3.1: 'Response indicators/early warning systems and report of lessons learned from 2010 eruption' in which the international aviation colour code system was introduced for Iceland's volcanoes providing official and publically available notifications of the status of each volcano. This information is simple and informs all stakeholders of any detected volcanic unrest, escalating unrest or ongoing eruption in Iceland. Importantly this information is available internationally but is particularly directed at agencies and sectors who may be impacted by distal hazards: the aviation sector and European civil protection in particular. Progress towards an alert level system for proximal hazards in Iceland has begun and will shortly be introduced on trial in Iceland by the Iceland Met Office.

These two deliverables (D3.1 and D3.2) comprise Task 3.2: 'Identification of appropriate response indicators of the Icelandic volcanoes, with the aim to improve early warning systems and preparedness'.

1.2 Additional opportunities during the Futurevolc project

Futurevolc Work Package 3 and its series of tasks and deliverables offer an unprecedented opportunity to research, document and facilitate the rapidly improving management and communication of volcanic hazards and risks in the North Atlantic and Europe.

This phase of the project has also included several opportunities. Futurevolc activities have taken place alongside significant volcanic unrest (Bárðarbunga 2014) and a long-lived fissure eruption (Bárðarbunga-Holuhraun 2014-15) providing unprecedented opportunities to implement and test in real-time new methods in both risk management and communication.

In addition, during this phase of the project, the UK Civil Contingencies Secretariat has implemented steps to plan for, and model the impacts of, a large magnitude fissure eruption scenario in Iceland. The UK now includes two Icelandic eruption scenarios in its national risk register.

There is also the UNISDR 2015 Sendai Framework for Action (SFA) on Disaster Risk Reduction which follows on from the Hyogo Framework for Action (HFA) 2000-2015. The HFA has been a useful blueprint for action in disaster risk reduction at national and international scales. These UN frameworks encourage nations to instigate monitoring, forecasting and early warning for natural hazards including volcanic eruptions. The frameworks also encourage preparedness, planning and assessment of hazards and risks. According to the results of our questionnaire in Deliverable D3.1, although the HFA has been familiar to some in civil protection, there is a perhaps surprising lack of awareness of HFA across sectors. The role of science and scientists in disaster risk reduction is a particularly important aspect of the HFA and SFA. Unfortunately, the essential underpinning role of scientists can still go unrecognised and documented evidence for the value of science to disaster risk reduction and disaster risk management is not as common as it should be. The Futurevolc project, in particular Work Package 3, will ensure that science is fully integrated into disaster risk reduction and disaster risk management in Iceland and beyond, and we will raise awareness of the post-2015 SFA and its potential within the Futurevolc project and beyond. We will compile the evidence to demonstrate the value of research science in DRR.

The Futurevolc milestones, deliverables and tasks have provided useful goals, active alongside these wider activities and initiatives, that have supported improvement of risk management and communication in real-time. EC FP7 Futurevolc funding has enabled European nations to collaborate scientifically and to contribute directly to more effective use of excellent science in risk communication and management.

2 Risk management and communication

Communication before, during and after a natural hazard situation is a key component in any prevention, mitigation and recovery operation. Communication of volcanic hazards and risks in the countries of Europe vary widely and are of many kinds: formal and informal, direct and indirect, between and inside, public and private institutions. The subject of this chapter is to analyse some of the key methods of communications now used by civil protection in Iceland and to account for some of the key stakeholders including the ERCC (see also Chapter 8).

Section 2.1 focuses on the Icelandic Civil Protection Alert Phase System. Section 2.2 focuses on the Scientific Advisory Board which ensures that national and international decision-making is based on the best possible scientific evidence and advice available at a given time. Section 2.3 focuses on the Icelandic National Crisis Coordination Centre (NCCC) and its role in Iceland and relationship with European civil protection (ERCC). Section 2.4 is on communication between Icelandic institutions and key stakeholders. Section 2.5 is on communication with the general public and media, via direct contact and social media. And finally, section 2.6 is on communication from the FUTUREVOLC project.

2.1 The Icelandic Civil Protection Alert Phase System

In accordance with the Civil Protection Act, Article 5, the Minister of Justice (now Minister of Interior) has issued a regulation (650/2009) on the Civil Protection alert levels, or phases (*Civil Protection Act No. 82*, 2008). According to the regulation the National Commissioner of the Icelandic Police is responsible for deciding on the alert levels in collaboration with respective District Police Commissioner, and to inform the minister of his decision.

In accordance with the regulation it is legitimate to issue alerts when an emergency situation is likely, imminent or ongoing. That goes for both natural and man-made disasters.

In the case of volcanic eruptions, seismic activity and other unusual geophysical activity a notification will come from the IMO, which is responsible for monitoring natural hazards in Iceland. If the issue is considered serious by the duty officers at the IMO and the Department of Civil Protection, the Scientific Advisory Board is summoned to a meeting, which will analyse the situation and evaluate the risk. After that meeting the Department Manager will advise the National Police Commissioner and the District Commissioner and suggest raising the alert level, if that is appropriate.

Here is a summary of the Icelandic Civil Protection Alert Levels:

Uncertainty Phase (Óvissustig):

Uncertainty phase/level is characterized by an event which has already started and could lead to a threat to people, communities or the environment. At this stage the collaboration and coordination between the Civil Protection Authorities and stakeholders begins. Monitoring, assessment, research and evaluation of the situation are increased. The event is defined and a hazard assessment is conducted regularly.

Alert Phase (Hættustig):

If a hazard assessment indicates increased threat, immediate measures must be taken to ensure the safety and security of those who are exposed or are in the area. This is done by increasing preparedness of the emergency- and security services in the area and by taking preventive measures, such as restrictions, closures, evacuations and relocation of inhabitants. This level is also characterized by public information, advice and warning messages.

Emergency (distress) Phase (Neyðarstig):

Emergency phase is characterized by an event which has already begun and could lead, or already has led to, harm to people, communities, properties or the environment. At this stage, immediate measures are taken to ensure security, save lives and prevent casualties, damage and or loss.

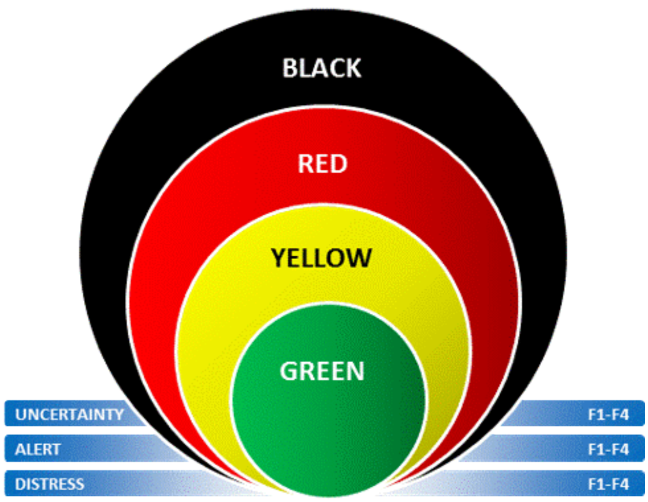


Figure 2-1 A diagram showing the NCIP phases of emergency. Severity is defined by the three alert phases (see text), urgency by levels F1-F4 and magnitudes by colours green to black (black most severe).

2.2 The Scientific Advisory Board in Iceland

The Department of Civil Protection and Emergency Management of the National Commissioner of the Icelandic Police (NCIP) has the obligation by law to coordinate the response of emergency situation that may threaten the life and health of the general public, the environment and/or property in Iceland (art. 1) (*Civil Protection Act No. 82*, 2008).

The department has for years operated an informal Scientific Advisory Board where scientists with specific knowledge on a variety of hazards, depending on the issue at hand, come together with staff members of the department to discuss the issue freely and informally. The emphasis here is on the informality of the scientific advisory board. The board is not mentioned in the law and therefore neither institutions nor individuals have a fixed position in it. On the other hand the law states that the department can request information and help from both public and private parties while preparing for, and during, operations (art. 18).

Individuals who attend those meetings cannot be held accountable for something that they said or did not say there. All members of the board are joined in the mission to help in times of crises in the spirit of civil duty. This working procedure is the cornerstone of the Scientific Advisory Board.

During a volcanic hazards and risk situation, like the one ongoing now at Bárðarbunga volcano, volcanologists, seismologists and other earth scientists from the Institution of Earth Sciences, University of Iceland, and IMO have been attending the meetings regularly from the onset of the operation. Meteorologists from IMO, representatives from the Icelandic Environmental Agency and the Directorate of Health have also attended the meetings from time to time.

The informal status of the advisory board has made it flexible in its operation which is reflected in the number of scientists and institutions who take a part in its meetings and in the number of meetings held.

In a normal situation or in a normal year, the NCIP has called for a meeting of the Scientific Advisory Board twice a year. The aim of these meetings has been to preserve and strengthen the close collaboration between the NCIP and the scientific community in Iceland, as well as to go over the latest research on natural hazards in Iceland.

During the current operation at Bárðarbunga volcano, which is the longest single operation in the history of the Department of Civil Protection, meetings of the Scientific Advisory Board have been held much more frequently to discuss the ongoing and persistent activity and the possible scenarios that have evolved with time. At the beginning of the operation, from August until the end of September, meetings were held daily or even many times a day. From October until the end of December meetings were held three times a week, and since January 2015 the Board has convened two times a week.

The Scientific Advisory Board is directed as to the needs and questions of stakeholders by participating members of NCIP and other sectors. Scientific discussion leads to a common understanding of key scientific evidence and issues, scientific terminology, uncertainties and gaps in knowledge between scientific organisations (which may represent different disciplines such as volcanology, meteorology and health) and between scientists and NCIP in particular. The Scientific Advisory Board usually ends its meetings by writing a joint statement on the status of operation, and in the current case, on the progress of the volcanic eruption. This statement aims for common and consistent language, a standardised format to summarize the discussion and provides a list of additional sources of information from contributors to the Scientific Advisory Board (e.g. IMO, UI, Department of Health). This statement is issued immediately after a meeting and provides a common official understanding of the changing situation and scientific evidence across sectors. These statements have been translated into English and are distributed to international media, to governmental agencies and other stakeholders in Iceland and overseas. The statements are sent out via email, published on the NCIP web site and on social media such as Twitter and Facebook (See section 2.5).

The Scientific Advisory Board directly informs, the National Crisis Coordination Centre (NCCC)

2.3 National Crisis Coordination Centre in Iceland

The National Commissioner of the Icelandic Police runs the National Crisis Coordination Centre (NCCC) which is located in Reykjavík. The Department of Civil Protection and Emergency Management runs the NCCC and is as such responsible for training the staff working in the NCCC. The term 'NCCC' is often used to describe the staff/committee active in the NCCC at any given time and its role.

The role of the NCCC staff/committee is to coordinate national response in Iceland during civil protection emergencies that affect several civil protection districts in Iceland, where the district Police Commissioner is responsible for the operation in their own district. The district Police Commissioner and civil protection committee can also ask the NCIP to take over an operation if they so consider.

The NCCC staff/committee comes from a number of organisations in emergency response in Iceland. These are:

1. The National Commissioner of the Icelandic Police
2. 112 Emergency Call Centre
3. Icelandic Coast Guard
4. The Icelandic Red Cross

5. The National Health Care system
6. ICE-SAR, volunteer search and rescue organization
7. The Capital area fire brigade
8. ISAVIA (air traffic control)
9. Several experts from other government agencies who participate in operations in an advisory role.

In late 2013 the setup of the NCCC was changed. That opportunity was used to introduce a new basic training course for the NCCC staff. The training course ran over three days and around 20 persons participated each time. From 2013 NCIP have run the course six times. Around 120 persons are now trained to work in the NCCC.

The basic training course for NCCC staff consists of three parts, several lectures and two separate exercises. The lectures are on topics such as the Icelandic incident command system, operational procedures, and operation planning and crisis information management. In the afternoon of day one of the course a short exercise on response to a mass casualty transport accident is run. The second exercise is larger in scope and runs over the better part of two days. The subject of the second exercise is response to an eruption at Hamarinn, a subglacial central volcano in the Bárðarbunga volcanic system underneath the Vatnajökull ice sheet. The scenario for this exercise includes both great amounts of volcanic ash and flash flooding (jökulhlaups) which calls for evacuations and a response to cutbacks in hydroelectric power production.

Other training of the NCCC staff mostly consists of short exercises, 3-5 hours in length. Two to four such exercises are held each year. The focus of most of these are mass casualty accidents. These shorter exercises usually are part of live exercises in the field when first responders and auxiliary manpower practice on the ground. The NCCC acts in its role as a national coordinating body in these exercises.

The Icelandic National Broadcasting Service (RUV) play a vital role in a civil protection situation, defined by law. RUV has a special broadcasting studio in the NCCC.

The NCCC media team is called out during periods of intense media pressure and during events of international interest. Media support is provided by Ministry press offices, Red Cross, ICESAR (Icelandic search and rescue team), Environment Agency and others. Provision of good and timely information and resources from the start helps stakeholders to understand their own information needs and enables planning and preparation across sectors.

The NCCC communicates with, and disseminates information to, a number of institutions, organisations, private enterprises, municipalities, committees, non-governmental organisations, researchers and individuals, during a crisis situation. To give an overview of these networks of communication a list is provided below showing primary email recipients. The numbers in the brackets represent the number of individuals or email addresses. In total these lists contain 1334 contacts of which several are civil protection agencies in Nordic countries, the UK and Europe.

- Icelandic Ministers and Permanent Secretaries (33)
- IMO national and international mailing list (450)
- Nordic Civil Protection (8)
- Foreign media emergency list (356)
- Icelandic stakeholders (109)
- Icelandic embassies (107)
- Icelandic media (48)
- Foreign Embassies in Reykjavík (43)
- Public administration (101)
- Tourist response list (46)

2.3.1 EU Civil Protection Training Programme

The National Training Coordination for the European Civil Protection Training Programme is hosted at NCIP. The department is sending all its duty officers to the Community Mechanism Introduction Course. This will make duty officers more capable of communicating effectively at a European level and will raise the level of knowledge to ask for or receive help in times of crisis. Duty officers at NCIP are responsible for communication with the Emergency Response Coordination Centre (ERCC) and the Common Emergency Communication and Information system (CESIS). In addition to the basic training (CMI) the NCIP is planning to train and have mission-ready 3-5 people at any given time. Today the NCIP has people who have started the training to be mission-ready, but they have reached different levels.

In 2012 NCIP sent 7 individuals from the civil protection sector in Iceland on EU courses. The NCIP sent 15 individuals in 2013, 6 individuals in 2014 and will probably send at least 5 individuals in 2015. The courses are:

- Community Mechanism Induction Course - CMI
- Technical Expert Course - TEC
- Operation Management Course - OPM
- Security Course - SEC
- Information Management Course - IMC
- Assessment Mission Course - AMC
- High Level Coordination Course - HLCR
- International Coordination Course - ICC

2.4 Communication between Icelandic Institutions

The Department of Civil Protection and Emergency Management (NCIP) is constantly in close contact and cooperation with a number of Icelandic institutions including scientific research institutions, private corporations, municipalities, private and public organisations and other key stakeholders. Writing contingency plans, carrying out hazard/risk/threat assessments and training, calls for a close cooperation and communication between potential stakeholders.

Since the volcanic eruptions at Eyjafjallajökull and Grímsvötn volcanoes in 2010 and 2011, NCIP has worked on a number of projects to improve communication with key stakeholders and to secure institutional learning, both within the department (NCIP) and within the wider community of institutions in Iceland as well as at the European and Nordic level.

The Futurevolc project has facilitated closer working between NCIP, IMO and UI in Iceland both in terms of research into volcanic processes, monitoring of unrest and eruptions but also in terms of recognising the need for clear information and communication on hazards and risks. The three Icelandic institutions taking a key scientific role in Futurevolc are all represented at Scientific Advisory Board meetings (IMO, UI, and NCIP). IMO, as an institution in charge of monitoring, provides information regarding the identification, the assessment, alert and forecast of natural hazards when possible and therefore fulfil the tasks of a volcano observatory for Iceland. Identifying, assessing and mitigating threats and risks is the role of NCIP (civil protection). UI carries out scientific research within and beyond Futurevolc which individual researchers share if it is of value in disaster risk reduction. The Futurevolc project has facilitated extensive real-time monitoring and therefore research discussions between Icelandic scientists and a variety of experts across Europe ensuring that the key information provided by high level and multi-disciplinary scientific discussions during SAB meeting, were delivered to NCIP for helping in the operational response.

The current volcanic eruption in the Bárðarbunga volcanic system in Holuhraun is both the longest ongoing operation in the history of the NCIP and also the largest volcanic eruption in Iceland for over 200 years. It has called for extensive communication and cooperation with countless institutions, organisations and private enterprises, both in Iceland and abroad.

2.5 Social media and communication with the general public

Communication with the general public is a principal task of the Department of Civil Protection (NCIP), especially during emergency situations. Providing information and data to the mass media, by issuing press releases and appearing in news programs and answering reporters' both directly and indirectly, is the classical form of those communications. Other institutions such as IMO and UI also communicate directly with the media and public but NCIP can significantly reduce the pressure on scientific organisations by taking a highly proactive stance. The emergence of social media, such as Facebook and Twitter, has fundamentally changed the relationship that an institution such as the NCIP, can have with the general public.

Communications become more open, direct and even personal, so the general public can now share and comment on the message sent out and query the sender directly. The general NCIP rule is to send out official press releases, when there is a development in a current event or a new event occurs, and then to post that official text on the NCIP web site and on Facebook.

The NCIP has operated a Facebook page (www.facebook.com/almannavarnir) since January 2011 and Twitter (https://twitter.com/almannavarnir) since April 2010. The Facebook page has been used more regularly and systematically over this period with steady increase in *Posts* and news. The Twitter account seems to have been almost completely inactive until the current operation during Bárðarbunga unrest and eruption, only 18 of the total 458 *Tweets* did not contain the hashtag #Bardarbunga.

Twitter is a somewhat unusual social media. It is not used as much as Facebook, by the public in Iceland and does not allow long texts. Twitter has been used mostly for foreign communication and to send links to official documents, such as minutes of the Scientific Advisory Board meetings. Twitter has proven to be a very good communication tool during the volcanic eruption in Bárðarbunga and a questionnaire aims to capture the evidence for this (see section 9 Next Steps). The foreign media is following new developments on Twitter using the hashtags #Bardarbunga and #Holuhraun. It has taken some pressure off the media team in the NCCC and partner institutions in Iceland, to be able to get information quickly and efficiently to the foreign media through social media such as Twitter.

The NCIP has seen the number of followers on both Facebook and Twitter grow over the years. The number of Facebook friends is now at 13,099 but was around 8.000 in August 2014. The Facebook posts reached 60,000 people during the peak of the Bárðarbunga event. The Twitter followers are now 3,816 and there the NCIP has seen a sharp increase following the events in Bárðarbunga. In August 2014 @almannavarnir had 212 followers and week later there were over 3,000.

But numbers of followers does not tell the whole story on Twitter. By using hashtags, the number of people who see your posts becomes much wider. When the seismic activity started in Bárðarbunga on 16th of August 2014 a conscious decision was made to promote and use the hashtag #Bardarbunga for the event. All tweets were marked with the hashtag and all new information on the development were tweeted as soon as they were officially approved for publication by the director of operations in the NCCC. The result was that in a period of 40 days, from mid-August until end of September, @almannavarnir got over 1.4 million impressions on Twitter.

