LARGE-MAGNITUDE FISSURE ERUPTIONS IN ICELAND: SOURCE CHARACTERISATION

Report on the source characteristics of a 'Laki-type' eruption for scenario modelling and findings of an expert consultation and elicitation

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Acknowledgements

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Contents

EXECUTIVE SUMMARY

The British Geological Survey and the Met Office together with government departments, agencies and academic partners across the UK and in Iceland are engaged in a programme of work that aims to ensure that plans are in place in Iceland, the UK and the rest of Europe to facilitate a coordinated and timely response to future eruptions that occur in Iceland.

As a consequence of the eruption of the Eyjafjallajökull volcano in 2010, Professor Sir John Beddington appointed a 'Scientific Advisory Group in Emergencies' (SAGE) which met several times during the eruption. One of the tasks of the SAGE was to consider potential future eruption scenarios that might affect the UK and as a result, volcanic eruptions were included for the first time in the UK National Risk Register (NRR). One of the scenarios adopted in the NRR (https://www.gov.uk/government/publications/national-risk-register-of-civil-emergencies) is based on the 1783-4 fissure eruption of Grimsvötn volcano, commonly known as the 'Laki eruption'.

The BGS was contracted to characterise source parameters and their uncertainties to enable further modelling of a Laki eruption scenario, a critical step towards better understanding the possible impacts of such an eruption. This report presents the outcomes of a meeting and expert elicitation held under contract to the Cabinet Office in May 2012. A multidisciplinary expert group with specialist knowledge of this particular type of eruption, volcanic degassing, remote sensing of gases and aerosols, atmospheric processes and dispersion modelling was nominated to take part, along with a few experts on the health and environmental impacts of volcanic eruptions to provide guidance on their modelling requirements. The elicitation was run by Professor Willy Aspinall.

It is hoped that the very short process that led to this report was nevertheless sufficient to stimulate valuable scientific discussion, to prompt planning initiatives and to motivate relevant research proposals. This report acts as a multidisciplinary resource with key research papers and the outcomes of the meeting presented as well as the elicited source parameters. Areas where scientific understanding is limited or is still emerging are highlighted here as 'knowledge gaps' and research to tackle these gaps is recommended.

Planning by government departments, research institutes and others is underway and can also be guided by the contents this report. It is suggested that consideration is given as to how scientific inputs should best be delivered in any future volcanic emergency, in the light of recent experiences.

Summary

What is the Laki eruption scenario?

The Laki eruption scenario is based on a large fissure eruption that occurred in 1783-4 for which there is published evidence of significant distal impacts across Europe (see below)[3]. The impact on Iceland was devastating: more than 60% of the grazing livestock was killed by fluorosis and ultimately ~20% of the island's population died in the aftermath as a result of induced illness, environmental stress and famine[4].

As well as lava flows, the atmospheric volcanic emissions from such an eruption include mainly water vapour, gases including carbon dioxide, sulphur dioxide, hydrogen chloride and hydrogen fluoride, aerosols (e.g. particles such as sulphates) and trace metals such as mercury, arsenic and iridium. At times, there may also be volcanic ash depending on how explosive the eruption is and the presence of water. Sulphur dioxide (SO_2) is chemically converted during atmospheric transport to sulphate aerosol. The rates of this chemical conversion vary depending on factors such as temperature, humidity and availability of oxidants. The main potential hazards of concern to the UK include volcanic gases and aerosol (air pollution), acid rain and deposition of acids and other aerosols.

> There have been four large fissure eruptions in Iceland in historical time (the last c.1130 years), the 1783-4 Laki eruption being the second largest in terms of the volume of volcanic material erupted. This type of eruption is characterised by huge outpourings of mainly lava, gases and aerosols (atmospheric particles) which can cause regional to hemispheric-scale impacts but most risks can be mitigated with effective planning.

Observations in UK and Europe in 1783

In the UK and Europe, from 12 June 1783 there were reports of an atmospheric 'haze' and 'dry sulphurous fogs' at different times which were almost certainly associated with volcanic aerosols[3] and possibly gases.

Contemporary records from England and other European countries document some environmental and health impacts of the haze (e.g. workers in fields suffering respiratory difficulty; crop and vegetation damage[5]) but the haze and its effects were variable spatially and temporally at a local scale. This significant variability is controlled by the eruption dynamics and by the influences of regional-to-local scale meteorology.

Meteorological records show that there was extreme heat in the summer of 1783 followed by an exceptionally cold winter in the northern hemisphere. There were unusual thunderstorms, ball

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[3] Thordarson and Self, 1993
[4] Thordarson and Self, 2003
[5] Grattan et al., 2003

lightning and large hailstones. It is not possible to prove that this extreme weather was linked to the eruption though the unusual meteorological phenomena caused commentators to make the suggestion at the time[6].

A published study[7] based on 404 parish records in England, provides evidence for two periods of crisis mortality during the Laki eruption period: one peak in August-September 1783 and a second peak in January-February 1784 with above normal mortality rates for the subsequent two months. It is not possible to directly ascribe these excess deaths to the Laki eruption but the unusual monthly mortality pattern indicates a forcing on mortality unrelated to normal seasonal trends and potentially unique in a fifty year series of such data. The significance of these findings and those of some other publications using death records at the time warrant further assessment for their value and possible implications for the UK and Europe today.

Modelling the scenario

In order to be hazardous at ground level in the UK, the air pollutants need to be a) transported to the UK by the wind, b) present at ground levels in the UK, and c) at harmful concentrations.

Different models need to be combined to understand key processes in this scenario – weather models, atmospheric transport (dispersion) models and chemistry models. To produce detailed modelling results including multiple physical and chemical processes requires considerable resources (time) and computing power. Solving the first order problem of whether or not volcanic emissions can physically reach the UK under particular eruption and meteorological conditions has been seen to be possible and can be probabilistically assessed using long range dispersion models but neglecting chemical conversion processes.

Atmospheric dispersion models require knowledge of the source characteristics of an eruption – for example the height of the column of emissions (ash, gas and aerosol) above the vent, the rate of emission and, for ash, the distribution of particle sizes between the vent and the top of the eruption column. In order to facilitate modelling of future eruption scenarios, this report presents a range of eruption characteristics (source parameters) for a Laki-type eruption and their uncertainties based on an expert elicitation. This reflects current knowledge. The report also presents information on the possible dynamic evolution of a future large-volume fissure eruption for modelling purposes.

Models and the results of modelling, and their hazard implications, need to be thoroughly understood by practitioners, in particular the effects of assumptions and uncertainties. Running several models with the same starting parameters helps understanding of these uncertainties and if validated against observational data may inform on model capabilities and limitations.

To inform risk assessments fully, given inevitable scientific uncertainties, a probabilistic modelling approach is needed. Eruption scenarios would be modelled using multiple years of meteorological data. Outputs suitable for health and environmental modelling, including deposition and air

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[6] Franklin, 1784
[7] Witham and Oppenheimer, 2004

concentration data and distribution maps for different scenarios e.g. summer and winter events, could be produced. Outputs can also be produced for different flight levels.

The better our understanding of eruptive and atmospheric processes, the more effective models can be when applied as part of the response to future events. Improved understanding is needed of the composition and transformation of gases and aerosols in the atmosphere and this is best achieved through focused collection of data between and during eruptions, laboratory studies and modelling. For example, more detailed studies are needed to establish wet and dry deposition rates and scavenging coefficients for different species.

A future eruption

The Icelandic Meteorological Office (IMO) is mandated to monitor volcanoes in Iceland and would expect some geophysical and/or geochemical evidence of unrest before a Laki-type fissure eruption. In 1783 there were felt earthquakes three to four weeks before the eruption. Currently, such an increase in activity would be communicated by IMO increasing the 'aviation colour code' (http://www.wovo.org/aviation-colour-codes.html) and distributing a notification called a 'Volcano Observatory Notice for Aviation' (http://www.icao.int/safety/meteorology/ivatf/Meeting%20MetaData/IP.10.pdf) thus informing the aviation sector, UK Met Office, BGS and others. When an eruption has begun, where possible, the IMO provides real-time eruption source parameters to the UK Met Office for operational forecasting purposes. It is not certain that the potential scale of a Laki-type eruption would be clear at the onset of the eruption.

Once an eruption is underway, the gases, aerosols and ash will be transported away from the volcano by the winds acting at the time. Assuming the worst expected meteorological conditions for the UK (strong wind flow from the northwest) we could have a minimum lead time of approximately six hours.

All large historical fissure eruptions in Iceland appear to have had very similar eruption dynamics with more intense and vigorous activity in the early stages of the eruption. In the case of Laki, about 96% of gases were released in the first 5 months and 60% in the first six weeks of the eruption[3].

Monitoring

The IMO make much monitoring data available online (e.g. http://en.vedur.is/earthquakes-and-volcanism/earthquakes/). The UK Government, BGS and others in the UK and across Europe are contributing to the IMO-led monitoring effort in Iceland partly in order to secure the maximum possible lead time and effective information flow during an emergency.

Ground-based, airborne and satellite monitoring techniques are of value both near the volcano and in the far-field (e.g. the UK). Nevertheless, none of the existing techniques in isolation would give a high resolution time-series of source parameters/data. There is significant potential to develop new, purpose-specific monitoring techniques and some novel techniques have been developed, or are being developed, but the technology is not yet available commercially. The ideal future situation

would involve improved capacity and the sustained coordination of resources and collaboration across institutes and nations in order to effectively respond to eruptions.

This report summarises existing monitoring capability in the UK. We recommend extending existing ground-based air quality networks to increase spatial and temporal resolution of data (e.g. more sites instrumented and more species monitored, especially gases and trace metals). There is currently no capability to monitor hydrogen sulphide, hydrogen fluoride or hydrogen bromide, for example, and also limited air quality monitoring in most rural areas (e.g. the Highlands and Islands of Scotland). Knowledge of the location and vertical characterisation of volcanic clouds can be improved using LiDAR (Light Detection And Ranging), aircraft, balloon sondes, UAVs (unmanned aerial vehicles); new methods could be developed. If there is fine ash, gas or aerosol deposited over the UK, sample collection and analyses should be coordinated (e.g. in a similar manner to the DEFRA Volcanic Ash Network). The UK could engage appropriate and available remote sensing resources, further exploit current sensors, develop new satellite payloads and plan for enhanced observation capabilities to facilitate crisis management.

For the present hazard scenario concerns, detailed analysis of observations from any eruption can lead to significant improvements in understanding processes, development of methods and planning for future eruptions. In this context, future eruptions around the world will offer opportunities to conduct observations, experiments, test new techniques and improve near real-time collection, integration and analysis of multi-parametric data. Observations and monitoring must be combined with improved numerical models of different eruption processes and laboratory experiments of eruption column processes in order to facilitate our future ability to harness data, observations and modelling to better assess eruption parameters in real-time and therefore forecast hazards effectively.

Health impacts

Unfortunately, historical records relating to 1783-4 cannot be critically analysed using the standard epidemiological methods used in modern air pollution research.   It is not possible to reliably infer the short-term exposure levels of people to individual air pollutants from the reports of odour, haze or vegetation damage. The available historical data are also inadequate for calculating age-specific death rates, or doing time-series analyses from the parish numbers of deaths, which are also known to be highly unstable in many parishes due to the high prevalence of endemic infectious diseases no longer seen in Britain today, and the much lower life expectancy in 1783.

For a future Laki-type eruption scenario, modelling ambient air concentrations of specific air pollutants is required to provide first order estimates of all-cause and disease specific mortality and morbidity, based on exposure-response data for SO_2 and particulate matter ($PM_{2.5}$ and PM_{10}) from clinical and epidemiological studies. In one published paper[8] the modelling forecasts that the concentration of volcanic $PM_{2.5}$ particulate matter (particles with diameters <2.5 micrometer) could double across central, western and northern Europe during the first three months of a future Laki eruption scenario. The model dataset was used to estimate the number of days (out of 266 days

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[8] Schmidt et al. 2011

considered) that could exceed the current World Health Organisation (WHO) 24-h mean $PM_{2.5}$ air quality guideline of 25 μg/m^3. Over land areas of Europe (excluding Iceland), the mean number of exceedances could increase by 36 days (range 14-63 days) compared to a 'normal' non-volcanic mean of 38 days. The authors estimate 142,000 additional cardiopulmonary fatalities could occur in Europe (with a 95% confidence interval 52,000-228,000) and the UK may experience an increase in mortality of about 3.5% (i.e. about 21,000 additional cardiopulmonary fatalities due to eruption on top of 595,800 all-cause deaths).

Global air quality guidelines are well-established for SO_2 (UK and EU guidelines are similar) which would be a major constituent gas in the erupted plume from Iceland. However, modelling studies are needed to establish the volcanic and meteorological conditions required for SO_2 to reach UK ground level before the gas is chemically converted to sulphate aerosol. At high enough concentrations SO_2 could trigger acute respiratory symptoms in asthma sufferers and aggravate the condition of patients with chronic lung problems. To assess health effects on such individuals, peak concentrations measured and averaged over periods of 15 minutes using air quality networks would need to be compared with existing guideline values.

Models, in theory, predict 15 minute mean SO_2 concentrations needed for health impacts (e.g. 15 minute WHO thresholds for SO_2) but crucially these outputs are considered much more uncertain (due to model limitations) when compared to, for example, 24-h mean concentration outputs. New statistical methods may need to be investigated in order to develop capacity to address health impact requirements given model output constraints.

Particulate matter and SO_2

Further research and modelling will be required to constrain UK-wide mortality and morbidity estimates in worst-case air concentration scenarios based on a future Laki-type eruption, including investigation of the interaction of volcanic with anthropogenic air pollution, evaluation of the role of volcanic sulphate aerosol and its possible neutralisation by ammonia (NH_3) in the atmosphere. Advice may be sought from an expert advisory group (e.g. COMEAP : Committee on the Medical Effects of Air Pollutants) on the potential health implications of likely air pollution scenarios. Contemporary records of mortality and ill-health associated with the Laki eruption in 1783 should be re-evaluated in the light of recent advances in our knowledge of air pollution and its health effects.

Environmental impacts

Any volcanic acid gases and aerosols that reach the UK are likely to be deposited (by settling or sticking) on any surface, including soils, vegetation, crops, buildings and critical infrastructure, vehicles and so on, and – importantly – into surface water such as lakes, reservoirs and streams. This will occur through wet deposition (in rain and snow) or dry deposition. The impacts will depend on pre-existing conditions, the concentrations of the acidic compounds and whether or not they can be quickly removed (e.g. by uncontaminated rainwater or hosing off).

Soil acidification and the potential to impact groundwater (via meteoric water) needs further investigation as well as possible ammonia neutralisation. In some parts of the UK the addition of

sulphur may benefit the soils, elsewhere soils are already acidified and sensitive ecosystems are at risk. Localised rainfall carrying a volcanic burden may produce deposition hotspots.

Effective environmental management will rely heavily on good monitoring networks and knowledge of the sensitivity of different crops, vegetation, ecosystems to the pollutants. The impacts of acid gases and aerosols on different vegetation types under different atmospheric conditions was studied to some extent in the late 20th century, however there is limited literature available so further research is needed to carry out sensitivity tests and experiments on a range of plants and crops to establish thresholds and likely impacts, particularly on crops. The development of new products to facilitate emergency management, such as hourly concentration maps based on deposition monitoring, would be of value.

Volcanic particulates and gases can also penetrate into infrastructure systems and buildings, and potential effects on modern electronics, for instance, are not clearly understood. Monitoring of dried grass would be necessary to identify risk of fluorosis. Livestock could be kept indoors to reduce exposure. A volcanic haze or 'vog' is likely to lead to reduced visibility and could impact different sectors including transport. Experience elsewhere suggests that such a haze and its impacts will be spatially and temporally variable.

Aviation and transport impacts

SO_2 and sulphate (in the form of sulphuric acid) could cause damage to airframes and sulphate deposits can accumulate in turbines blocking cooling holes and leading to overheating during flight[9]. Sulphate aerosols also accelerate corrosion thus leading to a need for increased maintenance and decreasing engine lifetime. There is the possibility of crew and passengers being exposed to toxic gases on a plane/helicopter if SO_2 for example has not fully oxidised in the atmosphere. In order to quantify what the effects may be, more research and modelling work is needed. The potential for reduced visibility would also need to be taken into account by others in the transport sector (e.g. shipping).