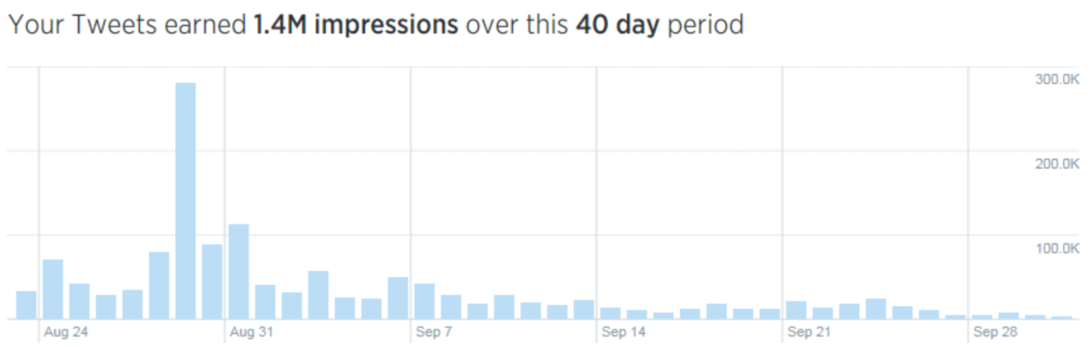


Figure 2-2 Screenshot showing impressions on the Twitter account @almannavarnir from mid-August 2014 till the end of September same year.

"Impressions" mean that the tweets have been delivered to the Twitter stream of Twitter users. It does not mean that everybody has read it, but it is rather a measurement of potential audience. In this case 1.4 million Twitter users were the potential audience of the unfolding events in Bárðarbunga.

Fortunately the volcanic eruption in Bárðarbunga did not affect the aviation industry. No flights were cancelled due to the eruption. The experiences during the Eyjafjallajökull eruption in 2010 and Bárðarbunga in 2014-15, both of which were long-lived indicate that using social media to communicate information directly from the NCCC to the general public can improve communication and save time for the duty officers, who might otherwise have to answer countless phone calls from journalists around the world.

II

Social media has also worked in the opposite direction, where the general public can provide vital information to the NCIP during a crisis. As it was the case during the power blackouts in December 2012, mobile phones were still working and online due to reserve power in the mobile telephone system, providing the public with access to Social Media.

At the end of December 2012 and into January 2013 a prolonged power blackout occurred in the West fjords, Iceland. The local power company in the area was, by coincidence, not well prepared for this kind of event, although the area has a long history of power blackouts due to extreme weather conditions and icing on the power grid. Another factor that was new to the equation at that time was the extensive usage of a new generation of smartphones, and the fact that the telephone companies had substantially improved the reserve power on the telecommunication grid.

The local power company had not taken social media into account in their contingency plan and had not started using social media to communicate information to their customers. As the power blackout became prolonged, social media became the platform for communication for the population in the area where discontent and frustration flourished. A duty officer at the NCCC in

Reykjavík was able to monitor the extent of electricity blackout in West-fjords by following public conversations on Facebook and managed to feed information into the community after contacting the repair team directly. The information did prove more precise and more up-to-date then the official statements from the power company. The community was reassured, knowing that everything was being done to shorten the power blackout and to restore full electrical power in the area.

As a result of this incident the local power company, and other electricity providers, have taken social media into their service and use it to communicate directly to their customers, and the NCIP is advocating for the use of social media in all contingency planning at international, national and local levels (Ríkislögreglustjórinn almannavarnadeild, 2013b).

III

The NCIP also uses its official web site (www.almannavarnir.is) to communicate with the general public, as has been mentioned above. The general rule in public communication is to send out press releases and publish that same text on the official website at the same time. The web site has a mailing list so people, and journalists, can subscribe to all news posted on the page. The web site is also available in English and French.

A new official web site is now being designed for the NCIP, which will open soon. In preparation for the new site, research was conducted on the usage of the web site (Haraldsson & Hugsmiðjan, 2014). The research showed that from August until the end of October 2014 over 93,000 visits were registered on the web site. Foreign traffic was 68% and domestic visits 32%. Mobile devices account for 41% of the traffic, which is above average in surveys similar to this one.

When the seismic activity started at Bárðarbunga in August 2014, it was all too clear to the duty officers at the NCIP and in the NCCC that the old, official web site of the NCIP would not work as a viable web site for the internet traffic expected due to foreign and domestic interest in the volcano. A temporary web site www.avd.is was therefore opened to communicate information in a format that would be accessible and readable on PC's, mobile phones, and tablets. The web site was both in Icelandic and English. Over 62,000 visits have been registered on the English web site since 5th of September and over 81,000 on the Icelandic web site.

In total 128 posts have been published on the Icelandic temporary web site and 65 on the English one, including a number of maps, pictures and graphs, explaining the progress of the eruption. The temporary web site has also been used to store minutes from the Scientific Advisory Board meetings (see section 2.2**Erreur ! Source du renvoi introuvable.**) and documents on the restricted area such as maps, regulations and application formats.

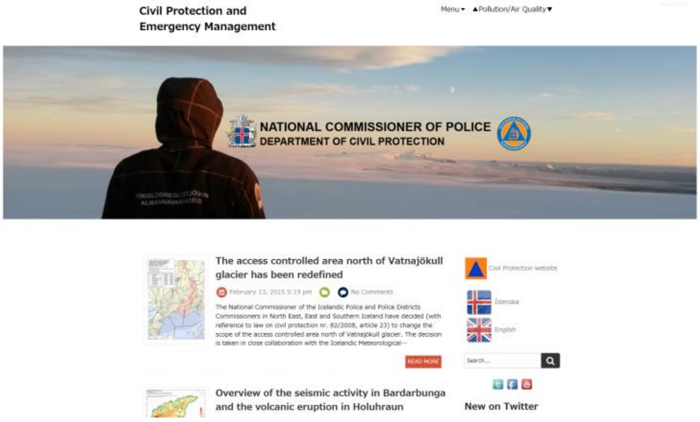


Figure 2-3 Screenshot of the Civil Protection web page www.avd.is

2.6 Communication of FUTUREVOLC research to official entities

As stated in the Introduction, a primary goal of Futurevolc is to ensure that excellent scientific evidence is being made available and accessible for decision making. Decisions are made by scientists, civil protection agencies, government departments, first responders, the aviation sector, the public and others before, during and after volcanic eruptions. These decisions may then influence risk, risk management and risk communication.

The NCIP has used the FUTUREVOLC research outputs, discussion outcomes, contacts and lessons learnt, during the operational response to the Bárðarbunga eruption. This has primarily been through the Scientific Advisory Board, members of which have participated in near real-time research discussions with the Futurevolc teams before updating the Board. This is an excellent example of scientific research supporting operational response in a timely manner.

In general the cooperation and collaboration between NCIP, IMO and the Institute of Earth Sciences at the University of Iceland has become even closer than before the Futurevolc project. The Futurevolc project has initiated numerous opportunities for cross-disciplinary discussion and debate and for the project and collaborative relationships within Iceland and across Europe to be highlighted by the media. The Futurevolc project gives a clear indication that 26 scientific organisations across Europe are working together collaboratively and effectively to jointly reduce volcanic risk. The clear processes and procedures described above are a critical framework that enable a research project like Futurevolc to achieve impact. In this case, the science, process and procedures are being improved concurrently through collaboration and cooperation.

Numerous scientific participants in the FUTUREVOLC project have visited NCIP and the NCCC over the course of the project so they understand how their research can have rapid and meaningful impact.

3 The Icelandic Aviation Colour Code System

3.1 Background

Following lessons learnt from the volcanic eruptions in Eyjafjallajökull in 2010 and Grímsvötn in 2011 an agreement was made between IMO and ICAO to apply the ICAO Aviation Colour Code (ACC) system on all volcanic systems in Iceland (Þorkellsson, 2012, p. 121). This system is described in Futurevolc deliverable 3.1 and its implementation in Iceland comprises MS19. The first map showing the ACC for each of Iceland's volcanoes was issued by the IMO in April 2012 and is now updated weekly and published on the IMO website. Any change in the ACC is sent real-time as an email notification to the London VAAC, BGS, UK Civil Contingencies Secretariat (civil protection), ERCC and others who distribute the information further across the European transport sector in particular.

The ACC system is not a universal and standardized global aviation system, which air-traffic control have a duty to use. The system has been developed by ICAO, independent national volcano observatories and the World Organization of Volcano Observatories (WOVO) and is optional. The system was designed to work as a notification tool to inform aviation stakeholders of the status of volcanoes and enable planning to divert aircraft around volcanoes showing escalating unrest or ongoing eruption if considered necessary (WOVO, 2010). In Iceland, the IMO is responsible for monitoring natural hazards including volcanoes and seismic activity (*Icelandic Met Office Act*, 2008). IMO is also, among other things, responsible for monitoring, predicting and issuing warnings for weather, floods and avalanches. To meet its obligations the office runs a 24/7 observation centre. The duty officer at the centre will be the first person to notice any unusual monitoring data or receive other direct information about the volcanoes. The duty officer will then notify a specialist at the IMO Earthquake Hazards division. If the specialist considers the issue to be grave, a phone call will be made to The National Commissioner of The Icelandic Police Department of Civil Protection and Emergency Management (NCIP), which has a duty officer on standby 24/7.

The NCIP is responsible for coordinating the response to an emergency situation that may threaten the life and/or health of the general public, the environment and/or property in Iceland (*Civil Protection Act No. 82*, 2008). The NCIP duty officer will further notify relevant police district officers, head of the local civil protection committee and so forth.

The IMO duty officer will also notify ISAVIA, responsible for air-traffic control in Iceland and in the Reykjavik control area, covering 5.4 million square kilometres in the North Atlantic and the London VAAC (now using the EMARC notification).

A process has not been defined by the IMO on how it is formally decided to change the ACC for a specific volcano (*Personal communication with IMO*, 2015). It is well-defined by ICAO what each colour stands for and what it means to raise or lower the colour code for a specific volcano, but the formal process for the scientific decision making has not been defined. This process is necessarily based on scientific judgement and can range from informal (based on semi-structured discussion) to formal (based on pre-defined thresholds and expert elicitation). This process is now being worked on in Iceland. The worldwide implementation of the ACC system has been investigated recently (Winson et al., 2015) and it is clearly applied differently in different places depending upon context, volcano type and other factors. Until now, in the cases described below, the decision to change the ACC has been made through discussion between the scientists at IMO in close collaboration with NCIP and ISAVIA.

3.2 Implementation

The first incident causing IMO to implement a colour change on an Icelandic volcano following the implementation of the ICAO Aviation Colour Code system came on 23rd of March 2013 when Hekla was raised to *Yellow* due to unusual seismic activity (Ríkislögreglustjórinn almannavarnadeild, 2013c). This situation only lasted until 4th April 2013 when Hekla returned back to normal status and was put back on *Green* (Ríkislögreglustjórinn almannavarnadeild, 2013a). Such episodes of unrest are not uncommon and provide an opportunity for all stakeholders in Iceland and overseas to check that contingency planning is in place should the situation escalate. Before the ACC system was implemented, some concerns were expressed that access to real-time information about unrest episodes, especially by those overseas (including official responders in governments and the media) might lead to over-reaction or over-familiarity (under-reaction). In particular, there were fears that raising the colour code for an episode of unrest that does not lead to an eruption might be considered a 'false alarm' and response to subsequent escalation in unrest might be tardy as a result. Implementation has not shown evidence for either type of response. In fact the ACC system appears to have enabled a broad sector of society across Europe to become more informed about, and familiar with, Iceland's volcanoes and their behaviour over time. This increased level of awareness and knowledge appears to be leading to improved evidence-based decision-making in a number of countries across Europe (e.g. UK and Norway). The ACC system is clearly a status notification and not an 'alert' – it appears to be being received for what it is – a useful piece of information to support other formal advice and information.

The hypothesis that implementation of the ACC system, concurrent improved international reporting and communication methods have enhanced awareness and knowledge across Europe will be tested in the next steps of the Futurevolc project (see Chapter 9).

The first real test for the newly implemented ACC system came in August 2014 as seismic unrest began under the Bárðarbunga volcano located under the northern part of the Vatnajökull ice sheet. The unrest was intense, unusual and scientific interest was piqued worldwide. Earthquakes were clearly migrating laterally at depth suggesting fracturing was moving towards the NE. Of primary interest was the question of whether the unfolding event was tectonic, magmatic or both? A particularly strong wave of seismic activity started on 16th of August 2014, and the Bárðarbunga ACC was raised to *Orange* due to the increased likelihood of a volcanic eruption under the ice that might produce an ash cloud similar in nature to the ones during the Eyjafjallajökull in 2010 and Grímsvötn 2011 eruptions. On 23rd of August observations suggest that a small eruption had started under the glacier due to the start of distinctive seismic signals. The volcano was put on *Red*, indicating an ongoing eruption (Ríkislögreglustjórinn almannavarnadeild, 2014a). All flights were banned in the area and notifications sent out through ISAVIA, the Icelandic Air Traffic Control Agency.

One day later the flight ban was lifted as there was no expression of volcanic activity at surface and the volcano was put back to *Orange* status (Ríkislögreglustjórinn almannavarnadeild, 2014b). Scientists concluded that an eruption had not started. Later, however, when volcanologists and other earth scientists' had gone over data collected during subsequent days, they would actually conclude that it was most likely that small volcanic eruptions *had* taken place under the very thick ice. None of these managed to break through the ice sheet but they did, after a few days, create depressions on its surface. This challenge of dealing with decision-making under uncertainty is targeted through a multidisciplinary volcanological monitoring FUTUREVOLC project.

On the 28th of August a swarm of earthquakes started at Askja volcano located northeast of the Vatnajökull ice sheet. This unusual seismic activity at Askja has been shown as to be a response to the changes indusec by the dyke propation within the crust. The volcano was put on *Yellow* ACC due to its seismic unrest.

A few minutes after midnight on 29th of August a subaerial fissure eruption started at Holuhraun just north of Dyngjujökull, a glacier extending from the Vatnajökull ice sheet. Bárðarbunga volcano was raised to ACC *Red* and ISAVIA closed down the surrounding airspace up to 18000 feet for instrumental flights (Figure 3-1). At 10:00 o'clock that same day the ACC was changed back to *Orange* since the eruption had stopped.

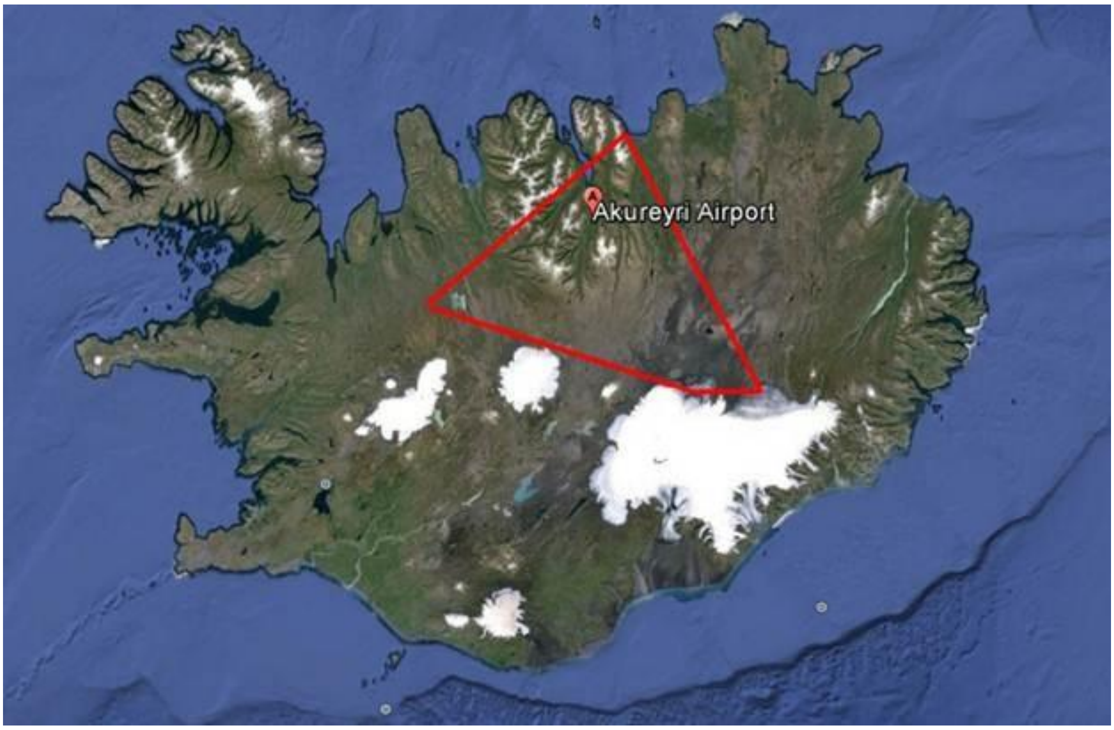


Figure 3-1 The airspace north of Vatnajökull closed off by ISAVIA for instrumental flights on the 29th of August 2014. Image: ISAVIA.

On 31st August, at 05:15, another fissure opened in the vicinity in the previous 29th August eruption at Holuhraun. Again the Bárðarbunga volcano was elevated to *Red* in accordance with the ACC system but lowered back to *Orange* in the afternoon, around 14:00. This eruption did stop on the 27th of February 2015. and lasted for 181 days, creating a lava field of 85 km^2 or 1.4 km^3, making it the biggest volcanic eruption in Iceland since the Lakagigar eruption (Laki) in 1783-84.

All indications at the current time suggest that implementation of the ACC has helped in risk management and communication. There have been difficulties in scientific decision-making under uncertainty (when and for what reason to change ACC) and this will be explored further.

III

The table of Icelandic volcanoes (Table 3-1), is a key product of the Icelandic ACC system. The list is taken from a document by IMO (EBE-032-3) sent weekly to the London VAAC. The document lists up all Icelandic volcanoes, their geographical position, Smithsonian Institution GVP number, current ACC, and (if relevant) a short description of current situation.

The map below (Figure 3-2*)*, shows the Icelandic volcanic systems with ACCs at the time of writing (January 2015). As can be seen on the map, Bárðarbunga volcano is marked *Orange*. All other volcanic systems are *Green* except

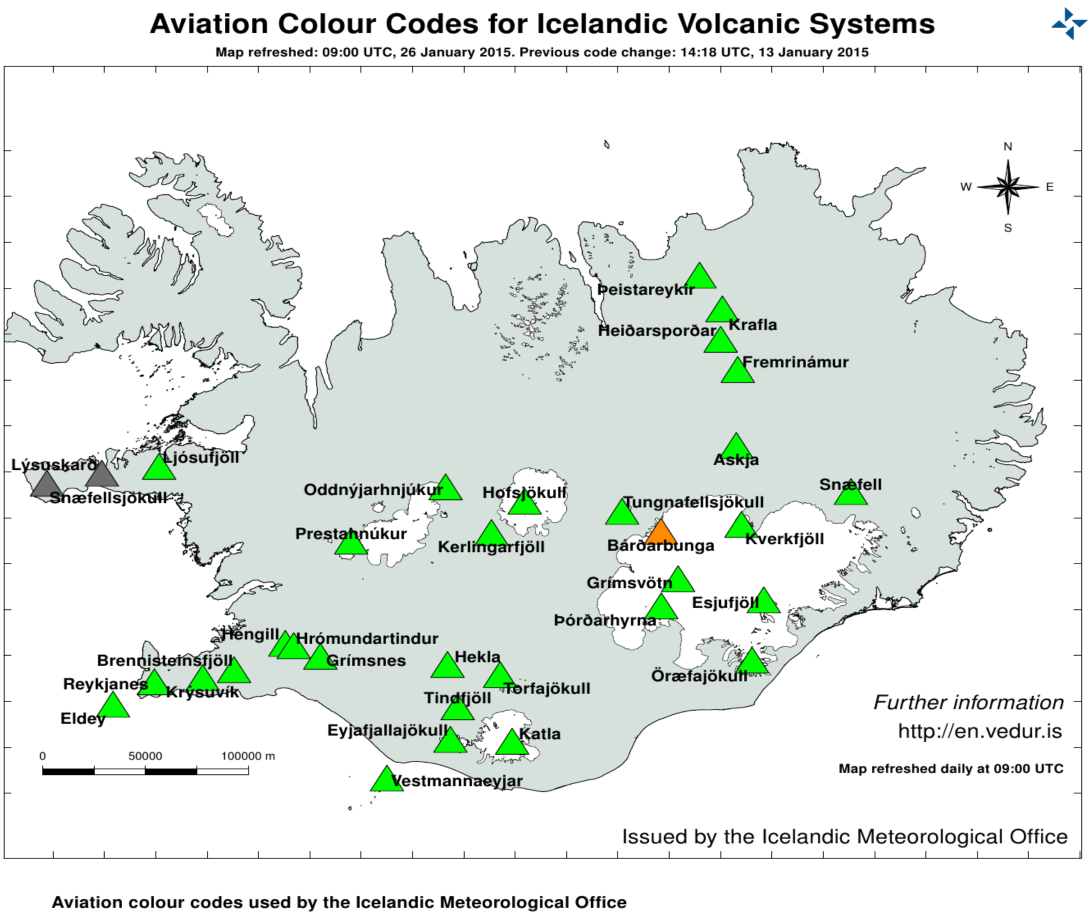
Snæfellsjökull and Lýsuskarð which are *Grey* signifying that these two volcanoes appear quiet but are not monitored adequately. All other volcanic systems in Iceland are adequately monitored and are in normal non-eruptive state and marked *Green*.

No	Volcano name	Latitude	Longitude	Smithsonian #	Colour code (G, Y, O, R)	Status description *[date]*
1	*Askja*	65.0457°	-16.7130°	373060	G	-----
2	*Bárðarbunga*	64.6368°	-17.5148°	373030	G	-----
3	*Brennisteinsfjöll*	63.9408°	-21.7922°	371040	G	-----
4	*Eldey*	63.7444°	-22.9674°	NA	G	-----
5	*Esjufjöll*	64.2875°	-16.5001°	374020	G	-----
6	*Eyjafjallajökull*	63.6261°	-19.6364°	372020	G	-----
7	*Fremrinámur*	65.4290°	-16.6590°	373070	G	-----
8	*Grímsnes*	64.0203°	-20.9406°	371060	G	-----
9	*Grímsvötn*	64.4166°	-17.3166°	373010	G	-----
10	*Hekla*	63.9917°	-19.6733°	372070	G	-----
11	*Hengill*	64.0784°	-21.2945°	371050	G	-----
12	*Hofsjökull*	64.7909°	-18.9031°	371090	G	-----
13	*Hrómundartindur*	64.0685°	-21.2092°	371051	G	-----
14	*Katla*	63.6352°	-19.0833°	372030	G	-----
15	*Kerlingarfjöll*	64.6375°	-19.2413°	NA	G	-----
16	*Krafla*	65.7142°	-16.8025°	373080	G	-----
17	*Krýsuvík*	63.8959°	-22.0991°	371030	G	-----
18	*Kverkfjöll*	64.6593°	-16.6931°	373050	G	-----
19	*Ljósufjöll*	64.9158°	-22.6664°	370030	G	-----
20	*Lýsuskarð/*	64.8669°	-23.2487°	370020	*	-----

No	Volcano name	Latitude	Longitude	Smithsonian #	Colour code (G, Y, O, R)	Status description *[date]*
	Helgrindur					
21	*Oddnýjarhnjúkur*	64.8592°	-19.7145°	371080	G	-----
22	*Prestahnúkur*	64.5864°	-20.6675°	371070	G	-----
23	*Reykjanes*	63.8647°	-22.5741°	371020	G	-----
24	*Snæfell*	64.7982°	-15.5588°	NA	G	-----
25	*Snæfellsjökull*	64.8012°	-23.8023°	370010	*	-----
26	*Tindfjöll*	63.7858°	-19.5678°	372040	G	-----
27	*Torfajökull*	63.9441°	-19.1500°	372050	G	-----
28	*Tungnafellsjökull*	64.7374°	-17.9075°	373040	G	-----
29	*Vestmannaeyjar*	63.4332°	-20.2506°	372010	G	-----
30	*Þeistareykir*	65.8819°	-17.0319°	373090	G	-----
31	*Þórðarhyrna*	64.2724°	-17.5318°	373010	G	-----
32	*Öræfajökull*	63.9955°	-16.6433°	374010	G	-----

Table 3-1 The table of Icelandic volcanic systems developed by IMO for ACC system notifications.

* Volcano appears quiet but is not monitored adequately. Absence of unrest confirmed. Shown as grey in the map.



GREY: Volcano appears quiet but is not monitored adequately. Absence of unrest unconfirmed.

GREEN: Volcano is in normal, non-eruptive state.
or, after a change from a higher alert level:
Volcanic activity considered to have ceased, and volcano reverted to its normal, non-eruptive state.

YELLOW: Volcano is experiencing signs of elevated unrest above known background levels.
or, after a change from higher alert level:
Volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.

ORANGE: Volcano is exhibiting heightened unrest with increased likelihood of eruption.
or, Volcanic eruption is underway with no or minor ash emission.

RED: Eruption is forecasted to be imminent with significant emission of ash into the atmosphere likely.
or, Eruption is underway with significant emission of ash into the atmosphere.

Figure 3-2 Aviation Colour Code map issued on 26th January 2015.

4 Catalogue of Icelandic Volcanoes

4.1 Eruption histories

On 25th of August 2014, the IMO with University of Iceland, published on-line a pre-publication of the catalogue of the Icelandic volcanoes dedicated to the Bárðarbunga volcanic system. The publication is, as stated in a note to the reader, an *"extract from the Catalogue of Icelandic Volcanoes. The full Catalogue will be made publically available in the coming months. The Catalogue of Icelandic Volcanoes is a collaboration of Icelandic Meteorological Office, Institute of Earth Sciences University of Iceland, and Iceland Civil Protection. The Catalogue is funded by International Civil Aviation Authority and the European Community's Seventh Framework Programme under Grant Agreement No. 308377 (Project FUTUREVOLC)"* (Larsen & Guðmundsson, 2014).

This catalogue, which is one of the products of FUTUREVOLC (WP4), provides background information about high risk Icelandic volcanic systems, including known eruption histories. The information will be in a standardized format, in English, and will be accessible for public and professionals' world-wide working in research, disaster mitigation and prevention. It improves eruption histories currently available via the Smithsonian Institution Global Volcanism Program (GVP), and indeed the new catalogue will be made available to GVP so they can update their 'Volcanoes of the World' database.

4.2 Eruption scenarios

The catalogue also contains information about possible future eruption scenarios at a given volcano. In the case of Bárðarbunga, these scenarios are numerous because an eruptive vent could in fact be almost anywhere along the 190km long system and its location will partly dictate what happens next. Eruptions may occur subaerially, subglacially, be of various eruption types and magnitudes, and glacier floods may affect drainages to the north or west each with significantly different impacts. Once a volcano has started to erupt, the eruption may evolve in different ways so a variety of scenarios for the evolution of the eruption is also necessary. Again, in the case of Bárðarbunga 2014, although the eruption began as a fissure eruption beyond the ice sheet, seismic activity continued below the summit caldera so the scenario of a subglacial explosive summit eruption was not ruled out.

The eruption scenarios developed for the Catalogue were used in the daily reports issued by NCCC for both the Bárðarbunga and Askja volcanoes. These volcano-specific scenarios demonstrate some of the uncertainty surrounding the evolution of volcanic unrest and eruptive episodes.

5 Bárðarbunga Volcanic Unrest and Eruption 2014-2015

The main eruption at the Bárðarbunga volcanic system, which started on 31st of August 2014 has resulted in the largest volcanic eruption in Iceland since Laki in 1783-4 and has dominated the day-to-day operations of the NCIP and IMO over the last six months (time of writing January 2015). The operation has already become the longest ever continuous operation of the Civil Protection Department, absorbing all its man-power and resources.

Real operations are essentially different from theoretical training sessions and research projects, they do not follow a pre-prepared plan. In order to avoid being entirely responsive to real-time events, planning, preparation and exercises are needed. Institutional learning is generally based on reviewing recent events with the ambition to learn from past mistakes and to enhance future preparedness.

The previous two volcanic eruptions in Iceland were explosive eruptions underneath glaciers that produced dispersing ash clouds which threatened the viability of air travel over the North Atlantic. A great deal of recent institutional learning at NCIP has been focused on these recent events and aviation safety as a result of volcanic ash. A, long-lasting, lava eruption with significant gas emissions, did not fit the 'model' of recent volcanic eruptions and so had not been planned for. Potential hazards such as gas emissions, or a glacier outburst flood (jökulhlaup) down Þjórsá, a river system responsible for about 40% of Iceland's electricity production had also not been considered in national planning.

In the UK, a national risk register is maintained and following the 2010 eruption of Eyjafjallajökull volcano a number of different past eruption scenarios with well-documented impacts were considered for national planning. One of these is a fissure eruption based on the Laki 1783-84 eruption, a scenario perhaps one order of magnitude larger than the Bárðarbunga eruption. Such planning provided useful in the UK – it enabled the UK to quickly decide in August 2014 that the situation had been planned for, procedures were in place, and therefore emergency responses such as a 'Scientific Advisory Group in Emergencies' were not necessary in this case. Underpinning this decision was nevertheless the need for regular reliable and detailed information about the evolution of the eruption, just in case the situation should change.

5.1 Gas and aerosol emissions (proximal and distal hazards)

Volcanic gas emissions, in particular sulphur dioxide ($S0_2$), is a hazard that has not been considered an issue in Iceland since Laki in 1783. The fact that volcanoes produce dangerous gases did not in itself come a surprise to Icelandic volcanologists nor NCIP duty officers but the quantity did, since gas emissions sufficient to impact society had not been documented in an Icelandic volcanic eruption for over 200 years. Nevertheless, gas emissions are a routine hazard at many volcanoes worldwide, even when there is no lava or volcanic ash being erupted. The question for NCIP became how to respond to a hazard of this kind? What are the implications? What are the risks?

There were mainly three institutions that worked with the NCIP on the gas pollution: The Environmental Agency of Iceland, the Chief Epidemiologist for Iceland at The Directorate of Health and the Occupational Safety and the Health Authority. Dr Peter Baxter, a public health consultant from Cambridge University Addenbrookes Hospital and expert on the health impacts of volcanoes was consulted extensively. He has worked at many volcanoes worldwide and contributed to documents available at the International Volcanic Health Hazards Network (IVHHN). These Icelandic institutions issued a document in September 2014 titled: *Health Effects of Short-term Volcanic S02 Exposure and Recommended Action* (see Appendix 1: FUTUREVOLC Communication: 11.4). The document was introduced to the mass media and published on official web sites of the institutions and social media (see chapter on social media below).

The Environmental Agency, in close collaboration with the IMO, started monitoring the gas pollution at ground level in populated areas and publishing data on the gas concentrations in real-time on its official web site www.loftgaedi.is (and in English on www.airquality.is).

The IMO also published notices and rapidly developed an interactive *gas dispersion model* with outputs showing three days forecasts for Iceland on its web site www.vedur.is (see Appendix 1: FUTUREVOLC Communication: 11.5 and **Erreur ! Source du renvoi introuvable.**). This is an example of a 'fit-for-purpose' communication tool in the sense that despite scientific uncertainties, the model outputs were valuable in allowing the public to understand the potential variation in emission dispersal directions s well as possible variations in concentrations. This tool facilitated decision-making at an individual and family level right up to government levels.

The NCIP held a number of formal and informal meetings with a variety of institutions and individuals to facilitate coordination while preparing for the publication of these documents, models and web tools. Following publication in the media the NCIP organized a number of community meetings where volcanologists, air quality specialists, health workers, local police and NCIP duty officers explained the development of the volcanic eruption, the existing contingency plans, the recommended response gas hazard and answered questions from the general public.

The NCIP duty officers also monitored the day-to-day and hour-to-hour modelled dispersion and measured concentration of the gas pollution and issued warnings when concentrations reached, or went over, defined health thresholds. On a number of occasions text messages where sent out to all mobile phones in a defined area with warnings about an imminent health threat from gas pollution.

The timely reports about the eruption from Iceland and discussions with UK Met Office and BGS enabled the UK Government Civil Contingencies Secretariat and

Government Office for Science to decide at an early stage (August-September 2014), that risks to the UK mainland at ground level (health) were likely to be low. The eruption was smaller than the scenario the UK has planned for. In the UK, the Scientific Advisory Group in Emergencies (SAGE) is called at the discretion of the government's Chief Scientist and usually only if an event exceeds established planning and expectations or if the Chief Scientist or other government staff need a rapid and thorough update. It was not called for the Bárðarbunga eruption thanks in part to excellent reports and communications from Iceland that reduced uncertainty and provided the evidence needed to make a decision. It was decided NOT to pursue an emergency response and hence saved considerable time and resources.

Several institutions including the UK Met Office used satellite remote sensing combined with dispersal modelling and routine ground based measurements of SO_2 and air pollution (PM_{10} and $PM_{2.5}$) arising from atmospheric conversion of SO_2, to monitor impacts at UK ground level or to UK air space. Given that the eruption was an order of magnitude less than the planning assumption (Laki 1783-84), the detected levels provided confidence in the recent Laki scenario impact modelling outputs (see section 7). Hazardous levels of SO_2 were detected once at ground level in Ireland. Increased levels of SO_2 and particulate matter were detected in the UK on separate occasions. Another ongoing research project in the UK is investigating the potential risks to aircraft passengers of airborne clouds of SO_2 and other gases.

There are no separate aviation guidelines concerning avoidance of volcanic gas and aerosol clouds. Nevertheless, advice is clear that any volcanic clouds are best avoided as it is not possible for a pilot to know in real-time what the exact constituents of the cloud are or their potential impacts on air frame, components and passengers. A sulphurous smell is suggested as an indicator of the need to change track. The International Airways Volcanic Watch (IAVW) give the following operational guidance to pilots:

'4.9.2 Volcanic eruptions emit various gases along with magma, including sulphur dioxide (SO2) and hydrogen sulphide (H2S). Volcanoes are the only sources of large quantities of sulphur gases at cruise altitudes, and both SO2 and H2S are detectable by smell. Thus, the smell of sulphur gases in the cockpit may indicate volcanic activity that has not yet been detected or reported and/or possible entry into an ash-bearing cloud. In some cases when sulphur gases are smelled, there may be little ash in the cloud owing to ash fallout during prior dispersion of the cloud, but flight crew do not have the means to determine directly that the cloud is non-hazardous and thus should seek to exit the cloud.'

Gas dispersal models have been made available to EasyJet by Fred Prata (Futurevolc, Norway) during the Bárðarbunga eruption and a future report will document how such products have been used by the private sector.

It is safe to say that volcanic gases issue have been a major, if not the dominating, hazard of the Bárðarbunga/Holuhraun eruption.

5.2 Flood hazards and scenarios (proximal)

During the increasing seismic activity at Bárðarbunga in August 2014 it became clear that a volcanic eruption in the Bárðarbunga summit caldera and along the fissure zone under the ice cap could produce a glacier outburst flood (jökulhlaup) with potential tremendous consequences for Iceland's electricity production. A flood could go down three different rivers depending on the exact location of the volcanic vent. The most likely path would be to the north down Jökulsá á Fjöllum (scenario I). Therefore that area was evacuated and defined as a *Restricted area* on the 19th of August 2014 and closed to all traffic except with permission from the NCIP (see Appendix 1: FUTUREVOLC Communication: 11.1). The proximal area at risk around this drainage, near to the ice cap, is in fact the eventual site of the fissure eruption. This meant that flooding (Jökulhlaup) was one of the most severe hazards that scientists working at and around the eruption site were exposed to.

Another possible path for the flood was to the northwest down Skjálfandafljót river (scenario III), and the third way was to southwest down Tungná and Þjórsá rivers (scenario II), a river system harnessed for about 40% of Iceland's hydro electricity production. With the Icelandic economy highly dependent on producing electricity for aluminium smelters, this potential threat quickly became a top priority for NCIP and the Icelandic government.

All of these rivers are major rivers in Iceland, draining the glacial water from Vatnajökull ice sheet to the sea. Major historical floods are known in Jökulsá á Fjöllum but the other two are only known for seasonal flooding due to melted snow on the glacier and in the highlands. This eruption provided the opportunity to greatly enhance assessment of hazards and risks due to flooding – IMO considered water volumes, velocity and likely area affected - to give hazards footprints upon which risk assessments could be based.

NCIP in collaboration with Icelandic Catastrophe Fund (Viðlagatrygging Íslands) established a task force to analyze these three scenarios in relation to possible flood size and distribution area, and the social and economic impact they would have. Legal obligations of different institutions and private enterprises were also looked at and key stakeholders were asked to provide their 'own view of risk'.

During 12 days, from 11th – 23rd of September, countless meetings were held with key stakeholders in the electricity production and distribution sector, and in the telecommunication sector. Police District Commissioners, the Public Roads Administration, earth scientists and engineers were also key contributors to the project product, a report presented to the Prime Minister and his cabinet on 23rd of September 2014 (Ríkislögreglustjórinn almannavarnadeild & Viðlagatrygging Íslands, 2014).

The main findings of the report, published publicly, in a slightly edited edition due to security issues, on 27th of October 2014, were that a flood down Tungnaá and Þjórsá, Scenario II, could cause tremendous disruption to Iceland's infrastructure and basic structure of the community. The threat was considered the most severe ever faced by Iceland, excluding only military threat from the Cold War era.

Based on the report's findings the NCIP hired a specialist from Verkís (an engineering firm) to lead a project group that would write a preliminary contingency plan for Scenario II, a 6000 m^3/sec flood down Tungnaá and Þjórsá. Again the mission was to work fast and to involve key stakeholders and interested parties and to have the process as open as possible to get the attention of those who would be affected by the flood.

As the work progressed, with a number of large open meetings, it became clear that quite a few of those who might be affected by such a flood were unaware of that fact. As it turned out, this open policy resulted in greater and growing awareness of the issue. A number of key sectors, institutions and corporations, updated or even wrote their first contingency plan, where emphasis was on access to reserve electricity capacity and substitutional telecommunication.

The NCIP and Verkís issued a Status Report on the 18th of December 2014 were the progress of the work was presented and the interested parties encouraged to finish the project by issuing a valid contingency plan for the flood prone area as soon as possible (Ríkislögreglustjórinn almannavarnadeild & Verkís, 2014).

6 Scenarios for European impacts

6.1 Building resilience to natural hazards using scenarios

National planning for adverse natural hazards events is typically carried out in civil protection departments of national governments. The Hyogo Framework for Action (2000-2015) provided a clear framework for governments to identify activities that can help assess national risks, mitigate them where possible and build national resilience. The post-HFA strategy on Disaster Risk Reduction (DRR) will be launched in March 2015 and members of the Futurevolc consortium have contributed to the new strategy. The Futurevolc consortium offers an opportunity to support coordination of national DRR efforts at a European regional scale. In an ideal world, planning would be based on fully probabilistic assessments that cover all hazards scenario possibilities as well as aspects such as likelihood, frequency and magnitude. In reality, such an approach is not possible at a regional scale (considered here) due primarily to lack of resource (computer time and person time).

A pragmatic approach is to select some well-characterized scenarios on which to base planning. Such scenarios are usually based on historical events so that existing data on the hazard and its impacts can be analysed. The approach may include running multiple simulations of the chosen scenario to maximise understanding of the potential variability of particular complex systems. When considering potential distal impacts it's essential to identify what the first order controls on dispersal of potentially hazardous materials are (e.g. eruption mass flux, eruption column height, wind speed and direction) and their relative influence on distal impacts.