Official advice in an emergency

In the event of a Laki-type eruption, guidance will be needed for the public and all sectors including transport workers, schools, farmers, veterinarians, water managers and critical infrastructure on living with and managing the consequences of volcanic air pollution. Modelling is needed to establish the likelihood of SO_2 or other gases and aerosols reaching the UK and planning should be in place in the event of a future eruption for warning and advising the population on the possibility of peaks in gas and aerosol concentrations (which cannot currently be modelled at appropriate resolution with sufficient accuracy to characterise human exposure). Modelling and further investigation is also needed to establish whether SO_2 or other gases and aerosols could be a hazard to crew and passengers at flight levels.

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[9] Miller and Casadevall, 2000

1. Introduction

1.1 Background

1.1.1 During the 2010 eruption of the Eyjafjallajökull volcano, the Government's Chief Scientific Adviser Sir John Beddington convened a Scientific Advisory Group in Emergencies (SAGE) in order to respond to the situation. One of the tasks of the group was to assess future scenarios of volcanic activity in Iceland that might impact the UK. Each scenario had to be based on a documented historical event.

1.1.2 Two scenarios were adopted for the National Risk Assessment (NRA): Eyjafjallajökull 2010 (a prolonged small-moderate-magnitude explosive eruption[10]) and Grímsvötn 1783-4 (a large-magnitude prolonged fissure eruption from the Laki craters). The Laki 1783-4 eruption represents the 'reasonable worst case scenario' in NRA terms. Based on data available at the time, the probability of such an event occurring in given future time periods and subsequently the likely impacts of such an event were documented for the NRA. Volcanic eruptions were identified in the National Risk Register (NRR) for the first time in 2011, based on the NRA.

1.1.3 The British Geological Survey (BGS) receives some funding from government to provide a national capability in volcanology. Therefore BGS responded to the 2010 eruption in several ways including a) providing advice to government and agencies when required and particularly during the crisis, b) liaising with partners in Iceland at the University of Iceland (UoI), Icelandic Meteorological Office (IMO) and Icelandic Civil Protection (National Commissioner of the Icelandic Police), c) supporting capacity building in Iceland and in the UK by enhancing existing monitoring networks (e.g. geophysical and gas monitoring in Iceland, volcanic ash collection and analysis in the UK), d) supporting contingency planning for future eruptions.

1.1.4 As part of this effort, the Civil Contingencies Secretariat requested that the source characteristics of a future Laki-type eruption scenario be considered and documented to facilitate modelling of the potential future impacts on the UK. It was proposed that an expert elicitation would be the best way to establish preliminary values for source characteristics and uncertainties and to bring together a multidisciplinary group of experts. Professor Willy Aspinall has many years of experience in conducting expert elicitations and led this element of the work. The task was commissioned in April 2012.

1.2 Aims and Objectives

1.2.1 The main aims of this work are to facilitate modelling of the 'Laki-type eruption scenario' and government planning for a future large magnitude fissure eruption in Iceland and also to engage the interest of the scientific research community.

1.2.2 The main objective of this work is to characterise a Laki-type eruption in terms of a range of appropriate 'source' parameters for modelling. Additional goals are to:

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[10] A glossary of terms including magnitude is given in Appendix E.

- establish likely eruption location, duration, dynamic evolution.

- evaluate the eruptive gases, aerosols, ash that may be produced and could ultimately lead to impacts in the UK.

- establish what chemical reactions, physical processes and meteorology should be included in modelling of plume transport.

- establish what the wet and dry deposition rates might be.

- characterise likely concentrations in the UK based on current knowledge.

- identify what the optimum monitoring and observation networks might look like from source to UK.

- understand what data on concentrations and deposition are required by health, environment and infrastructure experts.

- identify knowledge gaps.

- make recommendations for further work.

1.3 Notes

1.3.1 We do not consider the effect of volcanic eruptions on global climate in this study.

1.3.2 This report contains a compilation of key papers in volcano and atmospheric science, the results of an expert consultation and the recommendations of the expert group based on a deliberative exercise and open discussion. These findings are primarily aimed at a professional multidisciplinary audience who will be involved in observing or modelling volcano eruptions and those who may have to respond to future eruptions.

1.3.3 We recognise that from a science perspective this is a multidisciplinary problem that requires co-working, collaboration and co-production across disciplines.

1.3.4 This is not an impact assessment but will facilitate the modelling needed to fully understand what the impacts across different sectors might look like.

1.3.5 This document was compiled during May-June 2012. The findings reported within this document reflect the current state of knowledge which will change with time and further research.

1.4 Methods

1.4.1 The literature reviews (chapters 2-5) were carried out before the May 2012 meeting and key papers were collated as a resource.

1.4.2 A multidisciplinary expert group from academia, research institutes and institutes with operational responsibilities was identified covering volcanology, meteorology and atmospheric science to discuss the source characteristics of a Laki-type eruption. Those identified were

invited to participate in a three day meeting in London. A small number of representatives from the health and environmental impacts fields were invited to join the discussions and present the requirements of modellers in these fields. The group size was limited by available funds.

1.4.3 The original intention had been to elicit scientists in Iceland as well but the logistics for this proved too challenging in the time available. It is hoped that the process can be repeated in a year or two to include our Icelandic colleagues and take into account what has been learned during this exercise.

1.4.4 The expert group was also invited to provide additional peer-reviewed literature to the collection.

1.4.5 Briefing notes on the fundamentals of expert elicitation and the scope of the exercise were circulated to the expert group (Appendix B).

1.4.6 A draft set of target questions for discussion and elicitation at the meeting was prepared and circulated to the expert group, who were invited to submit revisions or further questions. Several feedback responses and suggestions were provided by group members, ahead of the meeting.

1.4.7 The questions were combined into a list and then reduced to a number of key points that could be addressed in the available time. The revised list was circulated to the expert group for comment.

1.4.8 The meeting was held in London and comprised further discussion on the questions to be answered (day one), a deliberative exercise (on qualitative questions) and an expert elicitation to capture the current perception of uncertainties of source term characteristics for modelling (day two), and the presentation and discussion of results (day 3).

1.4.9 The outcomes of much of the deliberative exercise are presented in Chapter 6 on monitoring. The outcomes of the expert elicitation are presented in Chapter 7 with a brief discussion on impacts presented in Chapter 8 and a summary with knowledge gaps and recommendations highlighted in Chapter 9. Additional useful and relevant data and documents are presented in the Appendices.

1.4.10 There is a glossary (Appendix E) containing definitions of some terms.

2. Fissure eruptions in Iceland

2.1 Iceland's volcanic systems

2.1.1 Iceland is situated on the mid-Atlantic tectonic plate boundary and also on a mantle 'hot spot' both of which control the occurrence of volcanism. A wide belt of active volcanoes and faulting follows the plate boundary from north to south through Iceland (Saemundsson, 1979; Thordarson and Larsen 2007) this is shown as dark grey in Figure 1. The spreading apart of two tectonic plates through faulting, fracturing and volcanic eruptions is known as 'rifting'.

2.1.2 Principal volcanic structures within the volcanic zones are called 'volcanic systems'. A volcanic system comprises a fissure swarm (an elongate zone of fractures and eruptive fissures) or a central volcano or both and has a typical lifetime of 0.5-1.5 million years (Thordarson and Larsen 2007). Iceland has thirty volcanic systems. The Laki eruption was from fissures belonging to the Grímsvötn volcanic system.
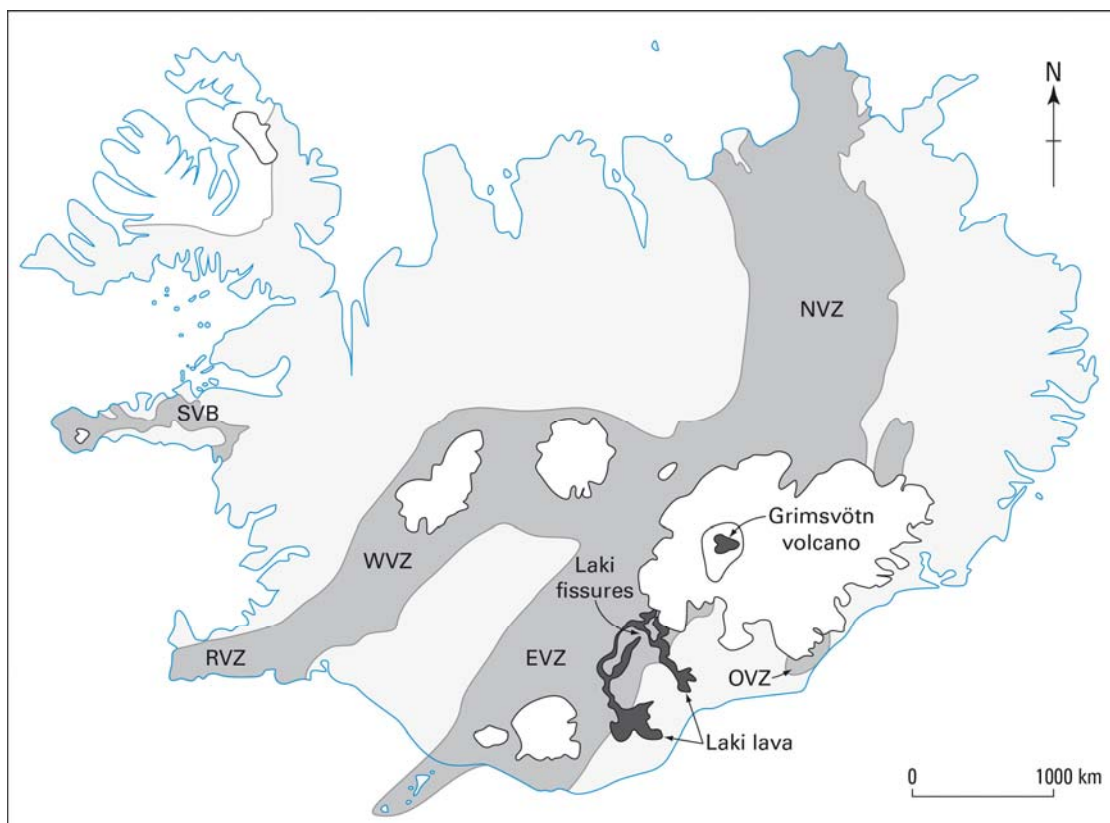
Figure 1. The active volcanic zones (dark grey) passing through Iceland include the Western Volcanic Zone (WVZ), Northern Volcanic Zone (NVZ), Eastern Volcanic Zone (EVZ), Öræfi Volcanic Zone (OVZ), Snæfellsnes Volcanic Belt (SVB) and Reykjanes Volcanic Zone (RVZ). The Laki 1783-4 fissures and lava flows (Grímsvötn volcanic system) in the EVZ are shown in black. The part of Iceland shaded light grey shows where >60% of the grazing livestock was killed, mainly from chronic fluorosis (Thordarson and Self, 2003). The map is modified from Thordarson and Self (2003), ©2003 American Geophysical Union. This material is reproduced with permission of John Wiley & Sons, Inc.

2.1.3 All volcanic zones in Iceland (dark grey in Figure 1) could be the sites of future eruptions. The main volcanic zones include the Northern Volcanic Zone (NVZ), the Western Volcanic Zone (WVZ), the Reykjanes Volcanic Zone (RVZ) and the Eastern Volcanic Zone (EVZ). The Eastern Volcanic Zone (EVZ) has been the site of most volcanic activity in historical times. The Öræfi Volcanic Belt (OVB) under the southern part of Vatnajökull glacier may be an embryonic rift zone and the Snæfellsnes Volcanic Belt (SVB) in the far west of Iceland is an older rift zone (Thordarson and Larsen, 2007).

2.1.4. Geological mapping combined with geochemical and petrological analysis and dating enables scientists to identify the eruption products and eruption histories of the different volcanic systems (e.g. Saemundsson, 1979; Jóhannesson and Sæmundsson, 1998; Thordarson and Larsen 2007).

2.2 Magma productivity in Iceland

2.2.1 Magma is molten or partially molten rock beneath the Earth's surface. The type of magma erupted from a volcanic system in Iceland (or any volcano) may vary between eruptions or even during phases of a single eruption and this affects the style of eruption. The most important magma variables that control the style of eruption are composition, temperature, crystal content and amount of gas (e.g. Parfitt and Wilson, 2008).

2.2.2 Magma undergoes chemical evolution from the moment it is first formed in the Earth's mantle until its eruption at the surface. Magmas erupted in close to their original state almost direct from magma reservoirs at the base of the Earth's crust are typically basaltic in composition. Some magmas undergo significant compositional changes, mainly during storage in the crust and may be referred to as 'evolved'or silicic.

2.2.3 Measurement of the total silica (SiO_2) content (by weight) of magma allows compositional classification as follows: basaltic magma (45-52% SiO_2), intermediate magma (52-62% SiO_2), silicic magma (>62% SiO_2). Magmas with lower SiO_2 content (basaltic magmas) typically have lower viscosity and higher temperatures than higher SiO_2 magmas (silicic magmas).

2.2.4 Eruptions of basaltic composition contribute 79% of the total erupted volume of magma in historical times in Iceland , intermediate composition 16% (95% of this attributed to Hekla) and silicic composition 5% (50% attributed to the Öræfi 1362AD eruption; Thordarson and Larsen, 2007). The Laki fissure eruption had a basaltic composition.

2.2.5 The total volume of magma erupted (measured as lava and tephra[11] volumes combined) in the last 1130 years (historical time in Iceland extends back to late 9th century) is 87 km^3 (DRE[12]). Of the total, 77% was erupted by just four volcanic systems in the Eastern Volcanic Zone (EVZ): Grímsvötn, Barðarbunga/Veidivotn, Hekla and Katla (Thordarson and Larsen, 2007, Table 1).

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[11] Tephra is fragmented material formed during explosions (includes ash)
[12] DRE - Dense Rock Equivalent

2.2.6 The EVZ accounts for ~79% (~69km^3) of the total erupted magma volume in historical time, the Western Volcanic Zone and Northern Volcanic Zone account for 15-16% (Thordarson and Larsen, 2007).

Volcanic zone		Number of eruptions in historical time	Volume of magma erupted in historical time (km^3)
EVZ	Katla	21 +	25
EVZ	Hekla	23	13
EVZ	Bardarbunga-Veidivötn	23 +	10
EVZ	Grimsvötn	~ 70	21

Table 1. The four most active volcanic systems in historical times (about last 1130 years) are in the Eastern Volcanic Zone. There were 205 historical eruptive events in Iceland and the total erupted volume was 87km^3, 77% of this was erupted by these four systems in the EVZ (data compiled from Thordarson and Larsen 2007).

2.2.7 Historical eruptions in Iceland have been defined by Thordarson and Larsen (2007) as follows: effusive (>95% of the erupted magma is lava), explosive (>95% of erupted magma is tephra), anything between these two end-members is referred to as a mixed eruption. The great majority of historical eruptions have been explosive (about three-quarters). The Laki eruption was mixed and produced a relatively large volume of tephra (see section 3.1).

2.3 Fissure eruptions

2.3.1 Volcanic fissures are linear vents, that are orientated parallel to the regional rift zone and are formed as a result of a single eruptive episode. The magma is believed to be fed from a great depth directly to the surface along a dyke. Initially, a long section of a fissure may erupt and then activity commonly becomes focused with time at several vents along the fissure (Fig. 2).

2.3.2 A fissure eruption may comprise several episodes, each opening a new fissure. Each episode begins with a short-lived explosive phase lasting hours to days followed by a phase of lower intensity typically characterised by lava fountaining.

2.3.3 Fissure eruptions are always characterised by magmas of basaltic composition (45-52% SiO$_2$), high temperature and low viscosity.

2.3.4 The degree of explosivity is controlled mainly by gas content of the magma, viscosity and eruption rate. When much of the dissolved gas in the magma is able to separate from the magma before the eruption, the resulting eruption may be just mildly explosive and characterised by lava fountains (or 'fire fountains') of incandescent fragmented magma that

rise above the vent and then collapse to either coalesce into lava flows or form spatter cones/ramparts (Fig. 2).

2.3.5 Fissure eruptions can be vigorously explosive, especially when a fissure first opens up. The interaction of water and magma can also lead to highly explosive hydromagmatic or phreatomagmatic eruptions that generate volcanic ash.

Figure 2. Example of an active fissure vent on the East Rift Zone, Hawaii. Magma erupts along the linear fissure and the intensity of activity varies through time. The eruption products are dominated by lava which flows away from the fissure (here into a previously active fissure) and gas/aerosol which rises in the atmosphere to different heights depending on eruption intensity and buoyancy effects. Published with permission: U. S. Geological Survey – Hawaiian Volcano Observatory.

2.3.6 There have been 205 eruptions in historical time (last 1130 years) identified based on the mapping of eruption products and analysis of historical records (Thordarson and Larsen, 2007). Of these, 13 have been classified as prolonged fissure eruptions with varied styles of activity mostly consisting of lava fountains and lava flows (Fig. 2).

2.3.7 Five of these 13 fissure eruptions produced substantial tephra (fragmented material formed during explosions). Three of these produced >1km^3 tephra (Thordarson and Larsen, 2007). For comparison, the Eyjafjallajökull eruption in 2010 produced a total of 0.27 km^3 tephra much of which was fine ash due to magma-water interaction (Gudmundsson et al., 2012). It is the grainsize of the tephra that largely controls the potential for it to be transported significant distances.Although fine ash is not normally a major eruption product of fissure eruptions it may be generated if the erupting magma interacts with groundwater, surface water or snow/ice.

2.3.8 Eruptive fissures and associated aligned fractures and faults are collectively known as 'fissure swarms'. Iceland has thirty volcanic systems but only twenty one of these feature existing fissure swarms.

2.3.9 Twelve of these fissure swarms are mature (e.g. Askja in the NVZ) and comprise a high density of fissures, faults and fractures (5-20 km wide and 50-200 km long), five are of moderate maturity and four are 'embryonic' (e.g. Katla and Grímsvötn) with only one or a few fissures (Jóhannesson and Sæmundsson, 1998; Thordarson and Larsen 2007; Table 2).

Volcanic Zone[a]	Volcanic System	Fissure Swarm[b]	Large volume fissure eruptions[c]
RVZ	Reykjanes/Svarts engi	xxx	
RVZ	Krýsuvík	xxx	
RVZ	Brennisteinsfjöll	xxx	
WVZ	Hengill	xxx	
WVZ	Grimsnes	xxx	
WVZ	Prestahnjúkur	xxx	
WVZ	Hveravellir	xx	
MIB	Hofsjökull	xxx	
MIB	Tungnafellsjökull	xx	
EVZ	Vestmannaeyjar	xx	
EVZ	Katla	x	Eldgjá
EVZ	Hekla - Vatnafjöll	xx	
EVZ	Bardarbunga-Veidivötn	xxx	Thjorsá
EVZ	Grimsvötn	x	Laki
NVZ	Kverkfjöll	xxx	
NVZ	Askja	xxx	
NVZ	Fremrinámur	xxx	
NVZ	Krafla	xxx	
NVZ	Theistareykir	xxx	
SVB	Ljósafjöll	x	
SVB	Helgrindur	x	

[a]RVZ – Reykjanes Volcanic Zone, WVZ – West Volcanic Zone, EVZ – East Volcanic Zone, NVZ – North Volcanic Zone, SVB – Snæfellsnes Volcanic Belt, MIB – Mid-Iceland Belt.
[b] xxx = 'mature' fissure swarm, xx ='moderately mature', x ='embryonic'
[c] erupted magma volume >1km^3

Table 2. Iceland's volcanic systems and the maturity of existing fissure swarms (based on Jóhannesson and Saemundsson (1998) and Thordarson and Larsen (2007). The three largest volume Holocene fissure eruptions (Laki from Grímsvötn, Eldgjá from Katla and Thjorsá from Veidivötn) all occurred during the early stages of development of a fissure swarm.

2.3.10 Following Thordarson and Larsen (2007), here we define large fissure eruptions in Iceland as those that erupt more than 1km^3 magma (DRE). Erupted volume can be converted to erupted mass (if the magma density is known) to give 'magnitude' which allows different types of eruptions worldwide to be compared. The eruptions typically have durations of months to years with several distinct episodes.

2.3.11 The 'embryonic' Katla and Grímsvötn fissure swarms produced the two largest fissure eruptions in Iceland in historical times (Eldgjá 934-938 and Laki 1783-4 AD respectively – Table 2). The overall largest Holocene (last ~12,000 years) fissure eruption, Thjorsá also took place when the Veidivötn fissure swarm was immature (Thordarson and Larsen, 2007).

Large-volume fissure eruptions (Holocene)

2.3.12 There have been fourteen large-volume fissure eruptions just from the Grimsvötn, Barðarbunga/Veidivötn and Katla volcanic systems during the Holocene (Thordarson and Larson, 2007). These three systems have been by far the most productive systems (in terms of erupted magma volume) during the Holocene (Thordarson et al. 2003), see Table 3.

Volcanic system	Eruption	Age (years BP)	Calendar age	Volume (km^3)
Veidivötn	Thjorsá lava	c.8600		22-25
Veidivötn	Rauðhóll –Flögd lava	>8000		1
Veidivötn	Háganga	>8000		1
Veidivötn	Háa-Botnar lava	>8000		1.1
Veidivötn	Tungnáa lava	6800		1.4
Veidivötn	Tungnáa lava	6700		3.8
Veidivötn	Sigalda lava	6200		3.4
Veidivötn	Brydja lava	c.4000		1
Veidivötn	Búrfell –Dreki lava	3200		6.5
Grímsvötn	Halsar-Botnar lava	c. 6000		>3
Grímsvötn	Núpar lava	3800		7
Grímsvötn	Laki	227	AD 1783-1784	15.1
Katla	Hólmsá	c.6800		>5
Katla	Eldgjá	c. 1070	AD 934-938	19.6

Table 3. Holocene large-volume fissure eruptions in the Veidivötn, Grímsvötn and Katla volcanic systems. Years BP are calculated from AD 2010 (modified from Thordarson et al., 2003 and references therein), © The Geological Society of London 2003.

2.3.13 The three largest Holocene fissure eruptions in Iceland were: Thjórsá 8600BP, Eldgjá 934-938 AD, and Laki 1783-4 (Thordarson et al., 2003; Tables 2, 3 and 4). The historical record, available data and research on each of these eruptions is less as one goes back in time and is summarised in Table 4.

2.3.14 The large-volume Holocene fissure eruptions are not equally distributed through time but have tended to occur mainly in distinct time periods of a few hundred years duration between 9000-8000 BP, 6800-6200 BP, 4000-3200 BP and a historical period including events in 934 AD and 1734 AD (Table 3).

Large-volume fissure eruptions (historical time)

2.3.15 Based on a combination of geological mapping and historical documents, four large-volume fissure eruptions are known to have taken place in Iceland during historical time (the last 1130 years): 1. Eldgjá 934-938 AD (Katla- EVZ),2. Hallmundarhraun ~950 AD (WVZ), 3. Frambruni pre-13th century (NVZ) and 4, Laki 1783-4 (Grimsvötn - EVZ). According to Thordarson and Larsen (2007), these four historical eruptions account for more than one half (54%) of the total erupted magma volume in historical time in Iceland.

Fissure eruptions	Eruption date	No. of episodes	Erupted volume (km^3)	References
Krafla	1975-1984	9		
Surtsey	1963-1967	6-7		
Askja	1921-1929	5-6		
Trollahraun	1862-1864	2-3		
Skaftáreldar (Laki)	**1783-1785**	**10-11**	**15.1**	Thordarson & Self, 1993; Thordarson et al., 2003a, 2003b.
Myvatnseldar	1724-1729	6-7		
Veidivötn	1477-			
Illahraun	1227-			
Frambruni (Dyngjuhals)	**Pre-13th C**		**4.0**	Thordarson and Larsen, 2007
Krysuvikureldar	1151-			
Y-Hellnaharaun	C10			
Husafellsbruni	c. 950			
Eldgjá	**c. 934**		**19.6**	Larsen, 2000, 2005; Thordarson et al. 2001, 2003
Hallmundarhraun	**c.900**		**8.5**	Sinton et al. 2005
Vatnaöldur	c. 870			

Table 4: Historical fissure eruptions in Iceland (modified from Thordarson and Larsen 2007 and references therein). Large-volume fissure eruptions (erupted magma volume >1km^3) are shown in bold.

2.3.16 The average recurrence rate for large-volume fissure eruptions in historical times in Iceland is 270 years, the last such eruption was Laki in 1783-4. Statistically, the very short time period (~1130 years) with reliable data available makes detailed analysis challenging. The eruptions vary considerably in terms of volume of erupted magma. For fissure eruptions of any erupted volume, the average recurrence rate in historical times is 88 years (Table 4).

2.3.17 Historical large-volume fissure eruptions have produced some tephra which is preserved as layers where it fell to the ground and these layers can be mapped and the minimum volume calculated, this ranges from 0.4 to 1.2km³ (Thordarson and Self, 1993; Thordarson and Larsen, 2007). If there is no magma-water interaction, most tephra will fall to the ground near-source.

2.3.18 The historical Vatnaöldur (~870AD) and Veidivötn (1477AD) eruptions were the two largest phreatomagmatic fissure eruptions in Iceland during the whole Holocene (Larsen, 1984; Thordarson et al., 2003; Table 4). These eruptions interacted with water which may have included groundwater, surface water, snow and ice.

2.3.19 In general, the uncertainty on calculation of erupted magma volumes of historical eruptions is substantial and variable (Table 5).

	Date	Total volume (km³)	Volume error	Mass (kg)	SO_2 (Mt)	SO_2 error	Duration
Thjórsá	8600BP	22-25	~25+%	-	150	20-25%	600 yrs (?)
Eldgjá	934-938AD	19.6	~25%	5.5×10^{13}	184	20-25%	1-3 yrs (?)
Laki	1783-1784AD	15.1	~15%	4.2×10^{13}	122	20-25%	8 months

Table 5. Published data for the three largest Holocene fissure eruptions in Iceland (Thordarson and Self, 2003; Thordarson and Larsen, 2007). The SO_2 error is discussed in section 6.1.41.

2.3.20 The largest volume fissure eruptions that have occurred during the Holocene in Iceland are still orders of magnitude smaller than the largest eruptions of this type that have occurred worldwide in geological time. 'Flood basalts' are very large magnitude basalt eruptions that correlate with mass extinction events (e.g. Courtillot and Renne, 2003). The volume of the Roza lava in the Columbia River Flood Basalt Province is ~1300 km³ (compared to the Laki flow volume of 14.7 km³). The duration of emplacement of the Roza lava and by inference the duration of the fissure eruption may have been as short as years to decades (Thordarson and Self, 1998).

3. Characteristics of large-volume fissure eruptions in Iceland

3.1 LAKI

3.1.1 The 1783-4 eruption of Grímsvötn (Laki craters) is the best-characterised historical large-volume basaltic fissure eruption in Iceland. It was the second largest fissure eruption worldwide in the last 2000 years (after the ~935AD eruption of Eldgjá). Some characteristics of the eruption based on the literature are presented below.

Eruption character

3.1.2 The Laki eruption of 1783-4 occurred from a 27 km long volcanic fissure in an ice-free portion of the Grímsvötn volcanic system (Fig. 1). It produced ~14.7 km^3 of lava (error ~15% see Table 5) 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 (Thordarson and Self, 1993; Thordarson and Self, 2003).

3.1.3 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 (Table 5; Thordarson pers. comm.).

3.1.4 The Laki eruption began on June 8, 1783 and lasted eight months (Thorarinsson, 1969; Thordarson and Self, 1993). The eruption occurred as 10 distinct episodes of activity, each starting with a short-lived Strombolian to sub-Plinian 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 and Larsen, 2007). Some of the first explosions were phreatomagmatic, probably caused by groundwater influx to the vent (Thordarson and Larsen, 2007).

3.1.5 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 episodes almost certainly injected materials into the stratosphere. This height, character and persistence of the eruption columns is believed to have had an impact on global atmosphere and environment with reports of aerosol clouds over north-eastern North America, Central Asia and Siberia (e.g. IPCC 3rd Assessment Report, 2001; Fiacco et al., 1994; Thordarson and Self, 2003).

Volatile emissions

3.1.6 Thordarson et al. (1996) calculated the total mass of major gas species emitted during the Laki eruption using petrological studies as shown in Table 6. Of this mass, it is calculated that about 96% was released during the first 5 months of activity (Figure 3). The first three fissure-opening episodes lasted just 10 days in total and released 40% of the total SO$_2$. About 60% of the SO$_2$ mass was released in the first six weeks.

3.1.7 The SO$_2$ release from Laki yields a theoretical sulphuric aerosol (H$_2$SO$_4$) mass of ~250 Tg (1 teragram (Tg) = 1 x 10^9 kg = 1 megatonne (Mt)), assuming a composition of 75 wt % H$_2$SO$_4$ and

25 wt % H_2O for the aerosols (Thomason and Osborne, 1992) and a complete conversion of SO_2 to H_2SO_4 aerosols (Thordarson et al., 1996).

3.1.8 For comparison, 76 Tg of SO_2 was ejected by burning fossil fuel and industry in 2001 (from all sources globally over 12 months) and induced 122 Tg of sulphate aerosols (IPCC 3rd Assessment Report, 2001). There were global anthropogenic SO_2 emissions of approximately 115 Tg during the year 2005 (Smith et al., 2011).

	SO_2	H_2O	HCl	HF
Laki	~122	235	235	15

Table 6 Estimates of the amount of SO_2, H_2O, HCl and HF released by the Laki eruption into the atmosphere in Tg (1 Tg = 1 x 10^9 kg = 1 Mt), from Thordarson et al. (1996).
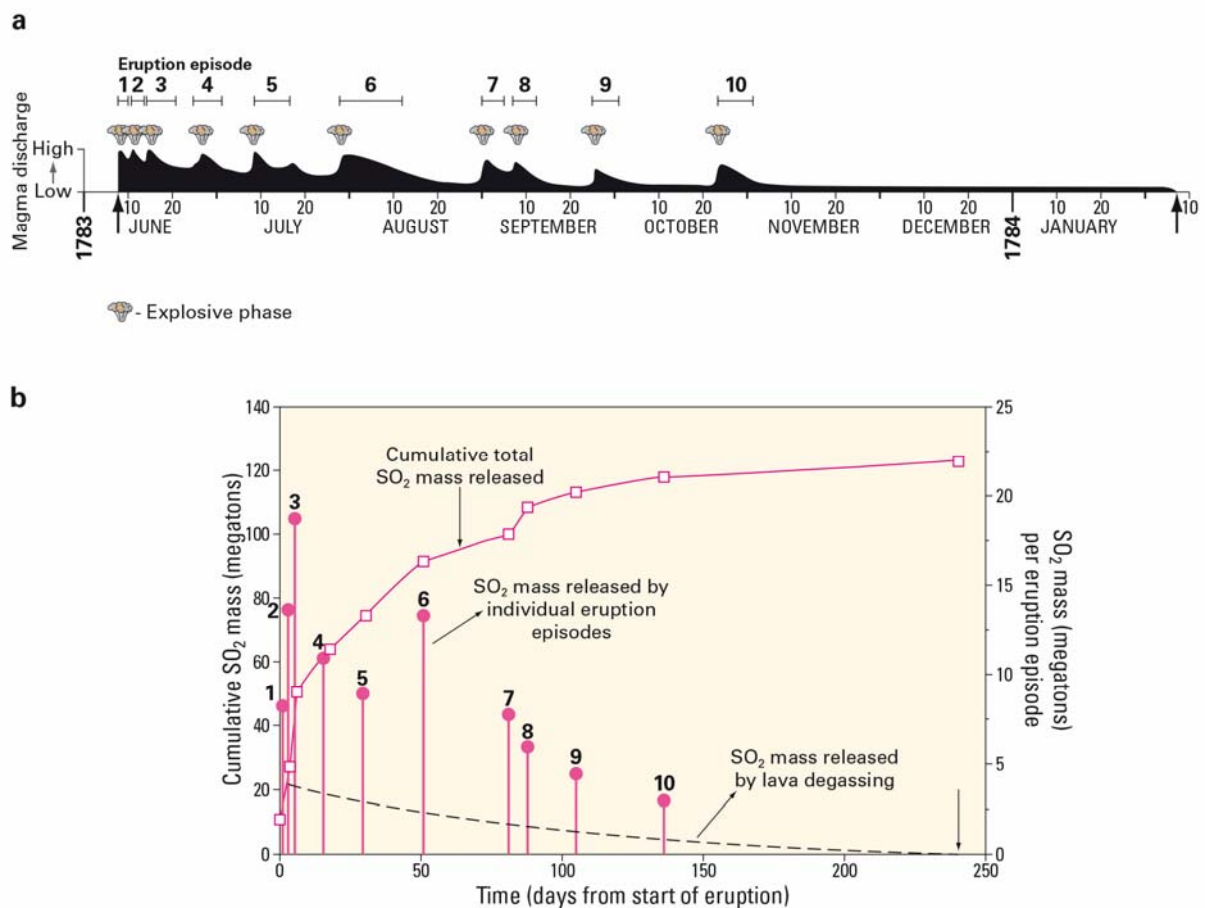

Figure 3. a) Time series showing each fissure opening episode, explosive phases and relative magma discharge rate. b) The SO_2 mass released by individual episodes, lava degassing and cumulatively through the eruption (1Mt = 1Tg). Modified from Thordarson and Self (2003), ©2003 American Geophysical Union. This material is reproduced with permission of John Wiley & Sons, Inc.