There is not sufficient resource in Futurevolc to actually carry out full scenario planning across Europe. Instead, we suggest some possible scenarios for consideration. We have investigated the planning efforts made by the UK and Iceland in recent years. We document these methodologies, we identify the Futurevolc contributions and make recommendations for the future which will be addressed in Deliverable D3.3 (Improving risk communication).

6.2 Frequency and magnitude of eruptions in Iceland

There are 30 volcanic systems in Iceland but only four of them (Hekla, Katla, Grímsvötn and Bárðarbunga) are responsible for ~90% of historical eruptions (in the last 1100 years). These systems have been the focus of Futurevolc research (Thordarson and Larsen, 2007).

Records of volcanic eruptions in Iceland compiled based on both geological and historical evidence and going back to the 9th century show that the *average* frequency of any type of recorded eruption in Iceland is one in every 4-5 years

(Iceland catalogue in prep. Futurevolc WP4). However, it is well known that as one goes back in time it is increasingly likely that some eruptions have gone unrecorded (Figure 6-1). The frequency of eruptions in the last two to three centuries since written records improved is the best empirical basis for future assessments. Over this time period, eruptions have occurred every 3-4 years and eight eruptions have occurred since 1991. There is some variability and clustering in the temporal distribution of eruptions. Globally, there is similar clustering, and large eruptions are most likely to occur during episodes of frequent volcanic activity. There may also be cyclicity. Thordarson and Larsen (2007) recognised a cycle of approximately 140-200 years duration in terms of frequency of eruptions (see Figure 1b showing a peak of 11 eruptions between 1721-1740).

In terms of frequency-magnitude relationships, large magnitude events are of course less frequent (Table 6-1). Over the 1100 year historical period it's unlikely that eruptions of more than 5km^3 magma went unreported. However, it's very likely that smaller eruptions were unreported before the eighteenth century when written records improved. The average recurrence time for smaller eruptions over the last 2-300 years is close to every 5 years.

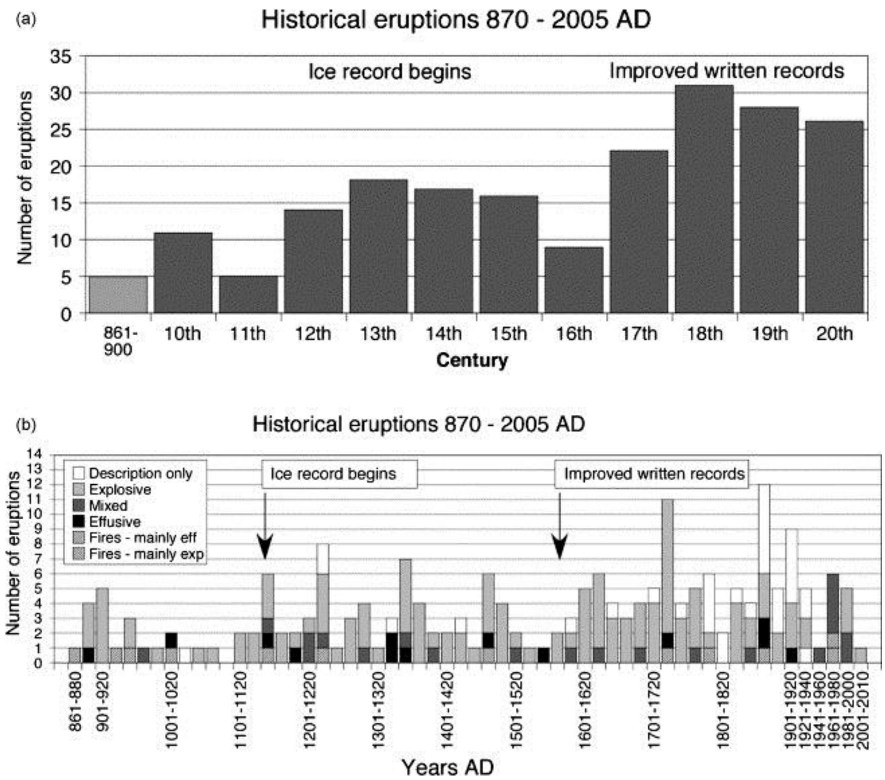


Figure 6-1 Eruption frequency and type in Iceland to 2007 ('Fires' are fissure eruptions). Explosive eruptions are the most common type (from Thordarson and Larsen, 2007).

Table 6-1 Recurrence times and size of all eruptions in Iceland (based on Gudmundsson et al., 2008), for the last 1100 years.

Recurrence time (yrs)	**Volume of magma in km^3 (DRE erupted as tephra and/or lava)**	**Example**
5-10	<0.01	flank eruption of Eyjafjallajökull 2010
5-10	0.01-0.05	Hekla 2000,
10	0.05-0.1	
10-20	0.1-0.5	Eyjafjallajökull 2010; Grímsvötn 2011
50	0.5-1.0	Hekla 1947
100	1-5	Bardarbunga (2014-2015)
500	5-10	Bardarbunga ~870
500-1,000	>10	Laki (Grimsvötn) 1783, Katla 934

6.3 Eruption characteristics in Iceland

For the purposes of this report, we only consider eruption scenarios that may be hazardous or disruptive at a regional scale. We therefore focus on eruptions that produce volcanic ash and/or volcanic gases which may be dispersed by prevailing winds across Europe. We also consider significant proximal impacts in Iceland which will also have repercussions across Europe. The term ‘tephra’, used below, refers to fragments of magma of a variety of sizes from large volcanic ‘bombs’ to fine volcanic ash and nanoparticles. The term ‘volcanic ash’ refers to particles smaller than 2mm.

Volcanic eruptions in Iceland are usually classified into 3 types: (1) explosive, where most of the erupted magma (>95%) is exploded/fragmented into volcanic tephra, (2) effusive, where magma is mostly erupted as lava and very little tephra is produced (<5%), and (3) mixed, where both lava and tephra are produced. The majority of Icelandic eruptions are explosive (~78%), followed by mixed eruptions (~13%) (Figure 6.1; Thordarson and Larsen, 2007). Volcanic eruptions in Iceland and elsewhere are highly variable in terms of magnitude, composition, duration, type, and environmental setting.

All volcanic eruptions in which magma reaches the surface produce magmatic gases but not all eruptions produce volcanic ash. For example, the eruption at Bárðarbunga/Holuhraun in Iceland (2014-15) produced large volumes of lava, gases and aerosols but no fine ash. Most importantly each eruption is dynamic, with characteristics such as plume height, mass flux and gas emission rates changing continuously and sometimes dramatically over time. The rates at which magma and associated gases are erupted can be very different. It is not unusual to have very high emissions of volcanic gases with low or even no eruption of lava/ash.

Explosive eruptions can be relatively gas-rich and ash-poor, such eruption plumes tend to look white rather than grey/black due to the dominance of condensing water vapour, the most abundant of volcanic gases.

After water vapour, the most abundant volcanic gases are carbon dioxide and sulphur dioxide. Other volcanic gases include hydrogen chloride, hydrogen fluoride, hydrogen sulphide, carbon monoxide, hydrogen and helium. Volcanic gases are hazardous in sufficient quantities but some convert in the atmosphere to produce aerosols that can also be damaging (e.g. sulphuric acid, which can impact aircraft, air quality, environment and climate). Volcanic gases can be injected anywhere in the atmosphere between very low altitudes (at, or near ground level) to very high altitudes (upper troposphere and stratosphere). Volcanic explosions are typically responsible for injecting gases into the upper parts of the atmosphere.

The emission of volcanic gases and volcanic ash involves different processes and therefore they can be injected in different proportions at different altitudes in the atmosphere even during the same eruption. In many explosive eruptions observed using satellite remote-sensing, ash-rich and SO_2-rich parts of the cloud have separated and followed different trajectories at different altitudes as a result of wind shear [e.g. Schneider et al., 1999; Constantine et al., 2000; Carn et al., 2002]. A very good example occurred during the large eruption of Grimsvötn in 2011 (http://disc.sci.gsfc.nasa.gov/gesNews/AIRS_and_Grimsvotn_volcano).

Volcanic gases and aerosols typically have a longer lifetime in the atmosphere than co-emitted volcanic ash. If they are injected into the stratosphere they can remain in circulation for months and may affect air traffic and even climate.

If volcanic gases are erupted through ground or surface water (including melting ice from ice-caps) they can be ‘scrubbed’. This means that a proportion of the gases are taken up by the water, converted to other compounds, and not injected into the atmosphere. Therefore, scrubbing reduces the emitted gas mass. However, in many instances the presence of water is short-lived. For example, during the Grimsvötn eruption in 2011, the ice cover above the vent was removed after just a few hours of explosive activity and during the Eyjafjallajökull eruption in 2010, melt-water flowed rapidly away from the summit area almost as soon as the eruption began, so ‘scrubbing’ probably only occurred at the very start of these eruptions.

6.4 Choosing scenarios

In terms of planning, a scenario is best selected on the basis of its likely impacts as well as an ability to effectively characterise it. The scenarios should allow planning across any sector that may be affected by volcanic eruptions.

In recent years, it's become clear that the disruption of air traffic can have far-reaching and costly implications. The Eyjafjallajökull eruption in 2010 was considered to have caused ~US$ 5billion in global losses (Ragona, Hansstein, & Mazzocchi, 2011). The duration of the disruption is a key element. The volume of air traffic is increasing worldwide and so such disruption is very likely to occur again. The final decades of the twentieth century were a period of relatively low eruption frequency in Iceland but we're now entering a period of increased frequency. Given the regional focus, a scenario that disrupts air traffic for possibly prolonged periods is considered.

A recent change relevant to increasing resilience is the number of tourists visiting Iceland. In 2014, visitor numbers exceeded 1 million for the first time. Yet during the 2010 eruption, Bird et al. (2010) recognised that tourists are one of the more vulnerable groups in Iceland during eruptions. Significant efforts to address this vulnerability have since been made, for example introducing more real-time alerts in English using social media and text messaging. A scenario that causes alarm among tourists particularly during the summer months and restricts their ability to leave Iceland, is considered.

Apart from aviation, volcanic eruptions that cause volcanic ash fall can have considerable impacts on agriculture, health, transport and other sectors. Volcanic ash is hazardous as it falls (particularly for driving), when it has landed (particularly on flat roofs) and also for long periods after an eruption has ended due to resuspension and reworking by intense rainfall. These impacts are well-documented and can be planned for (e.g. Wilson et al., 2014; Wilson et al., 2014).

In some eruption situations there may be potential for significant social, economic and/or political disruption. A thought experiment is needed in each country to consider what might generate such impacts and how they could be mitigated. In some instances simply providing timely advice and information to the public and potentially affected sectors may be one way to reduce panic or uncertainty.

The large magnitude Lakagígar eruption in 1783-4 had a devastating impact on farming, agriculture and health in Iceland as a result of both ash and gas emissions. There were also reports of health and environmental impacts across Europe. What would be the effects of such an eruption in modern times, in Iceland and across Europe? How would our modern social, political and economic systems cope – is it possible that we would or could be more resilient than in the eighteenth century? Iceland would suffer significant economic losses (Gudmundsson et al., 2008) as would other nations, so planning for cascading impacts of such losses is needed.

The above ‘impact scenarios’ can perhaps be addressed by considering only the two eruption scenarios: Eyjafjallajökull 2010 (prolonged proximal and distal impacts) and Lakagígar 1783-4 (prolonged proximal and distal impacts). In terms of investigating the scenarios, scientists must engage with policy makers and other stakeholders to establish what impacts are of concern and then to investigate the scenarios in more detail, potentially using modelling. In all cases, appropriate outputs and formats of scientific work should be agreed by users *before the work begins*.

6.4.1 Eyjafjallajökull

The first unrest signifying the reawakening of Eyjafjallajökull volcano was detected in 1992-4. There were further episodes of unrest in subsequent years. Intense seismicity and rapid inflation of the east flank of the volcano in January-March 2010 led to the start of a minor flank fissure eruption on 20 March 2010 which lasted until 12 April. At 01:15 UTC on 14 April an eruption began under 200 m thick ice within the summit caldera of Eyjafjallajökull (Þorkellsson, 2012). The eruption was both explosive and effusive and comprised distinct phases of activity (Magnús T Gudmundsson et al., 2012; Sigmundsson, 2013). The more explosive phases distributed fine ash widely across the north Atlantic and European region and caused significant disruption to aviation.

This was not a large eruption but the work of Stevenson et al. (2012) suggests that volcanic plumes that reach modest altitudes in the troposphere (~5-10km) may be the most likely to reach the European mainland when dispersed by winds. Large magnitude explosive eruptions by contrast tend to inject volcanic ash and gases into the stratosphere. The Eyjafjallajökull eruption was highly disruptive due to its highly fragmented magma (due to composition and water-magma interaction), its duration and its weak plume which was widely dispersed by tropospheric winds. This scenario has been chosen due to likely impacts particularly to aviation rather than scale (magnitude) of eruption.

6.4.1.1 Eruption character

The plume of volcanic ash, steam, gases and aerosols was first observed at 05:55 UTC on 14 April 2015. It had reached 9-10 km a.s.l. by the evening but in subsequent days was a relatively weak plume strongly affected by tropospheric winds. Northwesterly winds carried the ash plume towards the southeast across the north Atlantic towards Europe where small quantities fell out in UK, Norway and as far as Hungary (Stevenson et al., 2012).

The initial eruption was subglacial and magma-water interaction undoubtedly contributed to the explosive nature of the eruption. Nevertheless, the magma was also trachyandesite in composition (more viscous than basalt) and this composition of magma also has a tendency to be explosive. Fragmentation of the magma was therefore highly effective resulting in a plume of fine ash. The eruption lasted 39 days and volcanic activity fluctuated in type and vigour over the course of the eruption. It was divided into four main phases:

Phase I: Ash-rich explosive eruption, 14-18 April. The most powerful phase of the eruption.

Phase II: Mixed effusive-explosive phase (18 April – 4 May). A viscous lava flowed away from the summit caldera melting its way 3 km down an outlet glacier.

Phase III: Second explosive phase (5-17 May). This renewed activity was preceded by inflation and earthquakes of increasingly shallow depths and then vigorous degassing of SO_2.

Phase IV: Declining activity during the period 18-22 May before surface expression of the eruption ended (there was minor activity on 4-8 June, and 17 June in the summit caldera).

Overall, this was a small-moderate sized eruption with less than 0.02 km^3 dense rock equivalent of magma erupted in total.

6.4.1.2 Volatile release

During this particular eruption/scenario (Eyjafjallajökull) gas emissions were not a significant hazard. The eruption was best known for volcanic ash emissions but gas emissions (SO_2) were detected by satellite. The emissions preceding Phase III of the eruption were particularly noticeable and associated with significant geophysical monitoring signals interpreted as inflation (pressurisation). One of the reasons why the gas emissions were so clear at this time is that there were no concurrent ash clouds.

Ground-based remote sensing of gas to calculate daily average flux is also very challenging during ash-rich eruptions as almost all current methods rely on spectrometers (which require a clear view of the sun through the gas emission cloud).

These significant limitations for gas monitoring during ash-rich eruptions need to be taken into account for planning.

Ground-based monitoring of gases for health purposes is possible during ash-rich eruptions and is recommended (http://www.ivhhn.org/).

6.4.1.3 Impacts

This eruption affected a wide range of sectors in Iceland from agriculture and livestock, health, tourism and transport. Livestock was kept indoors for several weeks to mitigate risk of fluorosis but the long duration of the eruption and restrictions on livestock transport across Iceland made this an increasingly challenging situation. Facilitating the movement of animals between affected and unaffected areas would facilitate management of this particular problem in future. Fields and soils retained volcanic ash long after the eruption, potentially causing problems for grazing animals. Ash masks were made available to the public but nevertheless windblown and resuspended ash remained a health hazard long after the eruption had ended. The highest exposures were probably to farmers and volunteers involved in ash clean-up efforts as well as scientists involved in field work. A system to remove ash from farm and farmland and dump it elsewhere was established relatively quickly. Barns with large flat or gently sloping roofs were particularly vulnerable. Bridges were destroyed on minor and the major N1 route as a result of glacier floods (jökulhlaups) and this limited movement of the population in Iceland particularly to and from the south and southeast of Iceland for some weeks. The bridges were rapidly rebuilt. Tourists in Iceland tended to be unaware of official advisories (Bird et al., 2010) and it's clear that alerts and notifications of dangers to drivers on the main road for example need to be made in English as well. The Tourist Information needs to be able to spread advice about hazards and risks in Iceland. The flank eruption which was relatively small and picturesque drew large numbers of tourists and visitors to the eruption site which was accessible but highly exposed. Many lacked suitable clothing for the conditions and management of the situation added a considerable burden to NCIP and first responders before the main eruption had even begun.

Beyond Iceland, the disruption to aviation in the north Atlantic and Europe had widespread repercussions, for example to business and supply chains. Tourists stranded in holiday destinations either enjoyed the extended holiday or demanded that embassies work to return them home at any cost. The resilience of many people in Europe, not used to being affected by volcanic eruptions, was tested. The overall global losses were considered to be ~US$ 5billion (Ragona et al., 2011) with critical impacts to businesses as diverse as the Kenya cut flower trade and low-budget airlines in Europe. The disruption to air traffic for a period of roughly one week had consequences which can and should be prepared for by nations, public and private sector.

Further research on the impacts of all types of eruption to different sectors is undoubtedly needed in order to provide evidence on which planning can be based.

6.4.1.4 Monitoring and forecasting

The Icelandic Met Office displayed seismic and deformation monitoring information in close to real-time on its website in 2010 (Þorkellsson, 2012). In addition, IMO sent out regular status reports for example on the erupting column height to the London VAAC. The procedures for communication between IMO and London VAAC (UKMO) are practiced routinely every 6 months. This was perhaps the only sector that had practiced a response to a widely dispersing volcanic ash cloud from Iceland. The easily available IMO information meant that scientists across Europe were well aware of the increasing unrest before the eruption and were unsurprised when it occurred. However, for the most part volcanic risks had not been taken seriously by most sectors and the situation required a very rapid ad-hoc response.

The need for more detailed and precise information about an erupting plume became apparent. In particular the London VAAC was relying on an empirical relationship to establish mass eruption rate for its dispersal models and forecasts that assumed a vertical plume (Webster et al., 2012). The relationship relates mass eruption rate to column height. The Eyjafjallajökull eruption only occasionally demonstrated such a vertical column, it was mostly weak and 'bent' by the wind. New numerical relationships have been developed for such weak plumes and observation mechanisms have been improved (Woodhouse, Hogg, Phillips, & Sparks, 2013). Assumptions were also made about grain size distribution and dispersion of particular grain sizes by the plume. The Futurevolc project is trialling a number of new techniques attempting to establish mass eruption rate and also the grain size distribution of an erupting plume and fallout by combining remote sensing of the airborne particles with detailed assessment of material falling out. Additional mobile radar and lidar were immediately sought for Iceland to make observations of dispersing ash. Research planes flew in Iceland and across Europe, lidar networks were also utilised widely, both had existing Europe-wide networks.

The IMO did not provide official scenarios for potential evolution of the eruption in 2010 but this is now standard procedure. Short term forecasts of eruption evolution are extremely challenging due to the non-linear processes at work in volcanic and magmatic systems. However, once materials have been erupted their dispersal can be forecast. The London VAAC issued forecasts for aviation that came under intense scrutiny and have been well-documented (e.g. Webster et al., 2012). Such forecasts have uncertainties of course and are dependent on the source parameters used, the dispersal model, the weather model used but results can be validated using other observations (e.g. research planes, satellite observations).

Despite lack of planning in most sectors in 2010 for such a scenario and its impacts, existing procedures in, for example, the aviation and civil protection sectors enabled a rapid response. Existing relationships also facilitated the response across Europe. Updating of contingency plans has been carried out in most sectors (see D3.1) but such planning needs regular testing through exercises. In 2010, the demands for additional information made on Icelandic institutions, IMO in particular were at times extreme. The Futurevolc project is working to improve information flow in order to manage such demands more effectively.