3.1.9 Most of the SO_2 mass was released at the vents (80%) and was transported by eruption columns to lower stratospheric altitudes (>9 km; Thordarson and Self, 2003). About 20% of the SO_2 mass was released from the lava flows at heights estimated to be up to around 5 km and there were observations of a low altitude cloud and tephra deposits across eastern Iceland (Figure 1; Thordarson and Self, 1993).

3.1.10 The mass of magmatic water released into the atmosphere by the activity at the Laki fissures exceeded the amount of SO_2 by a factor of 1.9 (Thordarson and Self, 2003).

3.1.11 The winds transported the plumes eastward and the eruption maintained a sulphuric aerosol veil that affected the Northern Hemisphere for >5 months (e.g. Stothers, 1996, 1999; Thordarson and Self, 2003).

3.2 ELDGJÁ

3.2.1 The Eldgjá eruption which started in Iceland in 934 AD is one of the most voluminous basaltic fissure eruptions worldwide in historical time (Miller, 1989; Larsen 2000; Table 5). A total of 18.3 km^3 of lava and ~1.3 km^3 of tephra was erupted (Larsen 2000) but this is partially covered by Laki deposits so errors are larger than for Laki and the duration of the eruption is not well-constrained due to less complete contemporary records (Table 5).

3.2.2 The 75 km-long Eldgjá fissure vents extend from Myrdalsjökull glacier in the southwest to Vatnajökull glacier to the northeast and are part of the Katla volcanic system (Thordarson et al. 2001). The subglacial nature of parts of the fissures at least partially explains the large volume of tephra (there was effective magma fragmentation due to magma-water interaction).

Eruption character

3.2.3 The Eldgjá eruption is less-well reported than the Laki eruption, so deductions about the character of the eruption have been drawn largely from the stratigraphy of the tephra deposits and near-vent accumulations (Larsen, 1993, 2000; Miller, 1989, Thordarson et al., 2001).

3.2.4 Thordarson et al., (2001) suggested that the Eldgjá eruption had a near identical eruption character to Laki, with several discrete episodes of activity each starting with vigorous explosive activity releasing >80% of the volatile mass. There may have been as many as 35 separate episodes.

3.2.5 Deposits suggest phases of vigorous explosive activity and intense lava fountaining (similar to Laki). Proximal spatter deposits have been found capping surrounding topographic highs (50-200m above base level; Thordarson et al. 2001). Tephra deposits around the vents record strombolian activity from the subaerial part of the fissure system.

3.2.6 More than 96% of the total erupted volume was subaerial (no ice and minimal groundwater interaction). The subaerial part of the fissure system also produced much of the lava. The southwestern end of the fissure system was dominated by phreatomagmatic activity (<4% total volume) due to interaction with meltwater from Myrdalsjökull (Thordarson et al. 2001).

3.2.7 The large volume of tephra (~1.3 km^3) had a wide dispersal, with 0.5 cm thick deposits located up to 100 km from the source (Larsen 1993, 2000; Thordarson et al. 2001).

3.2.8 It has been suggested that the initial phreatomagmatic (subglacial) eruption columns for Eldgjá are likely to have reached 14-16 km above vent (Larsen, 1993), based on the plume observations from the 1918 summit eruption of Katla.

Volatile emissions

3.2.9 Several studies have sought to estimate the sulphur yield of the eruption. Petrologic estimates by Palais and Sigurdsson (1989) produced 55 Mt SO_2. Hammer et al (1980) and Zielinski et al. (1995) used acidity data from ice-cores in Greenland to estimate the H_2SO_4 aerosol loading at 165 and 93 Mt respectively. However, the most recent analysis of Thordarson et al. (2001) suggests magma degassing occurred in two stages, releasing ~184 Mt SO_2 at the vent site, with a further ~35 Mt emitted from the lava flow surface and a H_2SO_4 aerosol yield of ~450 Mt.

3.3 THJÓRSÁ

3.3.1 The Thjórsá lavas are part of the Veidivötn fissure system that extends ~80km to the SW of Bárðabunga , one of the most productive volcanic systems in Iceland in the Holocene (Thordarson et al., 2003).

3.3.2 The Thjórsá lavas were erupted *c.*8600 BP and are the earliest of the Veiðivötn fissure eruptions, with a volume of ~22-25 km^3 (Thordarson et al. 2003) they are the most voluminous lavas in Iceland and the largest fissure eruption on Earth in the Holocene (Halldorsson et al. 2008). The Thjorsá lavas are buried by multiple deposits and have experienced erosion so there is some uncertainty on the total erupted volume.

Eruption character and volatile emissions

3.3.3 Thordarson et al. (2003) report *c.*150 Mt of SO_2 produced during this eruption (using petrological methods) and they suggest that this eruption had a similar dynamic character to Laki.

3.3.4 Characterisation of the eruptive activity is difficult because the vents for these lavas are covered by younger lavas. There is also uncertainty on the duration of the eruption (Table 5).

4. Atmospheric dispersion and chemical transformation

4.1 Background

4.1.1 During a large-volume basaltic fissure eruption, gases and particles will be released from eruptive vents over a prolonged period of time forming a 'volcanic plume' that may, during intense explosive episodes, reach the stratosphere and have far-reaching effects (see section 3). Eruptive stratospheric plumes and their atmospheric impacts are the subject of much study (e.g., Robock, 2000; Robock and Oppenheimer, 2003) but we will not consider climatic effects in detail here, we focus instead on the troposphere.

4.1.2 Volcanic plumes are characterised by the atmospheric dispersal of volcanic gases and aerosols which undergo complex chemical and physical transformations in the troposphere during transport. The rates of reactions in a plume may be very different to the background atmosphere, reflecting higher temperatures, humidity, aerosol content and possibly radical production (e.g. Gerlach, 2004).

4.1.3 A volcanic plume interacts with the atmosphere in several ways including both physical and chemical processes. The prevalent meteorology, in particular wind direction, dictates where a plume is transported to and at what rate, it also controls critical factors such as cloud cover, humidity and removal mechanisms such as wet deposition (see section 4.2). Chemical reactions include gas-phase reactions (homogeneous reactions) and reactions on, in or between suspended gas, solid and liquid particles (heterogeneous reactions). Understanding the chemistry is critical to understanding how the constituents of a plume are transformed with time.

4.1.4 Volcanic plumes contain mostly gaseous water (H_2O) and carbon dioxide (CO_2) and volatile acidic gas species such as sulphur dioxide (SO_2), hydrogen sulphide (H_2S), hydrogen chloride (HCl), hydrogen fluoride (HF) and hydrogen bromide (HBr) (Symonds et al., 1994). Although H_2O is emitted in the gas phase (and is hence invisible), plumes contain abundant potential condensation nuclei, so liquid water droplets condense to give the distinctive cloudy appearance. The presence of these water droplets is significant to the fate of the more soluble gas species (Horrocks et al., 2003) see section 4.3.

4.1.5 Information about the processes and rates of removal of acid gas species such as SO_2, HCl and HF from the gas-phase is most important for volcanoes and volcanic impacts. Carbon dioxide can be considered relatively inert during dilution in the atmosphere (e.g. Aiuppa et al. 2006).

4.2 Meteorological effects

4.2.1 Weather conditions directly affect the fate of volcanic plumes by controlling their dispersion, transport and deposition. The ambient atmosphere around a volcano influences how high into the atmosphere plume material can be lofted. Much depends on the strength of the eruption; the weaker it is the more scope there is for atmospheric variations, such as wind-shear and stability to have an impact and reduce the eruption height. However, even for strong eruptions, where the plume extends into the stratosphere, the stability of the stratosphere will

eventually cap its rise and upper level winds will determine its distribution (Petersen et al., 2012).

4.2.2 The far-field dispersal of a volcanic plume depends on the wind speeds and wind directions that the plume encounters at altitude. These winds are governed by the mean wind field, which is primarily determined by the large (synoptic) scale meteorology. Strong winds promote rapid transport of the plume away from source whereas light winds result in the plume staying near the source. The distance of transport is also determined by various in-cloud processes that occur as the volcanic cloud moves, including processes affecting the aggregation and sedimentation rate of volcanic particles (Petersen et al., 2012). Atmospheric water content determines the rate of wet deposition of particles from the plume and two main processes are involved: washout where material is swept out of the atmosphere by falling precipitation and rainout where material is absorbed directly into cloud droplets as the particles act as cloud condensation nuclei.

4.2.3 Typically, the evolution of a plume will be influenced by differences in wind speed and direction at different heights and one part of the plume may be transported faster or in a different direction to other parts. The evolution of the plume is also influenced by synoptic scale features, such as frontal uplift or subsidence due to high pressure systems (Dacre et al., 2011). This can cause plumes to move upwards in the atmosphere or to become "trapped" behind frontal features.

4.2.4 Chemical reactions in plumes are influenced by atmospheric temperature, humidity, precipitation, cloud cover and the amount of sunlight (UV) reaching the plume. Atmospheric water droplets are a medium for conversion of gas phase SO_2 to aqueous phase sulphate aerosol. In the boundary layer, a cycle of condensation on aerosols at night and evaporation by day can greatly increase the concentrations of pollutants in the droplets (Oppenheimer, 2011). Temperature inversions overnight can act to trap boundary-layer plumes at ground-level leading to concentration peaks during the night and early morning (demonstrated to occur at the degassing volcano Masaya in Nicaragua, Oppenheimer et al., 2011).

4.2.5 All of these processes are represented either in Numerical Weather Prediction (NWP) models or atmospheric dispersion models (that take NWP data as input) to varying degrees of detail. All stages from the specification of the eruption source term, the initialisation of the NWP forecast and the parameterisations within the models contribute to the level of confidence in model predictions.

4.3 Chemical and physical reactions – SO_2

4.3.1 Recent studies including von Glasow (2009) have demonstrated how volcanic plumes are highly oxidising relative to the background troposphere and this is critical to the fate of species such as SO_2.

4.3.2 In the gas phase, SO_2 oxidation occurs by reaction with hydroxyl radicals (OH) to form SO_3 and then sulphuric acid (H_2SO_4) but this reaction is relatively slow. Möller (1980) calculated tropospheric e-folding times for homogeneous gas phase oxidation by OH of 12 days (i.e. the time taken for SO_2 abundance to decay exponentially to 1/2.718 of its initial level). Sulphuric

acid is hygroscopic so rapidly condenses to either add to existing liquid aerosols or to create new ones (Fig. 4).

4.3.3 Oxidation of SO_2 in the troposphere is faster via multiphase reactions when it partitions into the aqueous phase (i.e. in cloud droplets or pre-existing liquid aerosols) where it reacts with dissolved hydrogen peroxide (H_2O_2) or ozone (O_3) to form sulphate (SO_4). This is a rapid process, especially if the condensed water content of the plume is high and Möller (1980) calculated mean tropospheric e-folding times of <6 hours for oxidation within liquid particles. The reaction with O_3 is rapid in the liquid aerosol but more pH-dependent than the reaction with H_2O_2 (e.g. Hewitt, 2001).

4.3.4 Very short e-folding times of just minutes at Montserrat (Oppenheimer et al., 1998) have been explained by the high humidity tropics promoting SO_2 oxidation in liquid particles (Rodriguez et al., 2008). The influence of increased humidity on SO_2 oxidation rates was also observed at power stations (e.g. Finlayson-Pitts and Pitts, 1986).

4.3.5 Other reactions for SO_2 oxidation in the troposphere may include transition metal catalysis (e.g. Fe^{2+} or Mn^{2+}) or via homogenous liquid aerosol reactions (e.g. Horrocks et al., 2003; Oppenheimer et al., 2011).

4.3.6 Photodissociation of SO_2 in the gas phase to SO and O cannot occur in the troposphere because UV solar radiation at the necessary wavelengths doesn't penetrate this far but it is important at higher levels in the atmosphere (Horrocks et al., 2003).

4.3.7 Sulphate aerosols tend to increase in size with time due to nucleation, coagulation and condensation (Fig. 4). Volcanic sulphate aerosols act as cloud nuclei allowing condensation of water to form clouds and often inducing rain near a volcano (e.g. Mather et al., 2003, 2004).

4.3.8 Sulphate aerosols may also lead to changes in existing clouds such as decreased particle size and increased particle number which can be detected by satellite (e.g. Gassó, 2008). The presence of sulphate in a plume tends to cause acidification of pre-existing atmospheric aerosol (von Glasow et al., 2009) and may lead to increased rates of acid-catalyzed aqueous reactions and revolatilisation of acidic gases (e.g. HCl, HBr, HF, HNO_3).

4.3.9 Sulphate aerosol may also act as a medium for other reactions to take place within and on the aerosol. This has been highlighted in kinetic models (e.g. Roberts et al. 2009; von Glasow, 2010). Von Glasow (2010) also shows how SO_2 may have a role in mercury speciation which may lead to elevated and harmful levels of mercury deposition around active volcanoes (Oppenheimer et al. 2011).

4.3.10 Heterogeneous reactions (those occurring on the surface of a solid) and multiphase reactions (those occurring within an aqueous medium) are usually more important at controlling concentrations of soluble gases in a plume than slower homogenous gas phase reactions (Ravishankara, 1997).
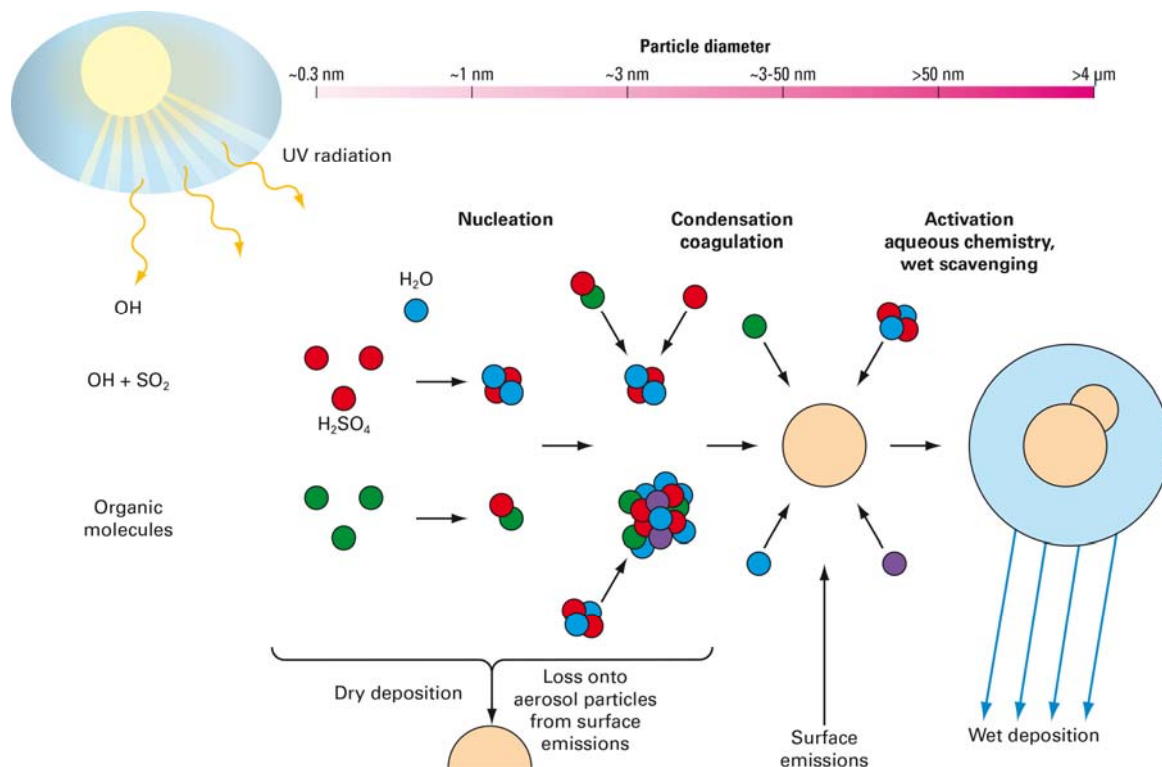
Figure 4 Diagram showing the main aerosol processes and tendency of aerosols to increase in size with time (making them more visible to satellites) but many still remain in the PM$_{2.5}$ and PM$_{10}$ range. Based on a figure by J. Kazil, © Jan Kazil, University of Colorado/NOAA.

4.1.11 Sulphate aerosols affect Earth's radiation balance because they backscatter incoming radiation (Charlson et al., 1992) and absorb outgoing long wave radiation, the competition between these two depends on particle size (Oppenheimer et al., 2011). Sulphate aerosols also affect the hydrological cycle (Penner et al., 2001) by promoting cloud condensation (Graf et al., 1997), by modifying the *albedo* of clouds (Twomey, 1977) and by modifying microphysical properties and the lifetime of existing clouds (Jones et al., 2001). Suspended aerosols in the troposphere and stratosphere also control atmospheric heating rates and photochemical processes (e.g. Grainger and Highwood, 2003; Horrocks et al., 2003).

4.4 Chemical and physical reactions – HCl and HF

4.4.1 HCl is not a criterion air quality indicator like SO$_2$ and so is less well-studied (even though chlorine is important in the stratosphere, Oppenheimer et al. 2003). HCl is much more soluble in water than SO$_2$ (Horrocks et al. 2003 based on Seinfeld, 1986) and its high solubility may mean that there are fewer reaction pathways for HCl to get into solution than for SO$_2$.

4.4.2 Uptake of HCl on aerosol and rain droplets is probably more important than dry deposition for HCl and the rate of HCl removal is likely to be more strongly affected by liquid water than

SO$_2$ due to its higher solubility. Johnson and Parnell (1986) showed that the pH of acid rainwater at Masaya Volcano (in the tropics) was controlled by the amount of dissolved HCl which was almost all removed from the plume by proximal rainfall, whereas SO$_2$ was still available for dissolution at long distances downwind.

4.4.3 Aiuppa et al. (2007) used observations and model predictions to show only minor HCl chemical processing during plume transport at Etna in low humidity (cloud-free) conditions and over the short term (minutes). They proposed that chlorine partitioning into the liquid phase is initially limited by the high acidity of the aerosol particles in the near-field but becomes important when the gas phase concentration is reduced by dilution. Even during rainy periods there was not substantial HCl removal from the plume over the short term (e.g. Aiuppa et al. 2006).

4.4.4 Delmelle et al. (2005) looked at the dynamics and kinetics of gas (SO$_2$, HCl, HF) uptake by and subsequent release from volcanic ash particles. They found that the presence of a water coating on ash enhances scavenging (i.e. surface adsorption) of HCl and HF – such a coating is highly likely in a 'humid' plume. They pointed out the need to assess how the gases interact with particles coated with ice.

4.4.5 Delmelle et al. (2007) noted that reactions between gases/aerosols and silicate ash particles remain poorly understood and this remains the case at the time of writing.

4.5 Deposition processes

4.5.1 Dry deposition is the removal of particles or molecules by settling on or sticking to ground-level surfaces (e.g. soils, vegetation, water, vehicles, infrastructure). Dry deposition rates depend on the nature of the surface so for example, rates of acid deposition increase if leaf surfaces are wet. Dry deposition velocities depend on the reactivity of the species, so in experiments, HF (with high reactivity) has a deposition velocity of 1-4 cm/s and SO$_2$ of 0.1-2 cm/s (Seinfeld, 1986). Delmelle et al. (2001) showed that SO$_2$ and HCl had similar deposition rates of c. 1.6 cm/s at Masaya volcano, Nicaragua.

4.5.2 Deposition of SO$_2$ direct onto surfaces is likely if the plume is at ground level or there are a high proportion of dry particles (e.g. ash particles) in the plume. It's also enhanced in dry, cool conditions.

4.5.3 Wet deposition is mainly about precipitation (Fig. 5). Aerosols, particles and gases are all efficiently removed by rainfall. In an environment rich in condensed atmospheric water, scavenging of the gas phase will be controlled by rates of reaction for different species. Scavenging rates for HCl and HF are likely to be higher than SO$_2$ which relies on chemical reaction in preference to physical dissolution (Horrocks et al., 2003). These rates have implications for monitoring.

4.5.4 Tabazedeh and Turco (1993) modelled the wet deposition from the 1991 Pinatubo eruption. Once water began to condense, HCl dissolved rapidly to form solutions of 1-5 wt% HCl. Large volcanic eruptions often induce rainfall so removal of HCl may in general be efficient.
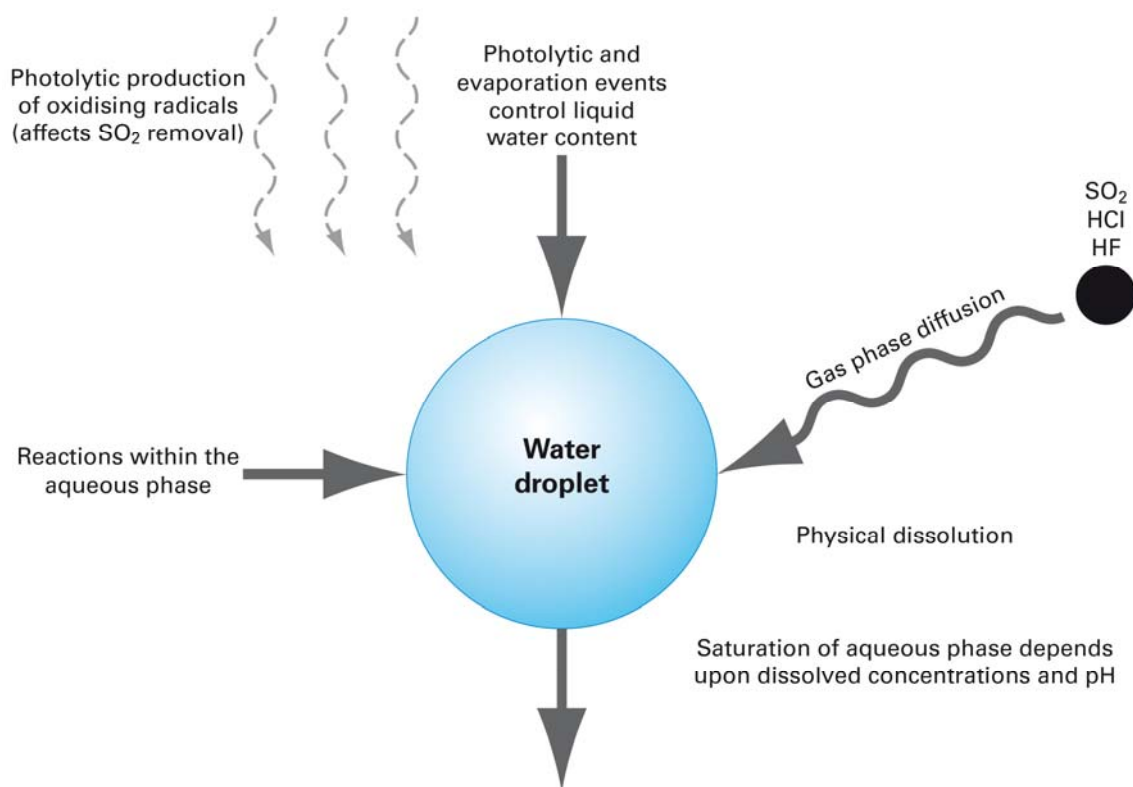
Figure 5. Factors relevant to aqueous removal of acid species from a volcanic gas plume. Reaction rates depend upon diffusion, liquid phase reactions and solubilities. Local meteorology controls atmospheric water content, and affects gas-phase diffusion. A range of other possible catalysts and reaction pathways are available in the real troposphere. Modified from Horrocks et al. (2003), © The Geological Society of London, 2003.

4.6 Chemistry and models

4.6.1 Atmospheric concentrations do not relate linearly to emissions because there is significant spatial and temporal variation in the local lifetimes of sulphur and other compounds in the atmosphere. To link emissions to concentrations, complex atmospheric models are generally understood to be required.

4.6.2 There are many different chemistry models in use for different purposes. Comparing different models and their outcomes on specific scenarios can be very valuable.

4.6.3 There may be situations when focusing on first-order transport of gases and particles (rather than chemistry) can be of value and the chemistry can be 'switched off' to allow faster model runs. Such models would forecast the pathways of volcanic emissions. Hydrogen fluoride, for example may act as a tracer and SO_2 will also act as a tracer once oxidants are used up. Alternatively, a decay constant can be used to describe SO_2 behaviour.

4.6.4 Ensemble modelling cannot currently be used in an operational situation but such approaches can be used to provide bounds for impact assessments. Models using defined source parameters (probability distributions) run over multiple years of numerical meteorological data can provide suitable probabilistic bounds for risk assessments.

4.6.5 The lifetime of sulphate aerosols and SO_2 in the troposphere is variable and depends on altitude and season, being of the order of 5-10 days at low altitudes between UK and Iceland (Stevenson et al. 2003a; Figure 5). Given northwesterly winds, the travel time of volcanic clouds between Iceland and UK is critical and may on rare occasions be as low as 6 hours for northern Scotland with travel times varying on a daily basis. The sustained supply of gas and aerosol from the source and unfavourable meteorology is necessary to maintain long-term (months) direct impacts in the UK.

4.6.6 Heard et al. (2012) tested the NAME model ability to model the release and dispersion of volcanic SO_2 and transformation to sulphate aerosol. The results suggest that the current chemistry scheme shows promise as a tool for modelling SO_2 and sulphate from volcanoes.

5. Observations, modelling and impacts of Laki 1783

5.1 Observations in Iceland and Europe in 1783

5.1.1 In Iceland, most of the grazing livestock was killed by chronic fluorosis following the Laki fissure eruption (Figure 1, Thordarson and Self, 2003). About 25% of the island's population died in the aftermath of the eruption as a result of induced illness, environmental stress and famine (Thorarinsson, 1979, 1981; Steingrimsson, 1998).

5.1.2 The first known observations of a volcanic haze in Europe were from the UK on 12 June 1783 (King and Ryskamp, 1981) and France on 14 June 1783 (Thordarson and Self, 2003) giving a maximum travel time of pollutants from Iceland to Europe of 5-7 days.

5.1.3 Accounts of health and environmental impacts throughout Europe and beyond have been collected from historical documents including White (1789) and Montredon (1784) who quickly concluded that the persistent haze across Europe was dry and sulphur-rich, his first descriptions imply high sulphur levels (Chenet et al. (2005). There were reports of extreme heat, dry 'sulphurous' fogs and extreme thunder storms, ball lightning and large hailstones (e.g. Durand & Grattan, 1999; Grattan et al 2003 and references therein; Brayshay and Grattan, 1999; Thordarson and Self, 2003; Table 7).

5.1.4 Ground frosts reported to have turned crops yellow in July 1783 were interpreted by Brayshay and Grattan (1999) as anomalous cold snaps (further references in Thordarson and Self (2003) and Grattan et al. (2003) but the 'frosts' may have been dry deposition.

5.1.5 Grattan et al (2003) collated observations of the weather and records of damaged vegetation across Europe in the summer of 1783 (Table 7).

5.1.5 There was an unusually hot summer in Europe in 1783 and an unusually severe winter (1783-4) in the northern hemisphere (Thordarson and Self, 2003). Franklin (1784) was the first to link volcanic activity with the unusually cold winter of 1783-4.

5.1.6 Kington (1988) reconstructed the weather patterns in the 1780s and demonstrated that a series of high-pressure air masses were positioned over northwest Europe throughout the summer.

5.1.7 Thordarson and Self (2003) present detailed historical observations of the European haze and coincident temperature anomalies. They proposed that Laki aerosols were delivered to the ground surface by subsiding air masses within anticyclones.

5.1.8 Highwood and Stevenson (2003) point out and summarise some uncertainties in earlier studies concerning the altitude of the reported haze and dry fog across Europe which in some accounts is at ground level but appears elsewhere to have been a higher altitude phenomenon. They point out though (following Robock, 2000), that the geographical pattern of any response to the volcanic aerosols, particularly temperature, would be spatially very complex.

Location	Observed weather	Summary of symptoms of damage	Source
England	'Uncommon gloom' Smoky fog	Cereal crops: yellowed Barley: withered awns Oats: withered Rye: mildewed in appearance Beans: whitened and dying Pasture: dried Trees: shedding leaves and appear scorched as if by fire	Cullum (Grattan & Charman, 1994) *Ipswich Journal*, 12 July 1783 Cambridge Chronicle and Journal, 5 July 1783 Sherbourne Mercury, 14 July 1783
France	Sulphurous dry fog	Vine flowers: burned Olives: fruit burned and falling Peas: badly damaged Melons: badly damaged Tree leaves: damaged Damaged the corn, which yielded hardly any crop	Rabartin & Rocher (1993)
Italy	Dry fog	Damaged wheat, empty ears, dried ears	Camuffo & Enzi (1995)
Netherlands	Persistent 'strong' fog with a sulphurous smell	Leaves of bean and pear trees 'affected' 'Changes to plants' bleached leaves Leaf and fruit fall Drying and bleaching of leaves, some developing spots Leaf fall	Swinden (2001) Brugmans (1787)
Norway	Smoky fog, 'acrid rain'	Withered vegetation Tree leaves 'partly burnt' Grass blackened	Thorarinsson (1981)
Sweden	Smoky fog	Crops destroyed Very poor harvest	Thorarinsson (1981)

Table 7 Observations and symptoms of damage on plants and crops in the summer of 1783 from Grattan et al., 2003. © The Geological Society of London, 2003.

5.2 Analysis of the Laki eruption

5.2.1 The reconstructions of the Laki event by Thordarson and Self (1993; 2003) together with the detailed compilations of observations from historical documents (e.g. Grattan et al., 2003) enabled the first atmospheric modelling to attempt to recreate the observed events (e.g. Stevenson et al., 2003b).

5.2.2 Volcanic aerosol was almost certainly the main cause of the haze over Europe as none of the major volcanic gases absorb or scatter visible light significantly (Ammann and Burtscher, 1993). Witham and Oppenheimer (2005) summarised that if the Laki emissions were a cause of mortality in England in 1783-4, the plume would need to a) be transported over England, b) be present in the atmospheric boundary layer, c) contain harmful concentrations of pollutants. There is sufficient evidence for a) and b) but c) can only be ascertained by modelling.

5.2.3 Thordarson and Self (2003) calculated that an estimated 200 Mt of H_2SO_4 aerosols were produced by the eruption and caused the visible dry fog that affected Europe and other regions in 1783, 175 Mt were removed as acid precipitation and the remaining ~25 Mt remained at tropopause levels for >1 year.

5.2.4 Grattan et al. (2003) reviewed understanding of the human health response to volcanogenic pollution and dry fog events and stated that in many respects the events of 1783 may have been typical of twentieth century severe air-pollution events in the UK. High air temperatures may have intensified any physiological impacts of the particulate matter in the dry fog.

5.2.5 Grattan et al. (2003) gave evidence for elevated degrees of illness and mortality in England coincident with the early stages of the eruption, suggesting an episode of crisis mortality in summer 1783 where mortality was greater than 10% in excess of the moving 51 year mean (Wrigley and Schofield, 1989). The apparent impacts varied considerably across England and were dependent on micro-meteorological and topographic features (Grattan and Charman, 1994).

5.2.6 Even bigger impacts were proposed in France based on anomalous peaks in mortality in many areas of France between August – October 1783 (40% above monthly average).

5.2.7 Witham and Oppenheimer (2004) analysed monthly burial data throughout England and Wales (404 parishes in 39 counties) and based on monthly analysis found evidence for two periods of crisis mortality during the Laki eruption: one peak in August-September 1783 (40% higher than the 50 year mean) and a second peak in January-February 1784 with above normal mortality for the subsequent two months (23% higher than the 50 year mean) (Fig. 6). Assuming the parish findings are representative of England as a whole, they represent ~19,700 extra deaths during this period. They state that the unusual monthly mortality pattern indicates a forcing on mortality unrelated to normal seasonal trends and potentially unique in a fifty year series. Nevertheless, the authors are cautious to ascribe a cause for the deaths. They also point out that the two periods of crisis mortality were not felt equally over the whole country.