6.4.2 Lakagigar 1783-4 ('Laki')

The 1783-1784 eruption of Grímsvötn (Laki craters) is a well-characterised fissure eruption. Our understanding is based on good historical accounts of the eruption and its impacts in Iceland and across Europe combined with modern earth science research (e.g. Thordarson & Self, 1993; 2003). The Laki eruption is defined as a 'flood basalt' eruption because more than 1km^3 of lava was erupted (T. Thordarson & Larsen, 2007). It was in fact the second largest 'flood basalt' eruption worldwide in the last 2000 years (after the ~935AD eruption of Eldgjá, also in Iceland). During the Laki eruption, there were documented impacts across Europe as a result of significant emissions of sulphur dioxide (SO_2) in particular which converts in the atmosphere to sulphates. Sulphates are a component of particulate air pollution and when removed from a plume by precipitation contribute to acid rain. This eruption scenario has been included in the 2012 UK National Risk Register pending further research and modelling work.

In total, there have been four large volume fissure eruptions in historical times (since late 9th century) with erupted volumes greater than 4 km^3. So, these eruptions are not frequent and yet we know that another one will occur, although it is not possible to say exactly where or exactly what size the next one will be. Modern monitoring techniques employed by the IMO (and currently the Futurevolc project) mean that we will likely have some warning before an eruption, but it may not be possible to foresee the eventual scale of such an event at its onset.

The planning process for such an eruption relies on improving understanding of how the modern world might be affected. Such work requires transdisciplinary science and the engagement of the many sectors that might be affected including agriculture, health and transport.

6.4.2.1 Eruption character

The Laki eruption of 1783-1784 occurred from a 27 km long volcanic fissure in an ice-free portion of the Grímsvötn volcanic system. It produced ~14.7 km^3 of lava (error ~15%) that flowed to cover an area of ~565 km^2, and about 0.4 km^3 of tephra. This is the second biggest tephra fall deposit by any Icelandic eruption in the last 250 years (Th Thordarson & Self, 1993; 2003). The calculated erupted volume for the Laki eruption is reasonably well-constrained as the lavas and tephra are well-exposed, the errors arise mainly from a need to recreate the pre-1783 topography (Thordarson pers. comm.).

The Laki eruption began on June 8, 1783 and lasted eight months (Thorarinsson, 1969; Thordarson & Self, 1993). It occurred as 10-11 distinct episodes of activity, each starting with a short-lived explosive phase (eruption rate <7000 m^3/s) followed by a long-lived phase of lava-fountaining (eruption rate 1000-3000 m^3/s) (Thordarson & Larsen, 2007). Magma discharge rate was highest during the explosive onset of each episode. Some of the first explosions were probably caused by groundwater influx to the vent (Thordarson & Larsen, 2007). Theoretical models suggest that eruption columns reached heights >13 km during the more intense phases and columns >10 km high were maintained during the first 3 months of activity (Woods, 1993). The altitude of the atmospheric tropopause in the region of Iceland is typically 9-10 km so these explosive events almost certainly injected materials into the stratosphere. This height, character and persistence of the eruption columns is believed to have had an impact on hemispheric atmosphere and environment with reports of a 'haze' over north-eastern North America, Central Asia and Siberia (Fiacco, R. J. et al., 1994; IPCC, 2001; Thordarson & Self, 2003).

6.4.2.2 Volatile release

Thordarson et al. (1996) calculated the total mass of major gas species emitted during the Laki eruption using petrological studies (Table 6.2). Of the total SO_2 mass of 122 Tg, they calculated that about 96% was released during the first 5 months of activity and more than 60% was released in the first 5 weeks (Figure 6.2; Thorvaldur Thordarson & Self, 2003). The first three fissure-opening episodes lasted just 10 days in total and released ~40% of the total SO_2.

The SO_2 release from this eruption produced a theoretical sulphuric aerosol (H_2SO_4) mass of ~200 Tg, assuming a composition of 75 wt % H_2SO_4 and 25 wt % H_2O for the aerosols (Thomason & Osborn, 1992) and a complete conversion of SO_2 to H_2SO_4 aerosols (Thordarson et al., 1996). Sulphuric aerosol is a major contributor to air pollution.

Table 6-2 Estimates (of the amount of SO_2, H_2O, Cl and F released by Laki into the atmosphere in Tg (1Mt = 1 x 10^9 kg = 1 Tg), respectively (Thordarson et al., 1996).

	SO_2	H_2O	Cl	F
Laki	~122	235	15	7

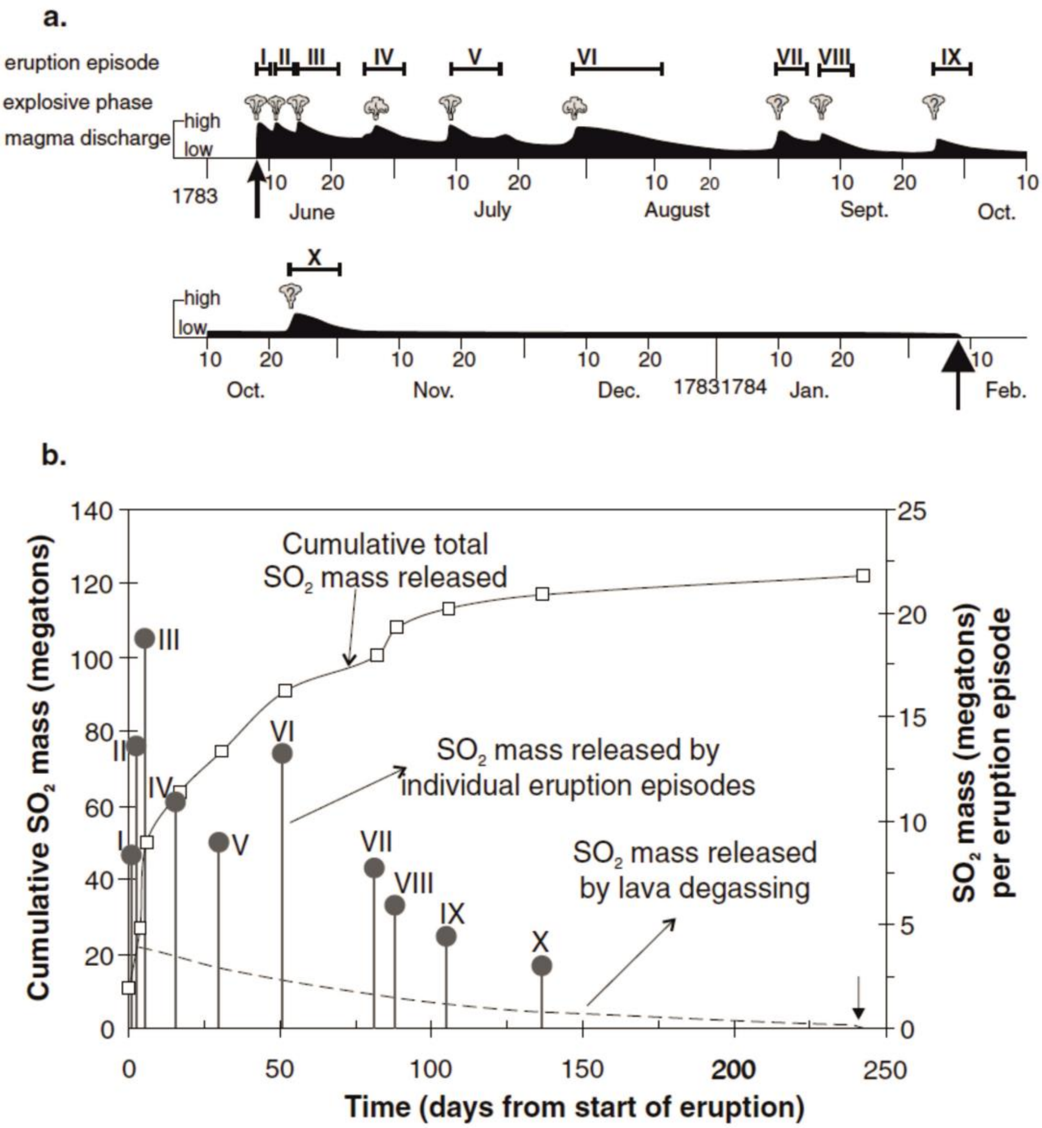


Figure 6-2 (a) Time series showing each fissure opening episode, explosive phases and relative magma discharge rate. (b) The SO_2 mass released by individual episodes, lava degassing and cumulatively through the eruption (1Mt = 1Tg). Thordarson and Self (2003).

6.4.2.3 Impacts

The impacts of the Laki eruption were felt most severely in Iceland, where more than 60% of the grazing livestock was killed by fluorosis. The resulting illness, famine and environmental stress caused the death of about 20% of the Icelandic population (Thorvaldur Thordarson & Self, 2003).

There were reports across Europe of an atmospheric haze and 'dry sulphurous fog' in 1783 which were almost certainly associated with volcanic aerosols and possibly gases. Thordarson and Self (2003) present numerous observations of the atmospheric and environmental effects of the eruption. Meteorological records also show that the summer of 1783 was unusually hot and was followed by an exceptionally cold winter; although it cannot be proven that this was related to the eruption.

Contemporary records from England and other European countries demonstrate some environmental and health impacts such as outdoor workers suffering respiratory difficulties as well as crop and vegetation damage (e.g. Grattan, Durand, & Taylor, 2003). However, negative reports from this period are more difficult to collate, impacts may have been spatially and temporally variable. Several published studies, including Witham and Oppenheimer (2004), demonstrate two periods of crisis mortality in England during the Laki eruption but although tempting, it's not possible to directly ascribe these to the Laki eruption.

Modelling of Laki eruption emissions dispersal by Schmidt et al (2011) suggested that the concentration of particulate matter with diameters smaller than 2.5 μm might double across central, western, and northern Europe during the first 3 months of an eruption. The current World Health Organization 24-h air quality guideline for particulate matter with diameters smaller than 2.5 μm could be exceeded an additional 36 d on average over the whole eruption. Based on the changes in particulate air pollution, they estimated that approximately 142,000 additional cardiopulmonary fatalities (with a 95% confidence interval of 52,000–228,000) could occur in Europe.

6.4.2.4 Monitoring and forecasting

In addition to the range of monitoring established during the Futurevolc project, monitoring of gas emissions is essential. The recent Bárðarbunga eruption has given an excellent opportunity to test a variety of methods including DOAS, scanning DOAS and FTIR. Ground-based remote sensing of gas to calculate daily average flux is very challenging during ash-rich eruptions (the explosive phases of the Laki eruption were ash-rich) as almost all current methods rely on spectrometers (which require a clear view of the sun through the gas emission cloud). The Bárðarbunga eruption offered excellent conditions in the sense that there was no volcanic ash, however the dense plume still provided a challenge. Access to the Bárðarbunga eruption site was also possible with appropriate emergency procedures in place, whereas a 'Laki scenario' might prove considerably more challenging as a result of attendant hazards and risks to scientists. Fissure eruptions provide additional challenges because emissions do not have a point source but may extend over long distances making emission fluxes very challenging to measure. Using the DOAS at some distance from source and driving or using a boat to scan emission plumes from below might be the best ground-based remote sensing strategy.

Ground-based monitoring of gases for health purposes is recommended (http://www.ivhhn.org/).

Unfortunately, because Iceland does not have the benefit of a geostationary satellite, gas sensor data is not continuous but dependent on satellite overpasses.

There may be only one satellite observation product for SO_2 emissions per day but it is possible to calculate a flux from this under the right conditions albeit with uncertainties. Satellite methods can be very effective at detecting SO_2 emissions under the right conditions – different sensors are more appropriate for different altitudes and in combination the coverage can be reasonable. Wind shear may separate ash and gas clouds in the atmosphere, also facilitating the ability to distinguish emissions in the atmosphere. The possibility of enhanced satellite provision for monitoring Iceland's volcanoes and erupted products should be explored. This will give a guaranteed source of information on emissions that may have distal impacts and will facilitate forecasting capabilities.

Currently forecasts of gas dispersal are provided locally in Iceland by IMO (instigated during the Bárðarbunga eruption). Images and forecasts of dispersing volcanic ash from Iceland are provided by the London VAAC. However, there is no operational requirement for the London VAAC to monitor or forecast the dispersal of volcanic gas and/or aerosol clouds. Dispersal of SO_2 can be modelled to provide forecasts for aviation in the same way as volcanic ash (Schmidt et al., 2014). There is evidence that aerosols derived from SO_2 cause long-term damage to aircraft (Bernard & Rose, 1990) but this has been described as a maintenance rather than safety issue for aviation. The topic of whether or not VAACs should include gas forecasts is currently under discussion (Schmidt, 2015). One issue is that the evidence base for gas and/or aerosol impacts to aircraft and passengers is limited. There are descriptions of corrosive damage to aircraft components but making a causative link to a volcanic eruption cloud is not always straightforward. The 2000 explosive eruption of Hekla in is one example where this has been possible. It was relatively small, short-lived and produced a diffuse plume that was considered relatively 'ash-poor and gas rich'. Yet it resulted in documented damage to an aircraft more than 1000km downwind whose pilots could not see the plume – it looked like a cirrus cloud (Grindle & Burcham, 2002; Rose et al., 2004). Eruptions on the scale of Hekla 2000 (< 0.1 km3) occur every 4-5 years (Magnus T. Gudmundsson, Larsen, Hoskuldsson, & Gylfason, 2008).

7 UK planning

In 2012 the UK Civil Contingencies Secretariat requested that the source characteristics of a future Laki-type eruption scenario be considered and documented to facilitate subsequent dispersal modelling by the UK Met Office (using the NAME dispersal model). Outputs from the dispersal modelling can be used for subsequent impact modelling (e.g. health, environmental and infrastructure).

7.1 Source terms for model simulations

It is essential to have sensible 'source terms' for any dispersal modelling simulations conducted, otherwise the model outputs will have minimal value or meaning. Good historical observations in Iceland in 1783-4 and excellent geological investigation mean there is a scientific basis for interpretation of observations of the Laki eruption (e.g. Thordarson & Self, 1993; 2003), which has formed the basis for assessments such as Schmidt et al. (2011) and Schmidt (2015). Nevertheless, for detailed modelling of possible future scenarios there is a need to capture the likely range of uncertainty for some of the eruption parameters. Expert elicitation is the best way to establish preliminary values for source characteristics and their uncertainties. An elicitation was carried out in 2012 (Loughlin et al., 2012) and we present here some of the limitations of that work and describe how it can be improved.

BGS considered that the best way to address source parameter uncertainty was to hold an expert elicitation. Scientists were asked to consider a fissure eruption of similar duration to Laki (8 months) and to give probability distributions for parameters such as maximum plume height, maximum magma production rates and SO_2 mass flux. It is unknown what a future eruption of this type will look like so an expert elicitation is a means for giving expression to the range of possibilities based on current knowledge, by capturing and formally combining the group's informed judgements. Scientists were also asked to give assessments of some source characteristics not available in the literature; the vertical distribution of SO_2 in the eruptive column is one topic that proved challenging. The results of the expert elicitation are given in Loughlin et al. (2012).

Since then a range of model simulations have been run on a simplified source term to test a variety of meteorological scenarios, all of which suggest that a Laki-type eruption could cause some hazards impacts in the UK at ground level under certain conditions. The results of this modelling work will be presented at EGU 2015 (e.g. Vieno et al. 2015; Witham et al. 2015; Braban et al. 2015). Monitoring the UK impacts of the recent Bárðarbunga eruption has confirmed that an eruption approximately an order of magnitude bigger would cause potential health and environmental impacts in the UK.

Despite this preliminary work there is significant potential to investigate further and explore the sensitivity of source term parameters using dispersion modelling. Only a limited number of meteorological scenarios have been considered so there is ample opportunity for further modelling to investigate potential impacts at sites across Europe. An eruption an order of magnitude larger than the Bárðarbunga 2014-15 eruption will take place in Iceland at some point and planning in Iceland and across Europe should be cognisant of this. Planning will increase resilience and enable a more effective, coordinated approach across the region.

7.2 Assumptions and uncertainties

Any modelling work will have a large number of uncertainties which should be accounted for at every stage of the process. Realistically modelling outcomes, particularly for distal impacts, will likely have significant uncertainties. This is still useful for planning and preparation if uncertainties are quantified.

The modelling work attempted so far has considered only SO_2 but other gases could also be investigated (e.g. HCl, HF), particularly to investigate potential impacts in Iceland.

A single major assumption in modelling efforts and the literature has been that the total erupted mass of magma relates to the erupted mass of SO_2. This empirical approach is based partly on petrological analysis of rock samples from past eruptions. Research ongoing as part of the international response to the Bárðarbunga eruption (NERC Urgency grant; Ilyinskaya, BGS) is investigating the source of sulphur and whether it can indeed be accurately assessed using petrological methods as widely assumed.

When elicited in 2012, scientists had difficulty in agreeing or even providing evidence for the vertical distribution of SO_2 in an explosive eruption plume. Is the SO_2 equally distributed up the plume or does more reach higher levels? It is well known that ash and SO_2 disperse at different heights as a result of wind shear implying that their vertical distribution may be decoupled. This requires more research.

A report on the overall results from the UK Civil Contingencies Secretariat modelling exercise is expected to be available in mid-late 2015 (Witham et al. in press).

8 Progress in standards with EU

On the basis of FUTUREVOLC deliverable D3.1 the NCIP has, in accordance with the aim of deliverable D3.2, initiated a formal cooperation between EU-ECHO Emergency Response Coordination Centre (ERCC, formerly known as EU- ECHO Monitoring and Information Centre or MIC) in Brussels. Standards in communications, procedures and protocols have been enhanced (Chapters 2-4) and tested (Chapter 5) for the benefit of ERCC and other sectors across Europe.

Iceland has been a formal partner of the European Civil Protection Mechanism since 1994 when Iceland became a part of the European Economic Area (EEA). The NCIP has represented Iceland in the Mechanism since 2003 when it established the Department of Civil Protection and Emergency Management and took over the role of the Icelandic National Civil Protection, which was closed down.

The goal of the formal cooperation between ERCC and NCIP, as opposed to the regular participation of NCIP in the Mechanism's meetings, training and general administration, is to transfer the expert knowledge of the Icelandic duty officers, to the European level. The Icelandic duty officers are experts in working with Icelandic volcanoes and volcanic hazards. They know the volcanoes; the different types of eruptions; the different kinds of volcanic hazards, and they also have expert knowledge on the European Civil Protection Mechanism.

As has been researched and presented in FUTUREVOLC Deliverable D3.1 (Heiðarsson, Loughlin, Witham, & Barsotti, 2014), there is a gap in the knowledge on Icelandic volcanoes and volcanic hazards, in the European Civil Protection Mechanism. That is also true of other sectors on the European level, such as Meteorological Service Providers (MSP), Academia and the Aviation sector, as was shown in the research. We have described in previous sections how, in Futurevolc, we are already addressing this gap. The reports issued by IMO and the NCCC Scientific Advisory Group (with additional information links) are already circulated to these users.

Nevertheless, communication, and close collaboration between, experts in Iceland and their counterparts in Europe and in different nations will help significantly to bridge this knowledge gap. The mission is to prepare the ERCC duty officers in responding to, and preparing for, a volcanic eruption in Iceland, which may cause impacts in many different sectors and nations in Europe, as became clear in the Eyjafjallajökull eruption in 2010. A good knowledge of the issue and a secure access to onsite experts with first-hand information on the development will strengthen the ERCC and make Europe as a whole more resilient.

The activities of national civil protection agencies in a number of European countries (e.g. UK, Norway) are already being shared and discussed and we will continue to support and enhance this coordination and collaboration.

9 Next steps

9.1 Improving risk communication

Progress in this work package is ongoing and next comprises Task 3.3 : 'Improve communication of volcanic risk'. .