5.2.8 Grattan et al (2003) and Witham and Oppenheimer (2004) draw attention to the fact that the summer mortality peak in England in 1783 lags behind the appearance of the haze (Fig. 6). Adverse health effects from volcanic gases are generally acute and would occur during contact with the gas. Witham and Oppenheimer (2004) go on to conclude that sulphate aerosols are more likely than volcanic gases to have had a direct effect on health in 1783. There is evidence of a fever epidemic in some eastern counties and high temperatures may have increased summer enteric diseases. Witham and Oppenheimer (2004) found no evidence for food shortages.
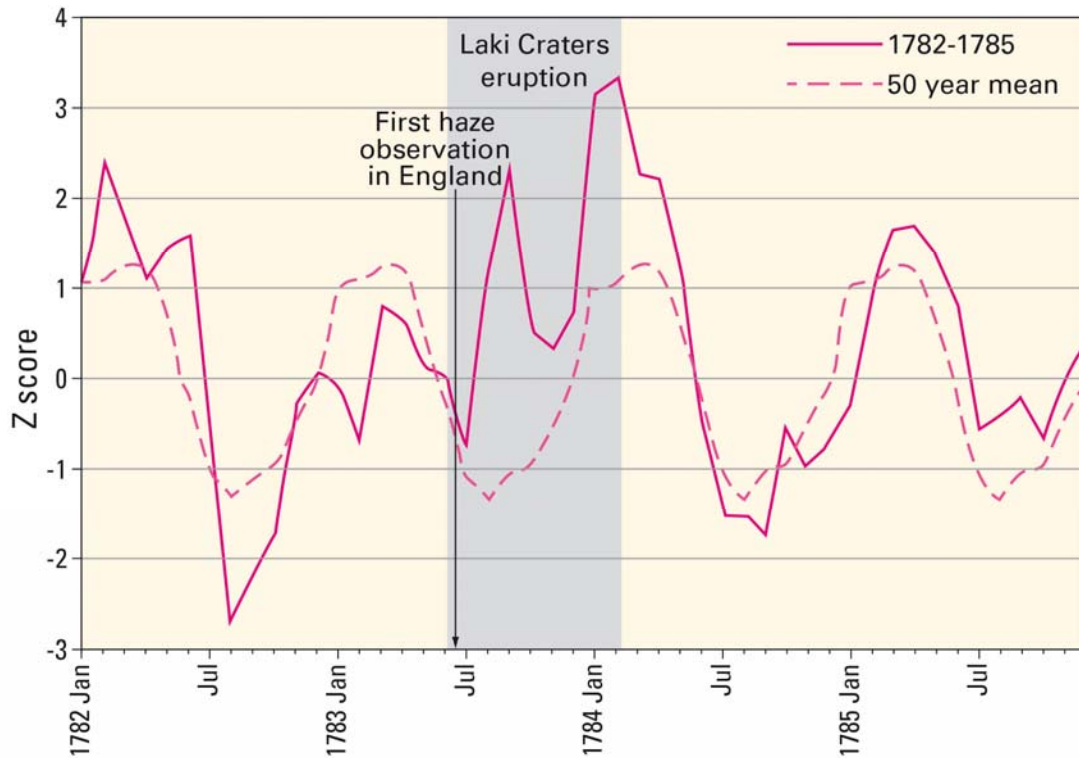
Figure 6. Comparison of monthly mortality Z-scores (series have been normalised by month) for the period 1782-1785 and the 50 year mean, both calculated with respect to the calendar year mean. Arrows indicate the timing of significant phenomena related to the Laki eruption and the shading shows the duration of the eruption. Modified from Witham and Oppenheimer (2004). © 2004, Springer-Verlag. With kind permission of Springer Science+Business Media.

5.2.9 Witham and Oppenheimer (2004) ascribe the winter 1783-4 mortality peak to the severe winter temperatures for which there is documentary evidence (Fig. 7). They summarise that the different causes of mortality in 1783-4 are complex and although the gas/aerosol may have weakened people through late summer, leaving them weak and more prone to disease and cold weather in the winter, this link cannot be conclusively made.

5.2.10 Witham and Oppenheimer (2004) point out that if the two mortality peaks in England were caused directly or indirectly by the Laki eruption, then the total known deaths ascribed to the eruption would make it the third most fatal eruption in history after Tambora (1815) and Krakatao (1883).
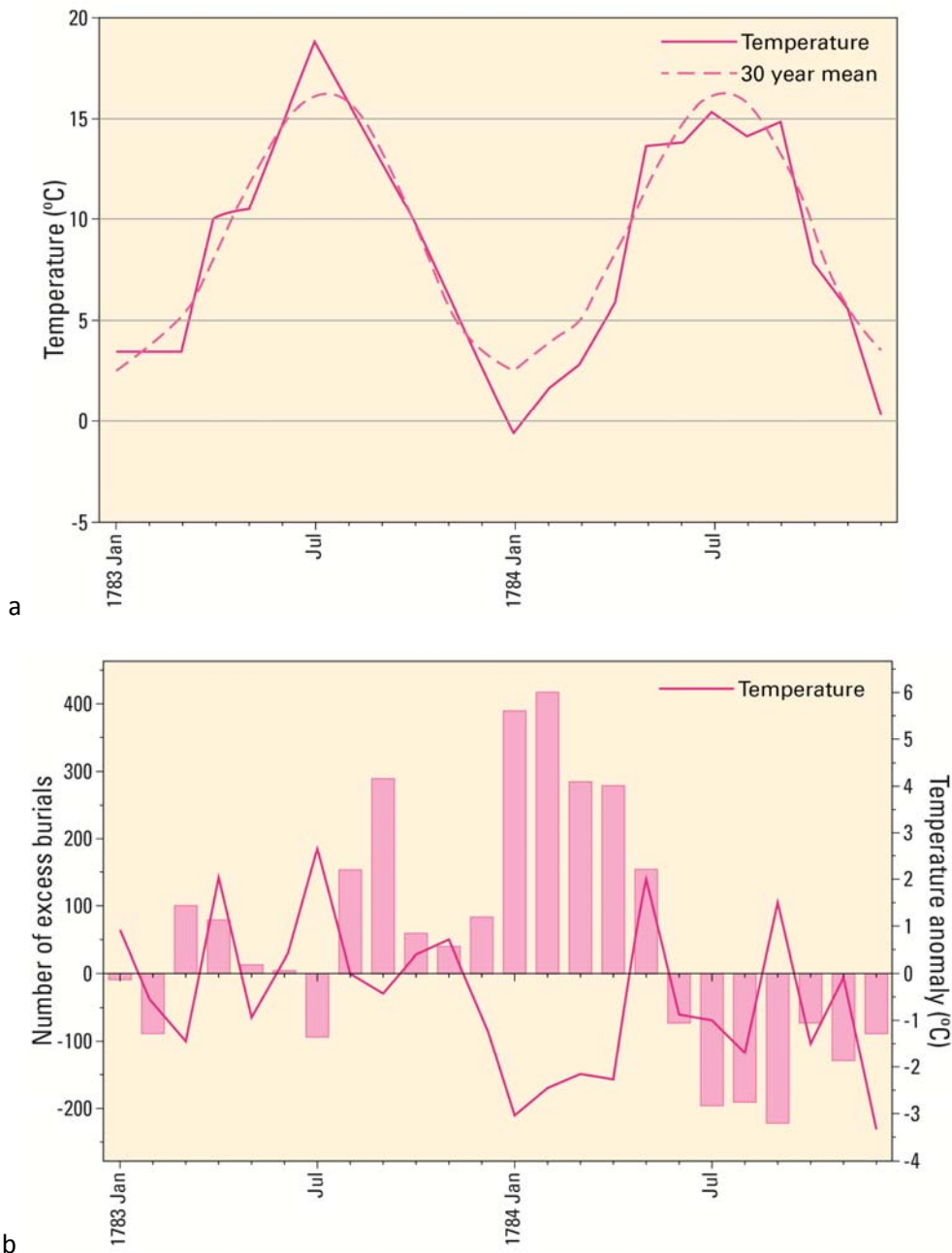
Figure 7. a) Monthly temperatures (^{o}C) in 1783 and 1784 compared to the mean of the 10-year period 1769-1798. (b) Monthly temperature and burial anomalies in 1783 and 1784 with respect to the 50-year means. Modified from Witham and Oppenheimer (2004). © 2004, Springer-Verlag. With kind permission of Springer Science+Business Media.

5.2.11 Unfortunately, published reports relating to 1783-4 cannot be critically analysed by standard epidemiological methods as used in air pollution research today.   It is not possible to reliably infer the short-term exposure levels of people to individual air pollutants from the historical reports of odour, haze or vegetation damage. The currently available data are also inadequate for calculating age-specific death rates, or doing time-series analyses from the parish numbers of deaths, which are also known to be highly unstable in many parishes due to

the high prevalence of endemic infectious diseases no longer seen in Britain today, and the much lower expectation of life from birth then.

5.2.12 For future Laki-type eruptions, modelling ambient air concentrations of specific air pollutants would be required to provide first order estimates of all-cause and disease specific mortality and morbidity using exposure-response data for SO_2 and particulate matter ($PM_{2.5}$ and PM_{10}) from clinical and epidemiological studies (e.g., Schmidt et al., 2011; see below).

5.3 Previous modelling studies of a Laki-type eruption

5.3.1 Some of the first atmospheric modelling of a Laki eruption scenario used general circulation models and considered the impact of sulphate aerosol on climate. Stevenson et al. (2003b) and Highwood and Stevenson (2003) suggested that the boundary layer concentrations of SO_2 during the eruption were less than 20ppb, much lower than the detectable odour range of about 0.5 to 1.5ppm (Baxter 2000, Wellburn, 1994). However, they didn't use the meteorology known at the time of the eruption or represent the full eruption chronology, although a variety of injection heights for SO_2 were used.

5.3.2 Chenet et al. (2005) modelled the sulphate aerosol pollution using an atmospheric general circulation model (AGCM) and a coupled atmospheric chemistry module that simulates atmospheric transport and fallout of sulphate and tephra in space and time. They used the ECMWF humidity, temperature and winds from 2000-2001 and a theoretical value of 200Mt of sulphate aerosol (Thordarson and Self, 2003). They used smoothed monthly mean injection rates (20% sulphate aerosol at 5 km and 80% at 10 km) and had to start the eruption (in model runs) two weeks in advance. Despite several other limitations and assumptions their model was consistent with many of the observations. They proposed that a visible haze forms at 5×10^{-9}kg sulphate aerosol per kg of air or 5 ppb.

5.3.3 Oman et al (2006a) simulated the chemical transformation of ~122Tg of SO_2 and the subsequent sulphate aerosol dispersion using a global circulation model coupled with a sulphur chemistry scheme. They attempted to reconstruct the eruption evolution as presented by Thordarson and Self (2003). They estimated a yield of 163-166Tg of total volcanic sulphate aerosol (assuming 75% H_2SO_4 and 25%H_2O from Thordarson and Self, 2003) and calculated a significant peak net radiative forcing at the top of atmosphere of -27 Wm^{-2} in August.

5.3.4 Oman et al. (2006b) found that the Laki eruption weakened the Indian and Asian monsoon systems and they demonstrated that this may be a consequence of many moderate-large-volume high latitude volcanic eruptions.

5.3.5 Gauci et al. (2008) found that the presence and deposition of excessive amounts of volcanic sulphate aerosol during the Laki eruption resulted in a significant suppression of the northern wetland methane (CH_4) source.

5.3.6. Timmreck et al. (2010) pointed out that fully coupled chemistry and microphysics models must be used in order to simulate the volcanic aerosol size distribution and correctly constrain the effect of large eruptions on temperature and environmental impact.

5.3.7 Schmidt et al. (2010) studied the impact on aerosol microphysical processes including the nucleation of new particles and their growth to cloud condensation nuleii (CCN) using the Global Model of Aerosol Processes (GLOMAP) which also includes microphysical processes such as hygroscopic growth, coagulation and cloud processing (oxidation of dissolved SO_2 to SO_4 in cloud droplets). This model allows an analysis of the evolution of aerosol size distribution. They found that the Laki eruption had the potential to dramatically impact global CN and CCN concentrations with an increase in total particle concentration in the upper troposphere over large parts of the Northern Hemisphere by a factor of ~16 during the first three months of the eruption.

5.3.8 Schmidt et al. (2010) also showed that the effects are strongly dependent on season with a summertime eruption having the biggest impact on upper tropospheric CCN concentrations. SO_2 rises into the troposphere and the subsequently formed H_2SO_4 vapour causes rapid nucleation of new particles at low temperatures, these grow by coagulation and condensation of further vapour during transport. Schmidt et al. (2010) found that particle concentrations in the boundary layer increased by a factor of 2-5 as far away as the Middle East, Asia and North America.

5.3.9 The meteorology used to force GLOMAP influences the magnitude of total SO_4 deposition however, different meteorologies produce similar patterns of deposition. Different models have different parameterisation of wet removal processes. The GLOMAP model may remove particles too efficiently in the Arctic due to simplification of nucleation scavenging but it is reliable over Europe (Schmidt et al. 2010).

5.3.10 Schmidt et al (2011) went on to quantify the potential health effects in Europe during a future 'Laki-type' eruption using a global aerosol model together with concentration-response functions derived from modern epidemiological studies. They found that the concentration of $PM_{2.5}$ particulate matter (<2.5 micron) is likely to double across central, western and northern Europe during the first three months of the eruption. The World Health Organisation $PM_{2.5}$ air quality guideline would be exceeded an additional 36 days on average during the eruption. They calculate this could result in 142,000 additional cardiopulmonary fatalities in Europe (with a 95% confidence interval 52,000-228,000).

5.3.11 Schmidt et al. (2011) ran the GLOMAP model for a year with a low incidence of northwesterly air flow (2003) and a year with a high incidence (2005), to quantify health effects they used concentration-response (C-R) functions appropriate for $PM_{2.5}$ (Pope et al. 2002; Ostro, 2004). They considered only a subset of health outcomes associated with PM. They found that the meteorology made only a slight difference to the total European excess mortality rate.

5.3.12 Schmidt et al. (2011) compared the estimated excess mortality rates for the UK, France, Germany, Ireland, Belgium and Netherlands in the year following a Laki-type eruption with baseline reported by the WHO for the year 2004. For the low northwesterly airflow case (2003), this equated to an increase in excess cardiopulmonary mortality of 8.2% (95% C.I 3.0-13.1) and for the high northwesterly airflow case (2005) an increase of 8.6% (95% C. I. 3.2-13.8).

5.3.13 Based on the modelling by Schmidt et al. (2011), the UK had an increase in mortality of the modern population of 3.5% (20,900 additional cardiopulmonary fatalities due to eruption on top of 595,800 all-cause deaths in the UK in 2004), smaller than the 10-20% increase in summer mortality in 1783 in England calculated by Grattan et al. (2003). This may be due in part to the better health and resilience to air pollution of modern populations (Schmidt et al. (2011).

5.3.14 Schmidt et al. (2011) found that summertime maximises total mortality due to more effective photochemical processing compared to a wintertime eruption.

5.4 The Laki eruption in a global context

5.4.1 Anthropogenic sources contribute about 70% of all sulphur emissions (60-100 Tg(S) per year), whereas volcanoes contribute on average about 6-20Tg (S) per year based on a 50 year running average (Penner et al. 2001). Halmer et al. (2002) estimated the global volcanic SO_2 emission as 15-21 Tg/year between 1971 and 2000. The Laki eruption in 1783-4 produced ~120 Tg SO_2 over 8 months, with most emitted in the first 4 months (Thordarson and Self, 2003).

6. Monitoring and operational activities

6.1 Qualitative discussions

6.1.1 One of the elements of the workshop was to prepare and discuss a number of quantitative and qualitative questions that had been circulated in draft form before the meeting. Some of the qualitative questions addressed issues around monitoring and suggestions, responses and resources are documented in this chapter. The quantitative questions and responses are presented in Chapter 7.

6.2 Monitoring near-source

Early warning

6.2.1 The monitoring of volcanoes in Iceland is the operational responsibility of the Icelandic Meteorological Office with specialist support provided by the University of Iceland. There is a well-established emergency response system in place in Iceland led by the Icelandic Civil Protection (National Commissioner of Icelandic Police).

6.2.2 The Icelandic Meteorological Office runs a real-time network of seismometers, continuous GPS stations and strainmeters for the purpose of supporting early warning. Much of the data is available online (http://en.vedur.is/earthquakes-and-volcanism/earthquakes/).There is also campaign-style monitoring of gas emissions and water chemistry to identify changes that may precede eruptions. The outflow from glaciers is also monitored in order to identify potential increases in geothermal gradient beneath ice sheets and regular ground-based, airborne and remote-sensing observations of volcanoes are made.

6.2.3 There were 3-4 weeks of felt earthquakes (volcano seismicity) before the Laki eruption began in 1783 (Thordarson pers. comm.). It is very likely, given that the largest magnitude earthquakes were felt in 1783, that the sensitive modern seismic networks would detect smaller earthquakes well in advance of a future eruption. Signs of significant geophysical unrest beneath a volcano would lead the Icelandic Meteorological Office to increase the aviation colour code (http://www.icao.int/icaonet/dcs/9766/9766_cons_en.pdf).

6.2.4 Nevertheless, it is still not possible to reliably predict the precise start of an eruption and high levels of seismic activity ('seismic crises') do not always lead to eruptions. Magma may move through the crust but then stagnate before it reaches the surface. Anticipating and identifying the actual eruption onset within reasonable uncertainty bounds is a challenge being addressed by the FUTUREVOLC EU FP7 research consortium (Appendix I) a 'Supersite' project that will install ground-based monitoring equipment to generate close to real-time data that can be integrated with in-situ and satellite data to enhance forecasting and early warning capability.

6.2.5 If precursors are not recognised, or if magma moves very quickly through the crust, it is possible that an eruption could begin with no or little warning. It is also uncertain if scientists would recognise the likely scale of a large-volume fissure eruption at the eruption onset.

6.2.6 Providing real-time source parameters for the purpose of operational ash/gas/aerosol dispersal modelling is extremely challenging (e.g. Bonadonna et al. 2011a,b). Quite apart from the technical challenges, logistics will also be problematic on the ground with access likely to be difficult and hazardous.

6.2.7 The heights of ash/gas/aerosol plumes and fire fountains would be calculated using a combination of a mobile ash-sensitive radar, Keflavik weather radar (e.g. Oddson et al. 2012) and other observational techniques including static cameras, pilot reports and satellite methods. It should be noted that gas is typically injected several km higher in the atmosphere than ash/tephra.

6.2.8 Knowledge of the height at which gases and aerosol are injected into the atmosphere and their vertical distribution is a key to realistic modelling. Most models assume an even vertical distribution from vent to top of eruption column height. Stevenson et al. (2003a) described vertical distribution as the largest uncertainty in modelling the fate of volcanic SO_2. Chin et al. (2000) used only the top one-third of the eruptive column for modelling.

6.2.9 Several methods to better understand source characteristics and support dispersal modelling are under development. Research consortia such as the EU Futurevolc consortium are developing new technologies specifically aimed at assessing particle size distributions for ash and other essential source parameters (Appendix I).

6.2.10 Vertical distribution in a dispersing plume near-source (rather than directly above the vent) can be targeted using UAVs, LiDAR, balloon-sondes and the Differential Absorption LiDAR (DIAL) shows promise. The 'near-source' is defined as up to 50-100km from the vent. None of the techniques would give a high resolution time-series unless coordinated campaigns by multiple institutions could be organised (e.g as planned by the EU Futurevolc and NERC VANAHEIM consortia).

6.2.11 Eckhardt et al. (2008) used a combination of SO_2 satellite column measurements and inverse transport modelling to establish a vertical profile.

6.2.12 The NERC VANAHEIM consortium is also developing modelling approaches (e.g. Woodhouse et al. 2012) and is also investigating the Eyjafjallajökull plume with respect to altitude-dependent layering which is persistent for great distances (Appendix I).

6.2.13 Calculation of the mass eruption rate of magma in Iceland (in order to assess first order SO_2 emission rates) during fissure eruptions might use a combination of techniques including ground-based, satellite and airborne observations. Modelling approaches to better understand controls on plumes above lava flows (e.g. Kaminski et al. 2011) provide complementary methods.

6.2.14 Measurements of SO_2, HCl and HF are needed if a dispersion model is to forecast transformation of these and related aerosols. In particular, peak concentrations are needed.

6.2.15 Oppenheimer and McGonigle (2004) summarised the state-of-the-art in ground-based optical sensing for volcanic gases (near-source) in 2004 and such technology has since been

developed further (Table 8). These techniques are only generally useful if there is only a little ash, or preferably no ash as they rely on the sun as a source, however useful data can be collected during weaker phases of an eruption and in more distal locations when most ash has fallen out (and before SO_2 conversion). Most of the techniques (especially airborne and satellite methods and LiDAR) would be useful both near-source and in the UK.

6.2.16 Open path Fourier transform infrared spectroscopy (OP-FTIR) is currently the most effective way to establish the composition of the gas phase of a volcanic plume but spectroscopy will not detect particles or aerosols.

6.2.17 Since HCl (and therefore probably HF) has such a high dissolution rate into water droplets, the measured gas phase composition will reflect rates of scavenging so SO_2/HCl or SO_2/HF ratios (measured by OP-FTIR) will tend to increase with distance from the source (e.g. Oppenheimer et al. 2003; Aiuppa et al. 2007). However, once water droplets in a plume are saturated with respect to acid gases, there is little scope for more compositional change (though see Oppenheimer et al., 2006 and Roberts et al., 2009).

Instrument	Transport methods	Volcanic gas species detectable	Flux measurements (Yes/No)
COSPEC (UV)	Car, aircraft, boat	SO_2	Yes
UV grating spectrometers (e.g. Ocean Optics USB 2000)	On foot, car, aircraft, boat	SO_2, H_2S, BrO	Yes
FTIR (e.g. Brucker OPAG 22, MIDAC AM series)	Car	CO_2, CO, OCS, CH_4, SO_2, H_2O, HCl, HF, SiF_4	Yes (with sun tracker)
Other NDIR (e.g. LI-COR CO_2 analysers)	On foot, aircraft	CO_2, H_2O	Yes (by plume profiling or ground flux surveys)
DIAL (i.e. using atmospheric backscatter to return signal)	Truck, ship	SO_2, other species feasible	Yes
Laser spectroscopy (short path, extractive)	car	As FTIR plus isotopes	No

Table 8. An overview of spectroscopic methods (UV, IR and laser) for ground-based optical sensing of volcanic gases from Oppenheimer and McGonigle (2004). The COSPEC is no longer routinely used. The UV and IR spectrometers are operational but DIAL and laser spectroscopy are still at research stage.

6.2.18 Given the likely broad area of the source during a fissure eruption, poor accessibility, poor visibility and abundance of tephra during explosive phases, assessments of the dispersing ash/gas cloud height, vertical structure and gas composition further than 50-100 km downwind

(i.e. in the north Atlantic) might be useful (e.g. using UAVs, balloon sondes, planes, ships etc). Locating equipment in the Faeroe Islands may also be of value.

6.2.19 Coordination of all the available resources and accessibility of data would be an ideal situation for rapid operational and research analysis.

Direct sampling

6.2.20 Direct sampling (i.e. sample collection) of volatiles at fumaroles and vents can be very effective before an eruption if there is detectable degassing (e.g. Giggenbach and Goguel, 1989) but is too dangerous during an eruption and is not real-time.

6.2.21 A suite of diffusion tubes can be left near gas sources to give an idea of plume dispersion and exposure at ground level (e.g. Aspinall et al. 2002; Aiuppa et al. 2006, 2007). Rainwater collectors and sulphation plates have been used to investigate deposition (e.g. Delmelle et al. 2001, 2003; Edmonds et al. 2003). These methods require laboratory analysis so are not real-time monitoring but are good for process understanding and quantifying concentrations for impact assessments.

6.2.22 Particle filters can be used to study the aerosol phase of volcanic emissions, and further development allows characterisation of the aerosol size distribution and chemistry (Mather et al. 2004; Martin et al. 2008; Ilyinskaya et al. 2010). The filters require analysis so this is not real-time monitoring but rapid analysis could be organised.

6.2.23 Volatiles scavenged by ash particles can be studied analytically by leaching samples with distilled water (e.g. Edmonds et al. 2003; Witham et al. 2005). This is dependent on good sampling and appropriate storage of samples for reliable results. The leachate analysis takes some days.

6.2.24 As part of the EU FP7 FUTUREVOLC consortium, the University of Iceland intends to establish a mobile lab to provide rapid chemical, grain size and leachate analyses of ash for distribution to relevant authorities in Iceland and beyond.

In-situ sensors

6.2.25 Electrochemical sensors show a great deal of promise in that they are cheap and mass-produced but they are unable to target gases, for example H_2S sensors are cross-sensitive to SO_2. However by using them in appropriate configurations they have been found to be reliable for measuring SO_2, H_2S and other species (e.g. Roberts et al. 2012). Long term installations using wifi, mobile networks or satellite telemetry are beginning to provide near- real-time insights into the relationships between surface emissions and magmatic processes (e.g. Aiuppa et al. 2007a,b).

6.2.26 The portable gas chromatograph is described by Oppenheimer et al. (2011) as a promising technique established some time ago but not yet widely used in volcanology. It is sensitive and able to measure a wide range of species including H_2S and H_2.

UV spectroscopy

6.2.27 Galle et al (2010) have set up successful scanning DOAS spectrometers at many volcanoes worldwide attesting to the value of this technique. Its main advantage is the capability for rapid SO_2 flux measurements during daylight hours. A system is being developed in Iceland.

6.2.28 Further developments include the use of tomography to reconstruct the plume's cross sectional area since identification of the plume height is critical (e.g. Wright et al. (2008) and other references in Oppenheimer et al. (2011)). Use of two-dimensional CCD detectors enables a user to build an image giving information on gas distribution in a plume (e.g. Louban et al. 2009) and use of UV cameras gives an even higher time resolution (Oppenheimer et al. 2011 and references therein). Two spectrometers with two slightly different fields of view offers a new approach that can provide accurate SO_2 flux measurements at very high time resolution and could in theory provide a real-time SO_2 flux meter (Boichu et al., 2010).

6.2.29 Further work is needed to establish the extent to which the interaction of the volcanic gases with the atmosphere affects spectroscopy measurements (e.g. Kern et al., 2010).

Broadband IR

6.2.30 OP- FTIR can detect multiple gases (Table 7; 6.2.16; 6.2.17) and can be used downwind from source during vigorous events to reveal insights into magma transport, degassing and compositional variation in the gas plume (Horrocks et al. 2011 and references therein). H_2S has not been detected in a plume by IR absorption spectroscopy.

Laser spectroscopy

6.2.31 LiDAR has been used to estimate concentrations and fluxes (by traverses) of sulphate aerosol as well as ash. Parallel gas sampling and aerosol measurement can enable estimation of gas to particle conversion rates (e.g for SO_2 to SO_4^{2-}; Rose et al. 1986). Further LiDAR capacity in Iceland might be useful.

6.2.32 Differential absorption lidar (DIAL) can reveal plume structure/vertical distribution but is costly, heavy and bulky so requires some innovation before it becomes a regular volcanological tool. It can remotely measure the concentration of a gas species by scanning a vertical plane in the atmosphere. DIAL can also measure flux (i.e. the emission rate) of the gases.

6.2.33 Near and mid-infrared diode based lasers can make sensitive measurements of isotopic abundances (Oppenheimer et al. 2011 and references therein).

Satellite remote sensing

6.2.34 OMI (NASA satellite-borne Ozone Monitoring Instrument) has a reasonable correlation at stratosphere levels with actual SO_2 emissions. Comparing AIRS (Atmospheric Infrared Sounder), MODIS (Moderate Resolution Imaging Spectroradiometer) and OMI, OMI is the most sensitive satellite payload to SO_2 in the troposphere and the only sensor capable of resolving low altitude cloud (e.g. Carn et al., 2009; Yang et al. 2007). However, most of these satellites just provide data once or twice a day. SEVIRI is a geostationary satellite (over the equator) producing data on both ash and SO_2 every 15 minutes (Prata and Kerkmann, 2007) but it is not

so good at retrievals over Iceland due to the low angle. IASI is an IR polar orbiting satellite that produces data day and night (e.g. Clarisse et al., 2008).

6.2.35 McCormack et al. (2012) have compared total SO_2 output calculated on the basis of OMI which is sensitive to passive degassing in the lower troposphere as well as the stratosphere with the total extrapolated using DOAS (Differential Optical Absorption UV Spectrometer). Neither technique is continuous hence the need for extrapolation. The OMI SO_2 output is ~20% of the total extrapolated from DOAS (at volcanic arcs). There is also uncertainty due to chemical processing of SO_2, dilution of SO_2 before satellite overpass, OMI reduced sensitivity to low levels in boundary layer, meteorological cloud interference etc.

6.2.36 IASI and AIRS can be used at night for both SO_2 and ash. The techniques for IASI and AIRS for detecting and quantifying ash are not as advanced as for the broadband sensors (e.g. MODIS and SEVIRI).

6.2.37 The EU FP7 EVOSS project uses SEVIRI, MODIS, IASI, OMI and GOME-2 to provide close to real-time products on ash and SO_2 via a web portal when there is an eruption. There are significant ongoing efforts to make this sustainable (see Appendix I). Retrieval algorithms are undergoing rapid refinement in the research community.

6.2.38 Meteosat 3rd Generation (MTG) due for launch in the 2020's will have a thermal infrared interferometer (MTG-IRS) onboard capable of detecting volcanic ash and SO_2.

6.2.39 A payload specifically for monitoring ash, gas and aerosol from Iceland on, for example, a telecommunications satellite would make a significant difference to the monitoring capability.

Assessing sulphur content

6.2.40 Based on empirical evidence, Blake (2003) proposed that for explosive eruptions, the emitted SO_2 correlates well with mass of erupted magma. The SO_2 yield is 0.1-1% by mass of magma irrespective of composition. Mass SO_2 (Mt) = 1.77 (mass magma Gt)$^{0.64}$. This becomes a useful method to provide a first order assessment of SO_2 yield in an eruption if mass eruption rate can be calculated.

6.2.41 A petrological method using the difference between melt inclusion and matrix glass method works well for Iceland, the analytical error is ~5%, so the overall error for Laki is ~20-25% (Thordarson and Self, 2003). When the petrological method has been tested against remote sensing on small basaltic eruptions in Iceland, the two methods give similar results. It works better for basalt than more silicic lavas. This is not a real-time method but it's a tool to combine with other measurements including remote sensing for validation.

6.3 Monitoring in the far-field

At altitude

6.3.1 The spectroscopy and remote sensing methods described in section 6.1 can also be used in the far-field.

6.3.2 The UK has access to the newly acquired Met Office Civil Contingency Aircraft (MOCCA) that is on 24hr call out notice.

6.3.3 The UK research plane operated by the Facility for Airborne Atmospheric Measurements (FAAM), a collaboration between NERC and the Met Office http://www.faam.ac.uk/, and the NERC Airborne Research and Survey Facility (ARSF) Dornier 228 research aircraft may be available but are not guaranteed .

6.3.4 The Facility for Ground-based Atmospheric Measurements (FGAM) operates two field sites at Chilbolton and Cardington equipped with an extensive set of ground-based remote-sensing and in-situ instruments used for atmospheric science research including Doppler radars, Doppler LiDARs, high power UV Raman LiDAR, radiometers and meteorological instruments. A mobile facility for campaigns with capability for meteorology and dynamics, aerosol and gas phase measurements is available from FGAM. http://www.ncas.ac.uk/fgam/

6.3.5 The Met Office 'Met Research Unit' at Cardington operates Doppler LiDARs, one of which is mobile.

6.3.6 The ideal is a network of multi-wavelength LiDARs which would allow estimation of mass loadings and size distributions, but such devices are not yet available commercially.

6.3.7 The existing upward looking ground-based LiDAR network includes an instrument on the Faeroe Islands and this may be a useful site for further instrumentation for the purposes of model validation. Engagement with North Atlantic shipping might also be valuable for additional observations and data.

6.3.8 When monitoring airborne particles, there is a need to know both where the plume is, the concentrations and vertical distribution. Satellite remote sensing is good for location (IASI/SEVIRI); LiDAR, sondes, UAVs and planes are needed for concentrations and vertical distribution – with the same difficulties of temporal and spatial resolution as near-source.

6.3.9 The research planes could attempt coordination to give a time series of measurements, although any flight is valuable. SO_2 is a potential hazard to plane crew in unpressurised cabins, so masks with filters to enable flights could be arranged.

At ground level

6.3.10 In the UK there are many different air quality and environmental monitoring networks, the main ones (e.g. coordinated by DEFRA) are summarised here and in Appendix F with recommendations for enhancement in order to deal with a Laki-type scenario.

6.3.11 The Automatic Urban and Rural Network (AURN) is the UKs largest automatic monitoring network and is used for compliance reporting against the Ambient Air Quality Directives. There are 131 sites that measure oxides of nitrogen (NO_x), sulphur dioxide (SO_2), ozone (O_3), carbon monoxide (CO) and particles (PM_{10}, $PM_{2.5}$) hourly and data is available online. Mercury (Hg) content of the air is also available hourly. An hourly map of concentrations could be made using this data. http://uk-air.Defra.gov.uk/networks/network-info?view=aurn

6.3.12 The DEFRA UK Eutrophying and Acidifying atmospheric pollutants (UKEAP) network measures air pollutants at rural sites across the UK including precipitation and the Acid Gas and Aerosol Network (AGANet) which measures monthly gas phase SO_2, HNO_3, HCl and major particulate phase inorganic anions and cations at 30 sites. http://pollutantdeposition.Defra.gov.uk/ukeap

6.3.13 The UK contributes to the European Monitoring and Evaluation Programme (EMEP) which has two supersites funded by the DEFRA UKEAP project which make high frequency measurements of water-soluble gases and particles at PM2.5 and PM10, mercury in air and ions in precipitation (including fluoride since 2012). http://www.emep.int/

6.3.14 A DEFRA report summarising the current understanding of pollutant concentrations and deposition across the UK was released in June 2012 and is available at http://www.rotap.ceh.ac.uk/home.