Following the survey in D3.1, in which communication during the volcanic eruptions at Eyjafjallajökull in 2010 and Grímsvötn in 2011 were the main subjects, design of a new survey is now underway for which the main focus will be communication during the Bárðarbunga unrest and eruptions. The survey will use the mailing lists used to disseminate the Bárðarbunga Factsheets, which were sent out from the NCCC and NCCC Scientific Advisory Board during the volcanic eruption at Holuhraun in the Bárðarbunga volcanic system. The quality of information dissemination, communication, and application will be the main focus of the survey.

The survey will be conducted both in English and Icelandic and will also be distributed via Twitter to try to capture the applicability of social media in natural hazards.

We will also consider new data generated by FUTUREVOLC to establish monitoring indicators/thresholds at each volcano that may indicate the need to change alert level.

The lack of a crisis or minimisation of disruption during unrest or an eruption can be mistaken as a 'non-event'. However, this can also signify highly effective risk management and communication. We will use the questionnaire to test this assertion but it seems that the provision of timely information allowed effective decision-making across sectors and across Europe reducing uncertainty and time spent on assessing possible future scenarios and impacts. The lack of crisis or obvious disruption to aviation is a result of effective communication in our opinion and we will present evidence for this in future reports. Recommendations will also be written on the most effective use of the new Futurevolc early warning system and its integration into operational procedures. Deliverable 3.3 will be a report entitled 'Mapping best practice in the dissemination of scientific data and information from the scientific community to stakeholders'. An exercise to test the Futurevolc early warning system will be held concurrently with an exercise to test wider dissemination of eruption notices and alerts, particularly through European civil protection agencies.

The final task in the Futurevolc project is Task 3.4: 'Consult end-users as to the impact of FUTUREVOLC and any outstanding requirements'. Questionnaires will be distributed and followed up with discussions to assess the impact of the project in terms of improvements in coordination, communication, collaboration, risk management and knowledge exchange but also to identify 'next-steps' beyond the project. Deliverable 3.4 will be a report on feedback of FUTUREVOLC impact from end-users across Europe.

Ultimately the best demonstration of effective risk management or risk reduction for national governments is in monetary terms. It is not a part of the Futurevolc project but quantifying the impacts (financial savings) to a single institution or organisation as a result of good communication could be attempted in a future task.

9.2 Future eruption scenario recommendations

Developing some of the ideas presented in this report, during the Futurevolc project in general and in Loughlin et al (2012) and particularly during the Bárðarbunga eruption, we present some recommendations for planning for future eruption scenarios:

a. Planning for proximal and distal impacts of volcanic eruptions requires the development of accessible *hazards* databases containing multi-parametric data and evidence from past eruptions in Iceland. Two types of data should ideally be gathered: 1. **Monitoring data and analysis**, 2. **Eruption histories and hazards**. Futurevolc is creating both and contributing to global databases such as WOVOdat and Global Volcano Model databases. The Icelandic Catalogue is an excellent step in the right direction for (2) but will require continued development and maintenance beyond the project. Data collection standards and uncertainties must be accounted for, sources and references included. Databases containing reliable data are needed to create hazard and risk assessments yet funding to develop the evidence base on which to build planning for, and future responses to, eruptions has been limited. We recommend that such funding opportunities be developed at national, regional and international scales.
b. Following on from (1), we also need to **document losses and cost benefits**. In order to demonstrate the value of scientific research in building resilience, risk reduction and risk mitigation, particularly to national governments, we must demonstrate the savings achievable by providing timely and effective scientific advice. There is already evidence accruing within the Futurevolc project of savings to staff time and effort based on effective evidence-based communications. Such savings could be quantified and documented in order to provide an effective cost-benefit analysis for future scientific research.
c. **Monitoring of gas emissions** (especially SO_2, HCl and HF) for future eruptions in Iceland should be a priority. Monitoring should ideally include ground-based, airborne and satellite methods, each technique has strengths and weaknesses so multiple methods are necessary. This is an example of an area where sustained capacity supported by multiple nations may be necessary.
d. The results of monitoring and research into the environmental **impacts of the Bárðarbunga eruption**, particularly in terms of different gas and particulate species (including trace metals) will help considerably in planning

for future larger magnitude eruptions. There is currently little evidence for environmental, societal and health impacts and such data is needed for planning purposes.

e. In a scenario of a volcanic plume being present at ground level, it is the peak levels of short duration (minutes) of SO_2 which are of main concern to human health, in particular asthma sufferers. Near real-time **monitoring of SO_2** is now available in Iceland and is present across Europe, especially in coastal areas but has been reduced in recent years as air quality has improved. Ideally a minimal level of SO_2 monitoring at least should be maintained especially in Iceland and western Europe.
f. Existing **air quality monitoring** networks (PM_{10} and $PM_{2.5}$) across Europe will detect volcanic particulates alongside anthropogenic particulates. The current assumption is that the toxicity of volcanic particulate air pollution (including ash and sulphate aerosol) is similar to anthropogenic air particulate for monitoring and health surveillance purposes. How the two interact, for example in urban environments, is not well understood, neither is their relative or combined toxicity. This is an area for further research.
g. In the event of a Laki-type eruption, **public health guidance** needs to be prepared in advance in all countries that may be affected. Advice will be needed especially for the public and those sensitive to air pollution (e.g. asthmatics). Guidance will also be needed for farmers, water managers, critical infrastructure and transport sector with consideration of potential peaks in gas concentrations or air pollution. In Iceland but also elsewhere, it should be considered that mixed eruptions (like Laki 1783-4) may produce considerable quantities of gas *and* ash.
h. **Coordinated monitoring** across Europe could focus on increasing spatial and temporal resolution of data (e.g. more sites and more species catered for especially gas and trace metals) but specific effort is needed in combining results. The LiDAR (EARLINET) and research plane (EuFAR) networks alongside capacity in balloon sondes, UAVs (unmanned aerial vehicles) and other methods will require some coordination. Ash collection can be improved by coordination of existing capability in-situ and on the ground; analyses (e.g. leachates) should follow existing international protocols (e.g. IVHHN). Europe could engage appropriate and available remote sensing resource, develop new satellite payloads and plan for new products to facilitate management such as hourly concentration maps based on deposition monitoring. EPOS also offers a long-term platform to formally improve monitoring infrastructure across Europe.

Access to funding during a volcanic crisis is essential to facilitate an efficient and coordinated real-time scientific response across Europe. The EC FP7 Futurevolc project has provided this capacity for response to the Bárðarbunga eruption. Nevertheless, in the future such unparalleled international cooperation, coordination and collaboration may be much harder to achieve.

10 Bibliography

Bernard, a., & Rose, W. I. (1990). The injection of sulfuric acid aerosols in the stratosphere by the El Chichón volcano and its related hazards to the international air traffic. *Natural Hazards*, *3*, 59–67. doi:10.1007/BF00144974

Bird, D. K., Gisladottir, G., & Dominey-Howes, D. (2010). Volcanic risk and tourism in southern Iceland: Implications for hazard, risk and emergency response education and training. *Journal of Volcanology and Geothermal Research*, *189*(1-2), 33–48. doi:10.1016/j.jvolgeores.2009.09.020

Civil Protection Act No. 82, Pub. L. No. 82 (2008). Iceland. Retrieved from http://www.almannavarnir.is/upload/files/Enska_Lög almv 82 2008 W tr 020908 _2_.pdf

Fiacco, R. J., J., Thordarson, T., Germani, M. S., Self, S., Palais, J. M., Whitlow, S., & Grootes, M. P. (1994). Atmospheric Aerosol Loading and Transport Due to the 1783–1784 Laki Eruption in Iceland, Interpreted from Ash Particles and Acidity in the GISP2 Ice Core. *Quat. Res. 42, 231–240.*

Grattan, J., Durand, M., & Taylor, S. (2003). Illness and elevated human mortality in Europe coincident with the Laki Fissure eruption. *Geological Society, London, Special Publications* , *213* (1), 401–414. doi:10.1144/GSL.SP.2003.213.01.24

Grindle, T. J., & Burcham, J. (2002). Even minor ash encounters can cause major damage to aircraft. *ICAO Journal*, *57*, 12–30.

Gudmundsson, M. T., Larsen, G., Hoskuldsson, A., & Gylfason, A. G. (2008). Volcanic hazards in Iceland. *Jokull*, *58*(58), 251–268. Retrieved from http://apps.webofknowledge.com/full_record.do?product=WOS&search_mode=GeneralSearch&qid=13&SID=Q1RzpdGgUMhHA5u5N62&page=2&doc=11

Gudmundsson, M. T., Thordarson, T., Höskuldsson, Á., Larsen, G., Björnsson, H., Prata, F. J., … Jónsdóttir, I. (2012). Ash generation and distribution from the April-May 2010 eruption of Eyjafjallajökull, Iceland. *Sci. Rep.*, *2*. Retrieved from http://dx.doi.org/10.1038/srep00572

Haraldsson, S. P., & Hugsmiðjan. (2014). *Greining og ráðgjöf*. Reykjavík.

Heiðarsson, E. P., Loughlin, S. C., Witham, C., & Barsotti, S. (2014). *European volcanological supersite in Iceland : a monitoring system and network for the future, Report on forensic analysis of the Eyjafjallajökull and Grímsvötn* *communication and risk management response across Europe .* (p. 198). Reykjavík. Retrieved from www.futurevolc.hi.is

Icelandic Met Office Act (2008). Iceland. Retrieved from http://www.althingi.is/lagas/nuna/2008070.html

IPCC. (2001). *Climate Change 2001: The Scientific Basis*. (X. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai & C. Mashell, K., Johnson, Eds.)*Climate Change 2001: The Scientific Basis* (p. 881). Cambridge University Press, Cambridge. doi:10.1256/004316502320517344

Larsen, G., & Guðmundsson, M. T. (2014). *Volcanic system : Bárðarbunga system* (pp. 1–11). Reykjavík. Retrieved from http://www.vedur.is/media/jar/Bardarbunga_kafli20140825.pdf

Loughlin, S. C., Aspinall, W. P., Vye-Brown, C., Baxter, P. J., Braban, C. F., Hort, M., … Witham, C. (2012). *Large-Magnitude Fissure Eruptions in Iceland: Source Characterisation* (p. 136). Edinburgh. Retrieved from http://www.bgs.ac.uk/research/volcanoes/LakiEruptionScenarioPlanning.html

Personal communication with IMO. (2015).

Ragona, M., Hansstein, F., & Mazzocchi, M. (2011). The Financial Impact of the Volcanic Ash Crisis on the European Airline Industry. Cheltenham, UK: "Edward Elgar Publishing, Inc." doi:10.4337/9780857935731.00013

Ríkislögreglustjórinn almannavarnadeild. (2013a). Óvissustig vegna Heklu aflétt. Retrieved February 9, 2015, from http://www.almannavarnir.is/displayer.asp?cat_id=8&module_id=220&element_id=3018

Ríkislögreglustjórinn almannavarnadeild. Rafmangsleysi á Vestfjörðum (2013).

Ríkislögreglustjórinn almannavarnadeild. (2013c). Uncertainty phase because of seismic activity in mount Hekla. Retrieved February 9, 2015, from http://www.almannavarnir.is/displayer.asp?cat_id=8&module_id=220&element_id=3007

Ríkislögreglustjórinn almannavarnadeild. (2014a). Lítið eldgos hafið. Retrieved February 9, 2015, from http://www.almannavarnir.is/displayer.asp?cat_id=8&module_id=220&element_id=3170

Ríkislögreglustjórinn almannavarnadeild. (2014b). Neyðarstigi aflétt - hættustig í gildi. Retrieved February 9, 2015, from http://www.almannavarnir.is/displayer.asp?cat_id=8&module_id=220&element_id=3178

Ríkislögreglustjórinn almannavarnadeild, & Verkís. (2014). *Greining á áhrifum flóða í kjölfar eldgosa í Bárðarbungu: Sviðsmynd II (Analysis of the impact of floods following a volcanic eruption in Bárðarbunga: Scenario II)*. Reykjavík. Retrieved from http://www.almannavarnir.is/file.asp?id=3298

Ríkislögreglustjórinn almannavarnadeild, & Viðlagatrygging Íslands. (2014). *Greining á áhrifum flóða í kjölfar eldgosa í Bárðarbungu: Mikilvæg úrlausnarefni (Analysis of the impact of floods following a volcanic eruption in Bárðarbunga: Important tasks)*. Reykjavík. Retrieved from http://www.almannavarnir.is/file.asp?id=3312

Rose, W. I., Gu, Y., Watson, I. M., Yu, T., Blut, G. J. S., Prata, A. J., … Flittner, D. E. (2004). The February–March 2000 Eruption of Hekla, Iceland from a Satellite Perspective. In *Volcanism and the Earth's Atmosphere* (pp. 107–132). American Geophysical Union. doi:10.1029/139GM07

Schmidt, A. (2015). Volcanic Gas and Aerosol Hazards from a Future Laki-Type Eruption in Iceland. In P. Papale & J. F. Shroder (Eds.), *Volcanic Hazards, Risks, and Disasters*. Elsevier Inc.

Schmidt, A., Ostro, B., Carslaw, K. S., Wilson, M., Thordarson, T., Mann, G. W., & Simmons, A. J. (2011). Excess mortality in Europe following a future Laki-style Icelandic eruption. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(38), 15710–5. doi:10.1073/pnas.1108569108

Schmidt, A., Witham, C. S., Theys, N., Richards, N. A. D., Thordarson, T., Redington, A. L., … Carslaw, K. S. (2014). Journal of Geophysical Research : Atmospheres, 1–17. doi:10.1002/2014JD022070.Received

Sigmundsson, F. (2013). Eyjafjallajökull Eruptions 2010. In *Encyclopedia of Natural Hazards* (pp. 311–316). Springer.

Stevenson, J. A., Loughlin, S., Rae, C., Thordarson, T., Milodowski, A. E., Gilbert, J. S., … Árting, U. (2012). Distal deposition of tephra from the Eyjafjallajökull 2010 summit eruption. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *117*(B9).

Thomason, L. W., & Osborn, M. T. (1992). Lidar conversion parameters derived from SAGE II extinction measurements. *Geophysical Research Letters*, *19*(16), 1655–1658. doi:10.1029/92GL01619

Thorarinsson, S. (1969). The Lakagígar eruption of 1783. *Bulletin Volcanologique*, *33*(3), 910–929. doi:10.1007/BF02596756

Thordarson, T., & Larsen, G. (2007). Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. *Journal of Geodynamics*, *43*(1), 118–152. doi:10.1016/j.jog.2006.09.005

Thordarson, T., & Self, S. (1993). The Laki (Skaftár Fires) and Grímsvötn eruptions in 1783–1785. *Bulletin of Volcanology*, *55*(4), 233–263. doi:10.1007/BF00624353

Thordarson, T., & Self, S. (2003). Atmospheric and environmental effects of the 1783-1784 Laki eruption: a review and reassessment, *108*. doi:10.1029/2001JD002042

Thordarson, T., Self, S., Oskarsson, N., & Hulsebosch, T. (1996). Sulfur, chlorine, and fluorine degassing and atmospheric loading by the 1783–1784 AD Laki (Skaftár Fires) eruption in Iceland. *Bulletin of Volcanology*, *58*(2-3), 205–225.

Webster, H. N., Thomson, D. J., Johnson, B. T., Heard, I. P. C., Turnbull, K., Marenco, F., … Golding, B. W. (2012). Operational prediction of ash concentrations in the distal volcanic cloud from the 2010 Eyjafjallajökull eruption. *Journal of Geophysical Research*, *117*, D00U08. doi:10.1029/2011JD016790

Witham, C. S., & Oppenheimer, C. (2004). Mortality in England during the 1783–4 Laki Craters eruption. *Bulletin of Volcanology*, *67*(1), 15–26. doi:10.1007/s00445-004-0357-7

Woodhouse, M. J., Hogg, a. J., Phillips, J. C., & Sparks, R. S. J. (2013). Interaction between volcanic plumes and wind during the 2010 Eyjafjallajökull eruption, Iceland. *Journal of Geophysical Research: Solid Earth*, *118*(October 2012), 92–109. doi:10.1029/2012JB009592

Woods, A. W. (1993). A model of the plumes above basaltic fissure eruptions. *Geophysical Research Letters*, *20*(12), 1115–1118. doi:10.1029/93GL01215

WOVO. (2010). Aviation Colour Codes. Retrieved May 14, 2014, from http://www.wovo.org/aviation-colour-codes.html

Þorkellsson, B. (Ed. . (2012). *The 2010 Eyjafjallajökull eruption, Iceland* (p. 206). Reykjavík.

11 Appendix 1: FUTUREVOLC Communication:

11.1 The Restricted areas north of Vatnajökull glacier

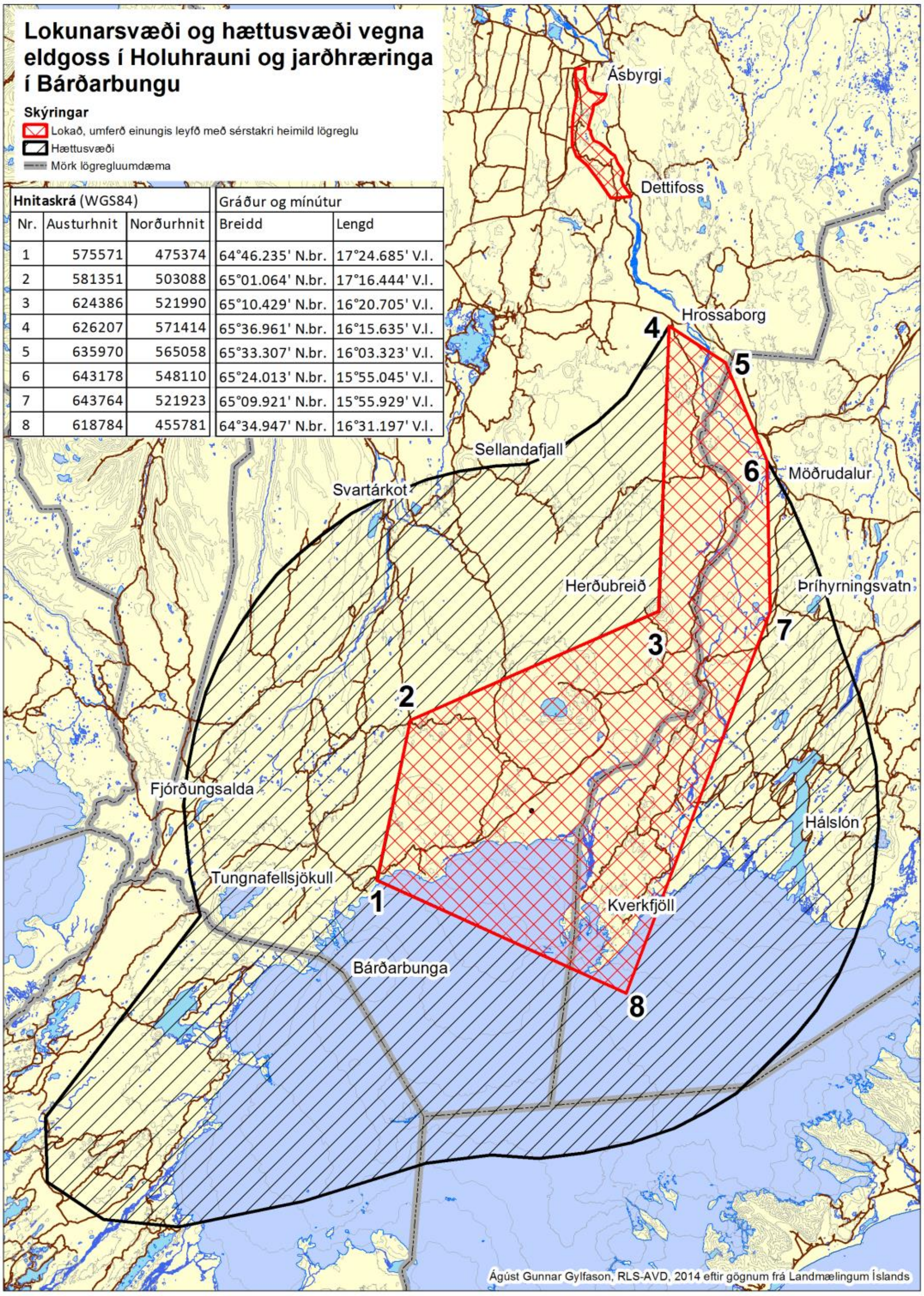


Figure 11-1 The restricted area north of Vatnajökull as defined by the NCIP on 14th of October 2014. The red area shows the zone closed to traffic, the black area shows possible volcanic gas hazard.

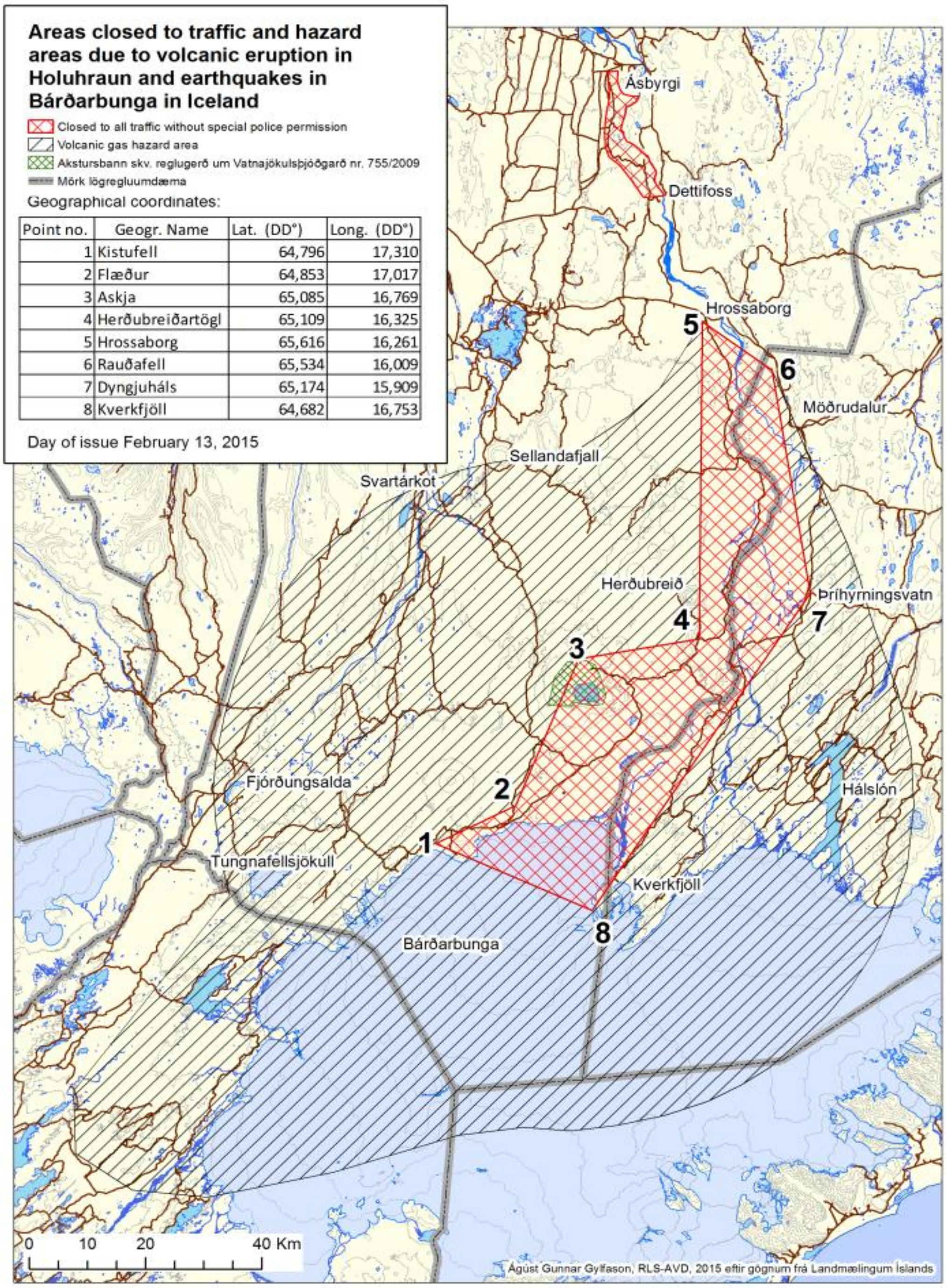


Figure 11-2 The restricted area north of Vatnajökull as defined by the NCIP on 13th of February 2015. The red area shows the zone closed to traffic, the black area shows possible volcanic gas hazard.

11.2 Hazards, scenarios and forecasts

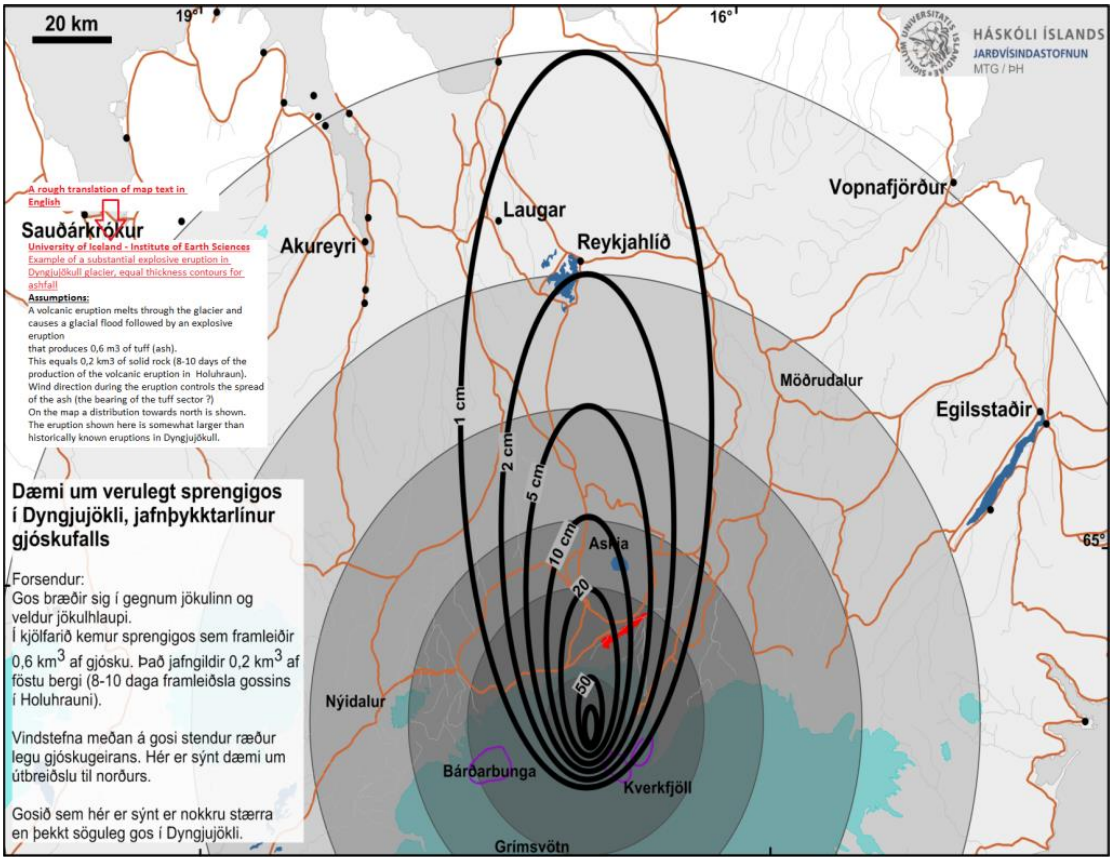


Figure 11-3 Ash fall from large explosive volcanic eruption scenario in Dyngjujökull, northern part of Vatnajökull glacier. Black isopach lines show ash fall thicknesses if winds are from the south.

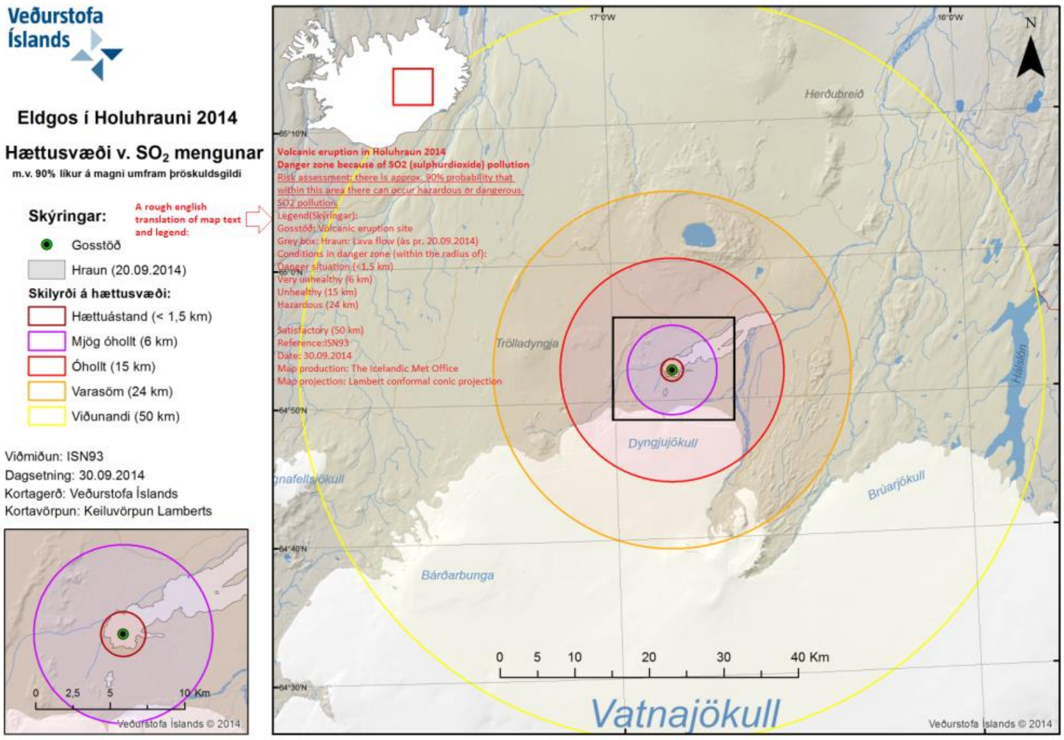


Figure 11-4 IMO map showing area of 90% probability of hazardous SO_2 pollution at ground level from the eruption site in Holuhraun

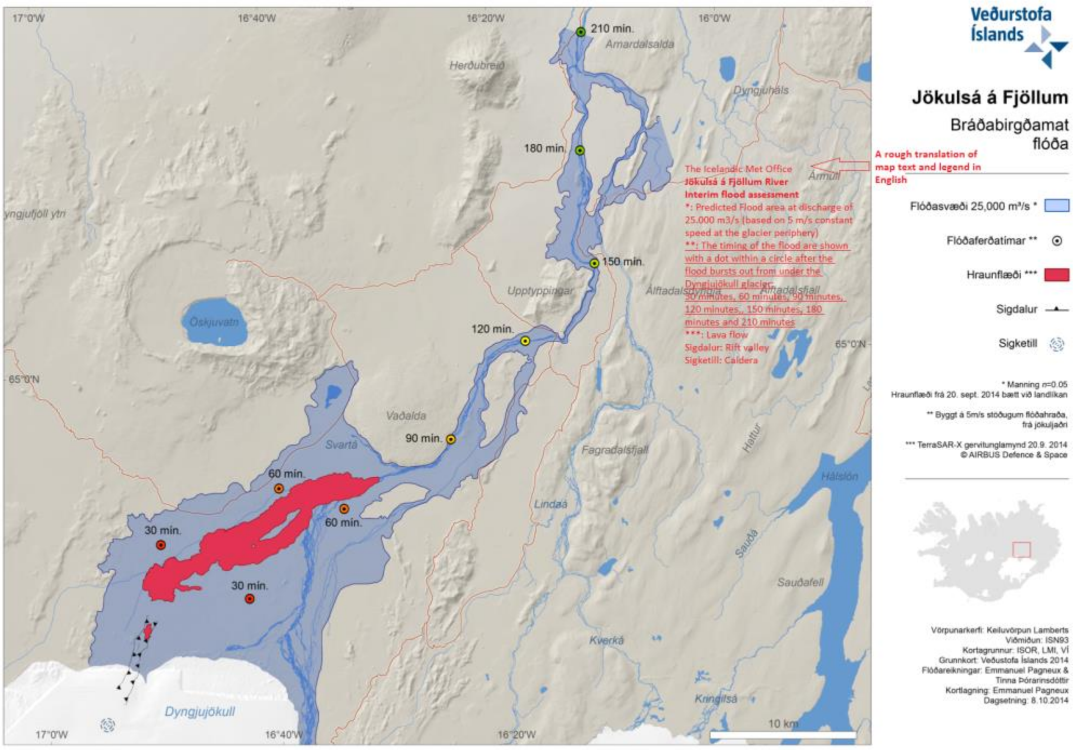


Figure 11-5 IMO map showing flood area (blue) and arrival times for a 25,000 m³/sec flood down Jökulsá á Fjöllum.

11.3 Posters at FUTUREVOLC Annual Meeting

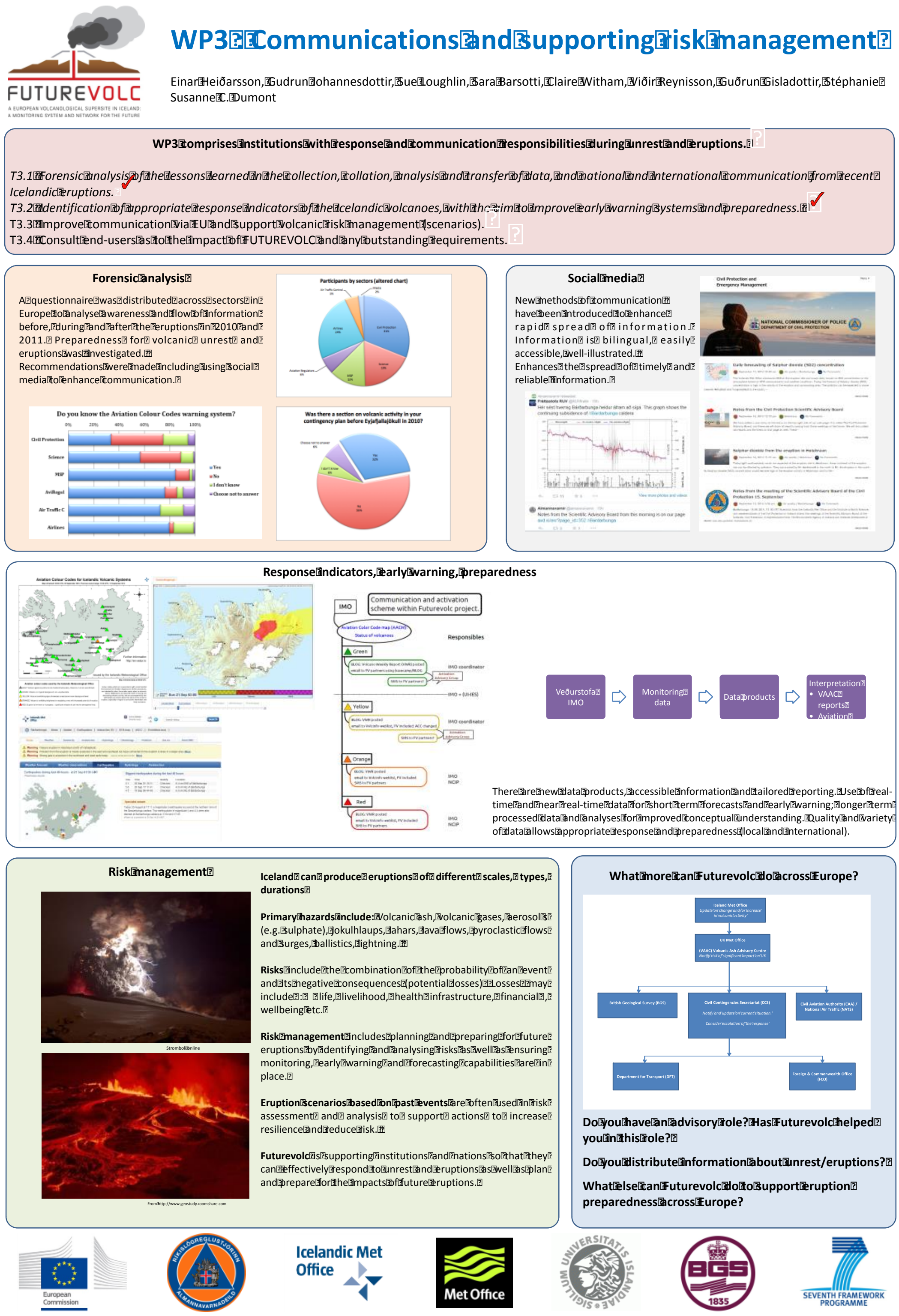


Figure 11-6 Poster 1 by NCIP and partners at the FUTUREVOLC Annual Meeting 2014.

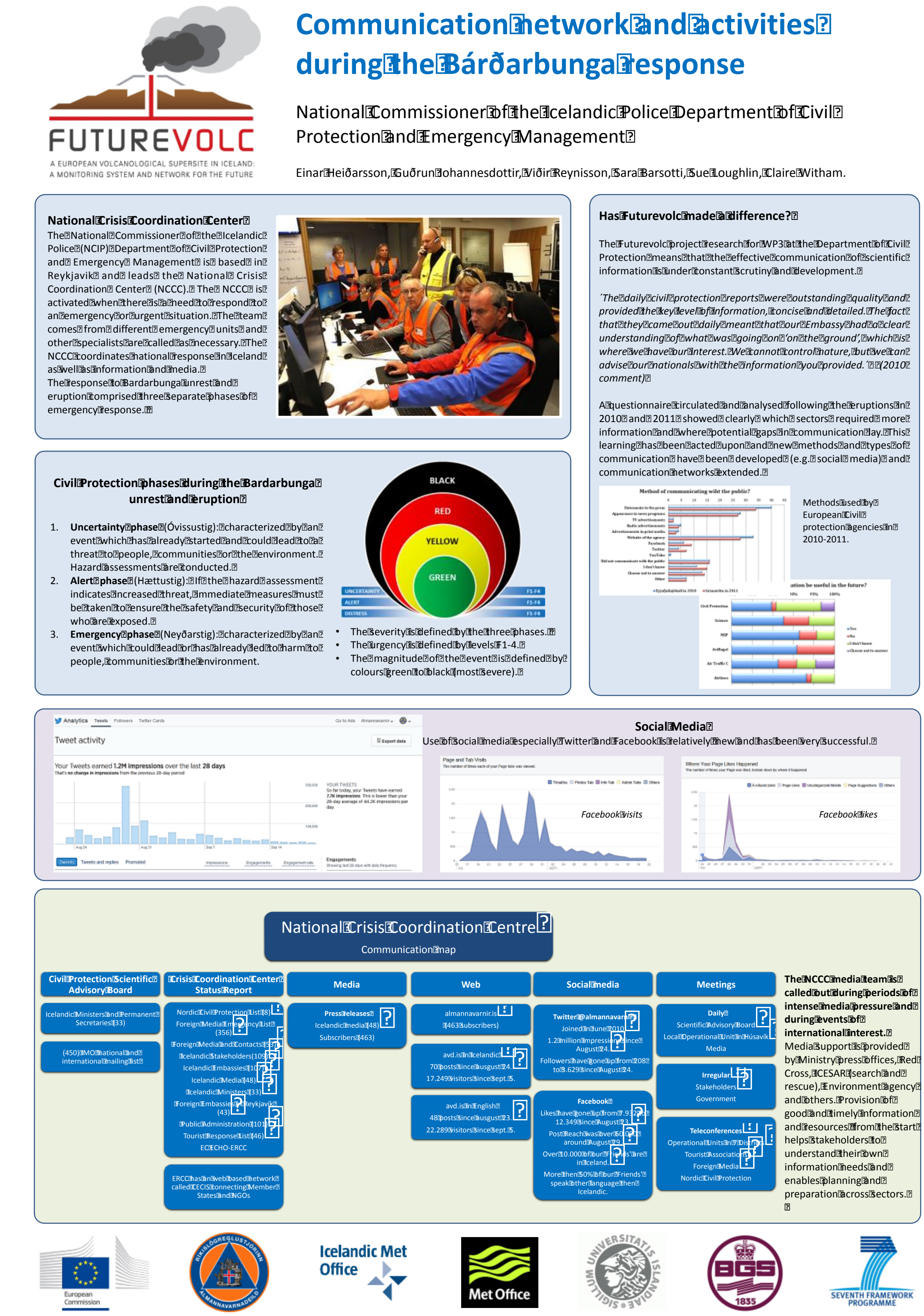


Figure 11-7 Poster 2 by NCIP and partners at the FUTUREVOLC Annual Meeting 2014.

11.4 Health Effects of Short-term Volcanic $S0_2$ Exposure and Recommended Actions

Health Effects of Short-term Volcanic SO_2 Exposure

and Recommended Actions

Quantity of SO_2*		Air quality description	Recommended actions	
µg/m^3	ppm		Sensitive Groups **	Healthy individuals
		Good		
0-300	**0-0,1**	Poses little or no health risk.	Can experience mild respiratory symptoms.	No health effects expected.
		Moderate		
300-600	**0,1-0,2**	May cause respiratory symptoms in individuals with underlying diseases.	Caution advised. Follow SO_2 measurements closely.	Health effects unlikely.
		Unhealthy for sensitive individuals		
600-2.000	**0,2-0,7**	Individuals with underlying diseases likely to experience respiratory symptoms. Health effects unlikely in healthy individuals.	Avoid outdoor activities.	Health effects not expected. Heavy outdoor activities not advised.
		Unhealthy		
2.000-9.000	**0,7-3,0**	Everyone may experience respiratory symptoms especially individuals with underlying diseases.	Remain indoors and close the windows. Shut down air conditioning.	Avoid outdoor activities. Remaining indoors advised. Close the windows and shut down air conditioning.
		Very unhealthy		
9.000-14.000	**3,0-5,0**	Everyone may experience more severe respiratory symptoms.	Remain indoors and close the windows. Shut down air conditioning. Follow closely official advises.	Remain indoors and close the windows. Shut down air conditioning. Follow closely official advises.
		Hazardous		
> 14.000	**>5,0**	Serious respiratory symptoms expected.	Remain indoors and close the windows. Shut down air conditioning. Follow closely official advises.	Remain indoors and close the windows. Shut down air conditioning. Follow closely official advises.

*Based on 15-minute average
**Children and adults with pre-existing bronchial asthma, bronchitis, emphysema and/or heart diseases. These recommendations also apply to pregnant women.

General recommendations:

1. Individuals with pre-existing pulmonary- and heart diseases are encouraged to have their medications readily available.
2. Recommendations to reduce SO_2 in inhaled air:
   - Breathe with your nose as much as possible and avoid physical exercise.
   - Remain indoors and close the windows. Shut down the air conditioning if visible haze.
   - If you are staying inside and experiencing respiratory difficulties due to high SO_2, take a cloth and saturate it with a thin paste of baking soda and water (5 gram per liter of

Figure 11-8 Advice distributed by NCIP and partners on health effects of short-term volcanic $S0_2$ exposure and recommended actions, based on IVHHN guidelines.

11.5 11.5 Gas dispersion modelling and forecasts

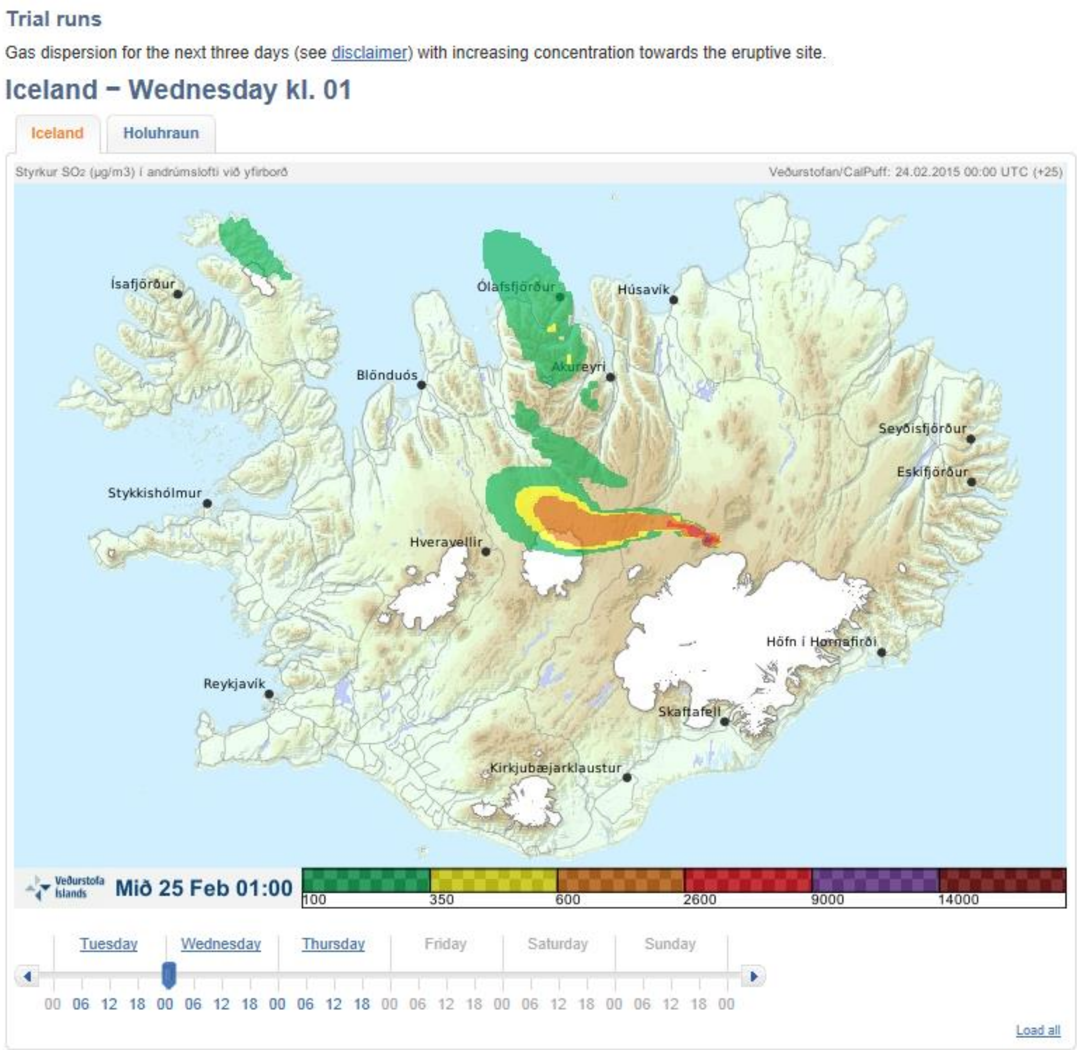
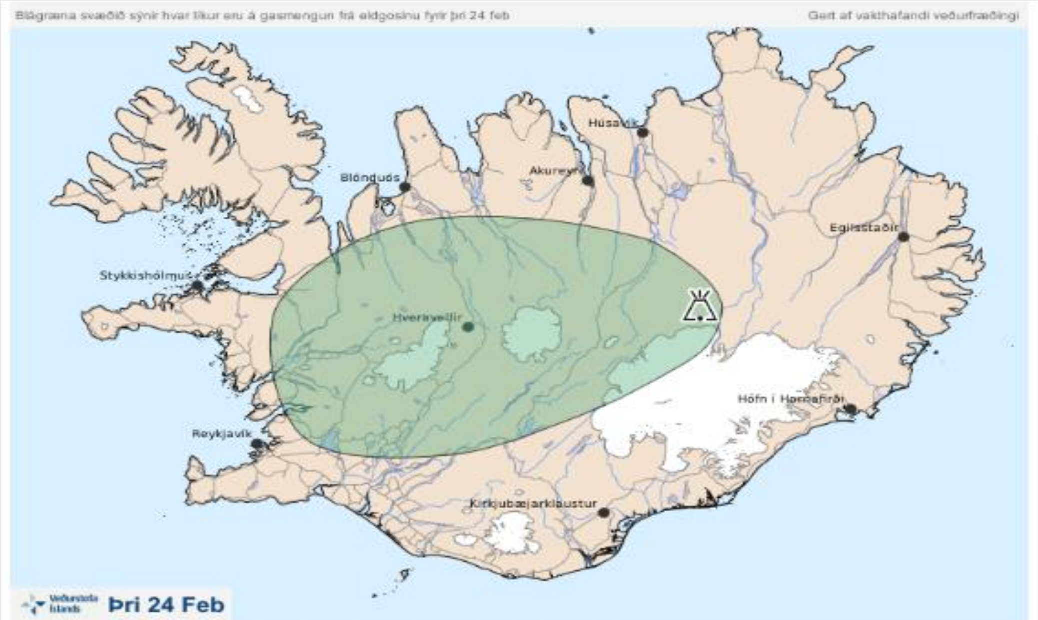


Figure 11-9 Trial 3-day gas dispersion forecasts distributed by IMO in February 2015. Hotter colours show higher concentrations of gases.

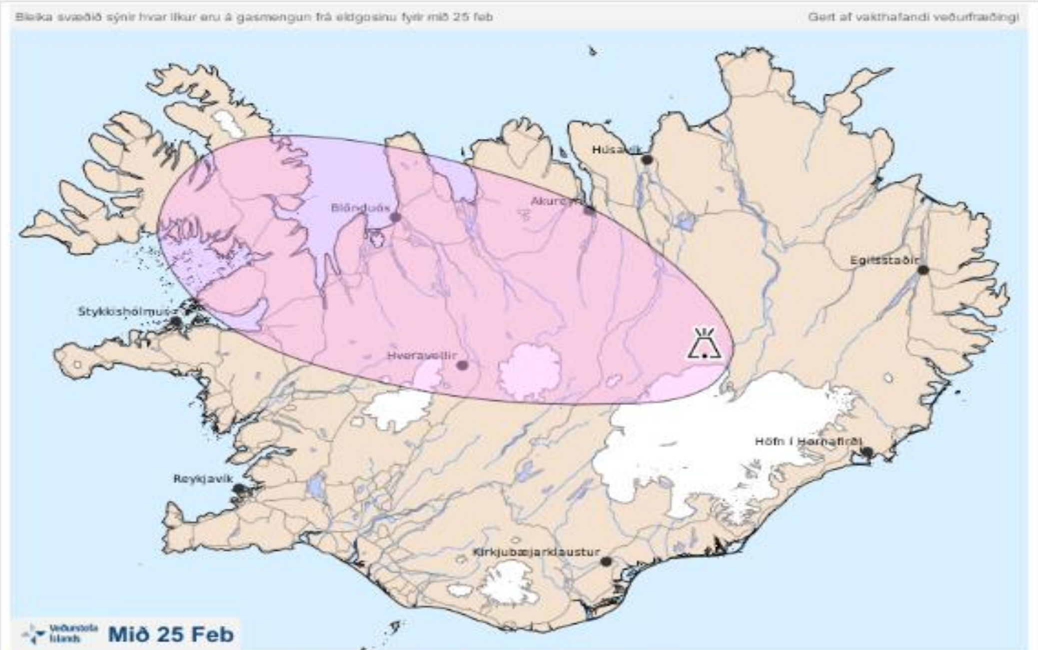
Gas Dispersion Forecast

Today (Tuesday) gas pollution is expected Southwest and West of the volcano.
Tomorrow (Wednesday) gas pollution might be felt to the Northwest of the eruption site.
Spá gerð: 24.02.2015 01:22. Gildir til: 25.02.2015 23:00.

Forecast for today and tomorrow



Enlarge. The bluegreen area indicates possible pollution today.



Enlarge. The pink area indicates possible pollution for tomorrow.

Figure 11-10 Daily gas dispersion forecast showing areas of likely gas pollution and a forward look (48 hours) issued by IMO in February 2015.

11.6 11.6 Scientific Advisory Board Factsheet Bárðarbunga eruption

NATIONAL COMMISSIONER OF THE ICELANDIC POLICE
DEPARTMENT OF CIVIL PROTECTION AND EMERGENCY MANAGEMENT

THE SCIENTIFIC ADVISORY BOARD OF THE ICELANDIC CIVIL PROTECTION		
Date: 31.10.2014	**Time: 09:30**	**Location: Crisis Coordination Centre, Skogarhlid.**
Regarding: Volcanic activity in the Bardarbunga system.		
Attending: Scientists from Icelandic Met Office and the Institute of Earth Sciences University of Iceland along with representatives from the Icelandic Civil Protection, the Environmental Agency of Iceland and the Directorate of Health.		

Main points

- **Volcanic eruption in Holuhraun**
- **Air quality**
- **Scenarios**

Notes

- The volcanic eruption in Holuhraun continues with similar intensity. The lava field is now 65,7 squere kilometres.
- Seismic activity in Bardarbunga continues to be strong. 200 earthquakes have been detected in the caldera over the last 48 hours. Just over ten earthquakes were bigger then magnitude M4,0. The largest one was M5,3 tonight at 01:30.
- The GPS station in the centre of Bardarbunga show that the subsidence of the caldera continues with similar rate as it has done over the last few weeks. The total depression in the caldera is now about 42 meters.
- Energy of the geothermal areas in Bardarbunga is now few hundred megawatts and the melting of water is estimated around 2 cubic meters per. second. The water goes into Skjálfandafljót og Jökulsá á Fjöllum. The flow is too small to effect the total water flow of the rivers.
- Around 20 smaller earthquakes are detected in the dyke and at the eruption site in Holuhraun, all around magnitude M1,0 and smaller.
- GPS measurements in the active area show minor changes.

A recommendation by the Scientific Advisory Board of the Icelandic Civil Protection: The Scientific Advisory Board concludes that it is necessary to increase monitoring of SO4 so it is possible to evaluate the concentration of sulphuric acid particles and its potential influence on health.

Air quality:

- Considerable sulphuric dioxide (SO2) pollution has been recorded widely around Iceland over the last few days. It is believed that reduced energy in the volcanic plume may result in that the gas pollution does not reach the higher layers of the atmosphere.
- Today (Friday) eastern gales are forecast so gas pollution is expected mainly in W-Iceland. Tomorrow (Saturday) light easterly winds are expected so gas pollution may be expected northwest and west of the eruption.
- The Icelandic Met Office provides two-day forecasts on gas dispersion from the eruptive site in Holuhraun. Most reliable are the forecast maps approved my meteorologist on duty, see Gas forecast. And although still being developed further, an automatic forecast, see Gas model, is also available (trial run, see disclaimer).

Continued overleaf

NATIONAL COMMISSIONER OF THE ICELANDIC POLICE
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- A new online gas detector has been put up in Hofn in Hornafjordur. Measurements of air quality can be found on the webpage www.airquality.is

- Instructions:
  - People who feel discomfort are advised to stay indoors, close their windows, turn up the heat and turn off air conditioning. Use periods of good air quality to ventilate the house. People experiencing adverse effects should be in immediate contact with their healthcare centre. Measurements of air quality can be found on the webpage www.airquality.is The Meteorological Office issues forecast on its web-page and warnings if conditions change to the worse.
  - Instructions from The Environment Agency of Iceland and Chief Epidemiologist can be found on their web-sites.
  - Check the Icelandic Met Office forecasts for sulphuric gas dispersion on the web as described above.
  - Handheld meters have been distributed around the country for SO2 measurements three times a day.
  - Information and any questions on air pollution can be sent to The Environment Agency through the email gos@ust.is. The Environment Agency is especially looking for information from people who have been in contact with high concentrations of gas; where they were, at what time it happened, how the gas cloud looked (colour and thickness of the cloud) and how they were affected by it.

- Three scenarios are considered most likely:
  - The eruption on Holuhraun declines gradually and subsidence of the Bardarbunga caldera stops.
  - Large-scale subsidence of the caldera occurs, prolonging or strengthening the eruption on Holuhraun. In this situation, it is likely that the eruptive fissure would lengthen southwards under Dyngjujokull, resulting in a jokulhlaup and an ash-producing eruption. It is also possible that eruptive fissures could develop in another location under the glacier.
  - Large-scale subsidence of the caldera occurs, causing an eruption at the edge of the caldera. Such an eruption would melt large quantities of ice, leading to a major jokulhlaup, accompanied by ash fall.

Other scenarios cannot be excluded.

- **From the Icelandic Met Office:** The Aviation Colour Code for Bardarbunga remains at 'orange'.
- The next meeting will be held on Monday 3 of November.

The National Commissioner of the Icelandic Police, Department of Civil Protection and Emergency Management
Almannavarnir Civil Protection and Emergency Management, Twitter: @almannavarnir

Figure 11-11 Scientific Advisory Board Factsheet on the Bárðarbunga eruption, October 2014.

11.7 11.7 Futurevolc, early warning and reporting in Iceland.

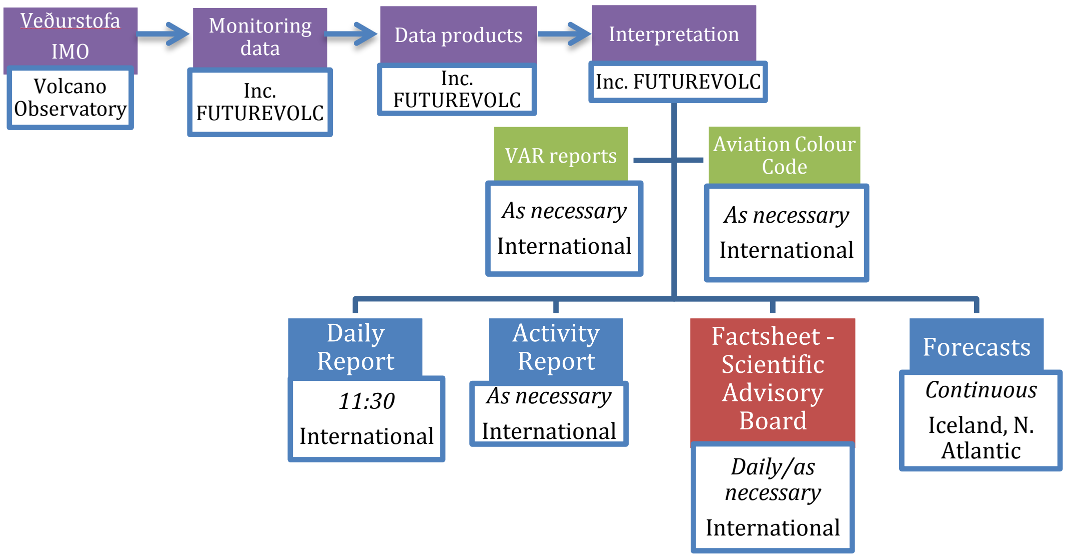

Figure 11-12 The role of Futurevolc monitoring data, data products and expertise/interpretations in early warning and reporting from Iceland.