6.3.15 For an assessment of the current UK air quality and environmental capabilities including AURN sites, UKEAP and the ECN network and recommendations on how they can be enhanced to deal with a Laki-style event, see Appendix F.

6.3.16 In terms of new technology, a mobile DIAL system could be developed for use in the UK to be mobilised in areas forecast to be badly affected.

6.3.17 There may be ash fall in Europe associated with a Laki eruption scenario and a strategy for ash collection (following from experience during Eyjafjallajökull and Grimsvötn eruptions e.g. Stevenson et al. 2012) and subsequent analysis is proposed in this document (Appendices F and H). A protocol for leachate analysis is available on the IVHHN website www.ivhhn.org. The DEFRA-led Volcanic Ash Network would coordinate activities in a crisis situation.

6.3.18 Rainwater collection networks would serve to collect ash as well as other depositing species (Met Office, CEH, SEPA and DEFRA). The rainwater needs to be sampled routinely for pH and soluble species, especially in areas where surface water or groundwater derived from meteoric water may be used for drinking (common in parts of the Scottish Highlands). See Appendix F for current monitoring networks.

7. Expert elicitation

7.1 Quantitative elicitation: proceedings

7.1.1 One of the main elements of the workshop was the structured elicitation of expert judgements to provide quantitative guidance on uncertainties associated with selected impact modelling factors and parameters, principally those that relate to volcanological source conditions and their characterization. The purpose behind the derivation of these uncertainty distributions is to use them provisionally with related inputs to any modelling aimed at estimating potential volcanic effects and impacts on UK due to a prolonged Icelandic fissure eruption scenario.

7.1.2 During the workshop, discussion in this context focussed on about sixty quantitative and qualitative questions that had been assembled in draft form and circulated before the meeting. In terms of the quantitative uncertainty-related items, the list was reduced to twenty-eight in number, with others deferred to off-line consideration with Icelandic colleagues, or removed as duplicates or of marginal consequence to the current issue. The qualitative questions were dealt with separately (see section 7.4).

7.2 Expert calibration

7.2.1 In terms of individual calibrations based on responses to the 'Seed Items' (questions to test ability to estimate uncertainty), the profile of the derived performance-based scores, expert by expert, produced no major surprises: those who achieved the heavier weights amongst the group are recognized as being particularly knowledgeable among their peers.

7.2.2 The rationale behind weighted pooling of opinions is that this expresses the collective group view on uncertainties on an objective basis and with appropriate maximal informativeness. The upshot is that the Performance Weights solutions for the quantitative questions ('Target Items') in the present elicitation mostly (but not invariably - see Table 9 and Appendix C) have tighter credible interval distributions for the associated uncertainty than do the counterpart Equal weights solutions. Averaging the views of the whole group almost inevitably involves integrating over a much wider range of opinions and, whilst 'democratic', does not represent a rational consensus.

7.3 Target Item results: summary

7.3.1 Of the twenty-eight quantitative questions ('Target Items'), the majority (22 in number) were essentially volcanological in nature – to some extent this reflected the preponderance of the specialists present, but also the roots of the original conception and purpose of the meeting, which was to address, inter alia, factors affecting the volcanological source term in a modelling context. The remaining six Items were associated with plume chemical processes.

7.3.2 With two exceptions, the volcanological questions ('Target Items') were responded to by between eleven and all fourteen experts, whilst the plume processes questions were tackled by between eight and eleven experts. The two notable exceptions in the former category

were, surprisingly, questions concerning the maximum and expected rates of magma discharge during an explosive phase of a Laki-like eruption. These attracted just seven and five valid sets of responses, respectively.

7.3.3 Overall, twenty of the twenty-two volcanological questions ('Target Items') provided pooled results from the performance-based weights Decision Maker (PerfWt DM) that appear to represent rational consensus outcomes for determining the associated uncertainty distributions. (Equal weights - EqWt DM - solutions are also produced as counterparts – see Appendix C).

7.3.4 Two volcanological questions[13] exhibit apparent major systemic discrepancies, with question definition issues, major uncertainty and knowledge gap connotations (see Table 8). Of the other twenty satisfactory Item results, about ten indicate that possible knowledge gaps may exist, eight are marked by very wide uncertainty spreads (which may be knowledge-related or due to genuine aleatoric randomness) and five may benefit from better question definition or terminological clarity.

7.3.5 In the cases of the plume process Items, on the face of it, all six provide convincing rational consensus outcomes, with one giving notably wide but plausible uncertainty bounds, two with features indicating possible knowledge gaps, and two possibly affected by terminology/definition issues.

7.3.6 These various features of the twenty-eight solicited questions, attributed by the facilitator from his elicitation experience, are summarized on Table 9. Cells highlighted by shading indicate aspects of the pooled expert opinion solutions which might be improved by further discussion of wording and technical issues, and by re-elicitation. Others, in the right-hand column, identify questions (' Target Items') that have particularly large, but perhaps irreducible, uncertainty ranges.

7.4 Expert elicitation - conclusions

7.4.1 Taken all together, the results exhibit collective traits that are quite usual for an expert elicitation of this type, when subject matter topics are addressed that are data-poor, extreme or exceptional.

7.4.2 The consequent identification of where potential knowledge gaps exist, and the diagnosis of terms and definitions that may be ambiguous or ill-defined are two valuable assets of the present structured elicitation method.

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[13] Item 10b_2 After the initial explosive phase (ie first days), what is the likely maximum sustained plume height for gases above the vent for the remainder of the active episode?

Item 15_1 What is the likely upper limit for the percentage of total SO_2 emissions that is released from vents?

7.4.3 The main accomplishment of the present exercise is that it offers quantified, provisional but objective uncertainty distributions for a number of inputs for modelling a large-volume fissure eruption scenario in Iceland, and thus suggests an initial enumerated start-point for simulation purposes. Indubitably, some of the uncertainties, ambiguities and expert response variability could be reduced by further discussion of the issues, and by re-elicitation – but that is in the nature of this sort of exercise. Such elicitations are seldom absolute or final, but can be updated with new data or theoretical insights.

7.4.4 The present elicitation exercise can be viewed as a productive first step and certainly proved successful in engaging the interest of specialists in research institutes, academia and those who may have an operational role during an eruption. However, all such elicitations are just snapshots of informed expert judgement at a given moment, and require updating from time-to-time as knowledge, data and understanding advance.

7.5 Qualitative questions

7.5.1 A second element of the workshop in London was to seek the opinion of a group of experts on a number of qualitative questions. The intention here was to identify areas where the group are generally comfortable with current understanding, published values or state-of-the-art and where there are areas of concern and/or uncertainty, clear knowledge gaps or areas for future research. It also enables those in one discipline to understand which papers/parameters/uncertainties are well-characterised and well-regarded by peers in another discipline.

7.5.2 These questions were posed during the workshop and about 10 minutes assigned for discussion following which each individual wrote down their key points. The questions were distributed in advance of the workshop. Notes were taken by three attendees during the discussion, the paperwork was collected at the end of the meeting and results used to compile the report. The questions are listed in Appendix D.

Table 9 (overleaf) Summary of inferences about elicited Target Item solution

Type	Code	Target Item	Rational consensus?	Knowledge issues?	Terminology issues?	Wide uncertainty?
Volc source	8	What is the likelihood that in the next Laki-like eruption there is an episode which releases 10 times more SO_2 on the same timescale as the peak eruption episode during Laki? [express as %age?]	Yes	No	No	No
Volc source	9_1	Given an eruption like Laki 1783-4 (flood lava eruption), what maximum total lava volume should be used for scenario modelling (in km^3)?	Yes	No	No	No
Volc source	9_2	Given an eruption like Laki 1783-4 (flood lava eruption), what expected (i.e. mean) total lava volume should be used for scenario modelling (in km^3)?	Yes	??	No	No
Volc source	10_1	What is the likely maximum explosion column height above vent during individual eruptive episodes (fissure opening)?	Yes	No	No	No
Volc source	10_2	What is the likely mean explosion column height above vent during individual eruptive episodes (fissure opening)?	Yes	No	No	No
Volc source	10b_1	After the initial explosive phase (ie first days), what is the likely average sustained plume height for gases above the vent for the remainder of the active episode?	Yes	??	No	Yes
Volc source	10b_2	After the initial explosive phase (ie first days), what is the likely maximum sustained plume height for gases above the vent for the remainder of the active episode?	??	??	Yes	Yes
Volc source	11_1	What is the likely upper limit amount of SO_2 released from the explosive vents per unit of lava volume (Tg of SO_2 per km^3 of lava erupted)?	Yes	No	No	No

Type	Code	Target Item	Rational consensus?	Knowledge issues?	Terminology issues?	Wide uncertainty?
Volc source	11_2	What are the likely average amount of SO_2 released from the explosive vents per unit of lava volume (Tg of SO_2 per km^3 of lava erupted)?	Yes	No	No	No
Volc source	12_1	What is the maximum rate of magma discharge in an explosive phase? (cubic metres / second)	Yes	??	No	No
Volc source	12_2	What is the expected average rate of magma discharge in an explosive phase? (cubic metres / second)	Yes	No	No	Yes
Volc source	15_1	What is the likely upper limit for the percentage of total SO_2 emissions that is released from vents?	??	Yes	??	Yes
Volc source	15_2	What is the likely lower limit for the percentage of total SO_2 emissions that is released from vents?	Yes	No	No	No
Volc source	16_1	What is the likely maximum number of fissure opening explosive phases during an eruption on the scale of Laki?	Yes	No	??	No
Volc source	16_2	What is the likely average number of fissure opening explosive phases during an eruption on the scale of Laki?	Yes	No	No	Yes
Volc source	16_3	What is the likely minimum number of fissure opening explosive phases during an eruption on the scale of Laki?	Yes	??	??	No

Type	Code	Target Item	Rational consensus?	Knowledge issues?	Terminology issues?	Wide uncertainty?
Volc source	17	What is the likely duration of the explosive phase of a fissure-opening episode?	Yes	??	No	No
Volc source	18	What is the typical gap between major gas outburst episodes?	Yes	No	No	Yes
Volc source	19_1	For phreatomagmatic activity, what is the likely % of total erupted volume?	Yes	??	??	No
Volc source	19_3	For phreatomagmatic activity, what is likely maximum eruption column height?	Yes	??	No	No
Volc source	24_1	What is the expected minimum ash volume produced w.r.t. the total erupted tephra volume (answer in % of the total erupted tephra volume)?	Yes	??	No	Yes
Volc source	24_2	What are the expected maximum ash volume produced w.r.t. the total erupted tephra volume (answer in % of the total erupted tephra volume)?	Yes	No	Yes	Yes
Plume	42_1	What is the typical e-folding time of SO_2 in the atmosphere (troposphere) in the winter within a Laki-like plume?	Yes	No	No	No
Plume	42_2	What is the typical e-folding time of SO_2 in the atmosphere (troposphere) in the summer within a Laki-like plume?	Yes	No	No	Yes

Type	Code	Target Item	Rational consensus?	Knowledge issues?	Terminology issues?	Wide uncertainty?
Plume	43_1	What is the e-folding time of SO_4 in the atmosphere (troposphere) in winter within a Laki-like plume?	Yes	??	No	No
Plume	43_2	What is the e-folding time of SO_4 in the atmosphere (troposphere) in summer within a Laki-like plume?	Yes	??	No	No
Plume	45S	By how much [expressed as %] does proximal adsorption on ash reduce the volcanic gas concentrations of S in the plume?	Yes	No	Yes	No
Plume	45F	By how much [expressed as %] does proximal adsorption on ash reduce the volcanic gas concentrations of F in the plume?	Yes	No	Yes	No

Notes to table:

"Rational consensus? = Yes" indicates the Decision Maker expert range graphs and solution distribution(s) do not evince major systemic discrepancies, egregious opinions or other evidence of suspect reasoning.

"Knowledge issues? = Yes or ??" identify possible knowledge gaps or hints of a dichotomy of expert knowledge.

"Terminology issues? =Yes or ??" point out Target Items where the question wording or terms may be ambiguous or convey different meanings to different people.

"Wide uncertainty? = Yes" flags Target Items where, prima facie, the associated uncertainty spreads are very substantial and could have a crucial effect for modelling impact.

8. Brief discussion on impacts

8.1 Health impacts (human and animal)

8.1.1 There is considerable evidence linking $PM_{2.5}$ (particulate matter smaller than 2.5 microns) and PM_{10} (particulate matter smaller than 10 microns) in the atmosphere with daily mortality and hospital admissions, exacerbation of asthma and non-fatal heart attacks (e.g. Pope and Dockery, 2006; Schwartz, 2001). Current evidence indicates that short-term (days) and long-term (months to years) exposure to $PM_{2.5}$ is associated with all-cause and cardiopulmonary mortality (Brook et al., 2010).

8.1.2 The smaller $PM_{2.5}$ can penetrate deeper into the lungs and so an increase in these fine particles has a more significant impact on health than PM_{10}.Tropospheric volcanic sulphate particles are typically <2.5 micron ($PM_{2.5}$) in diameter (Allen et al. 2002; Mather et al. 2003: Figure 4) and such particles can be present in the boundary layer far from the source volcano.

8.1.3 Several studies find strong associations between SO_4 air pollution and premature mortality (e.g. Pope and Dockery, 2006 and Pope et al. 2002). However, most studies on the exposure effects of particulate matter and aerosol are based on urban air pollution, rather than volcanic 'pollution'.

8.1.4 Hansell & Oppenheimer (2004) carried out a review of the health hazards of volcanic gases although most documented evidence is from proximal environments.

8.1.5 Details about volcanic gases and particulate matter (PM) and aerosol, exposure effects, current guidelines, volcanic incidents and examples, and references can be found on the website of the International Volcanic Health Hazard Network http://www.ivhhn.org/. For example, the health effects of exposure to hydrogen fluoride gas are documented (e.g. Baxter, 2000) and there are occupational guidelines.

8.1.6 Halogen and some sulphate aerosols are acidic, and it is thought that acidic PM may pose a greater risk to health than non-acidic. Metals contained in volcanic plumes, such as mercury, iridium, arsenic, and others, can catalyse reactions, and particularly in combination with acid gases and aerosols, increase health effects.

8.1.7 The analysis of F in surface waters and drinking water as well as vegetation would be important to ensure no risk of fluorosis (e.g. Baxter, 2000; Cronin and Sharp, 2002; Appendix F).

8.1.8 The International Volcanic Ash Task Force (IVATF) reported in June 2012 on task TF-SCI06: Health effects on aircraft occupants of exposure to volcanic SO_2. They stated that 'more research should be conducted to better understand the airworthiness effects, potential significant risk of sulphur dioxide to aircraft occupants, and any associated expeditious mitigation of the risk'.

8.1.9 There are several locations worldwide where populations live with active volcanoes and the responses of individuals to volcanic gases are documented (e.g. Miyakeshima Island, Japan: Ishigami et al. 2008; Kajino et al. 2004).

8.1.10 In Hawaii, the effects of exposure to SO_2 and particulate matter are well-documented (Longo, et al. 2005; Longo et al. 2008; Longo, 2009; Longo et al. 2010). There are established procedures for dealing with 'vog' and an SO_2 colour code system http://governor.hawaii.gov/emergency-information/important-information-about-vog/

8.2 Environmental impacts

8.2.1 Any volcanic acid gases and aerosols that reach the UK are likely to be deposited (by settling or sticking) on any surface, including soils, vegetation, crops, buildings and critical infrastructure, vehicles and so on, and – importantly - into lakes, reservoirs and streams. This will occur through wet deposition (including rain and snow) or dry deposition.

8.2.2 The impacts will depend on pre-existing conditions, the concentrations of the acidic compounds and whether or not they can be quickly removed (eg for example by uncontaminated rainwater or hosing). Grazing animals could be kept indoors to reduce exposure.

8.2.3 Delmelle (2003) reviews and presents evidence of impacts of volcanic gas plumes on vegetation in near-volcano environments. In terms of gas, the little available data suggests that atmospheric levels of HCl are too low to cause direct damage (Smith, 1990). However, SO_2 and HF may both be present at phytotoxic concentrations even though there is much less HF than SO_2 in most plumes.

8.2.4 Smith (1990) lists relative sensitivity of plants to damage by SO_2 or HF although Delmelle (2003) notes that different environmental conditions, weather, plant age, species and so on can affect sensitivity.

8.2.5 As well as better understanding what concentrations of SO_2 gas could be possible in UK airspace and at ground level, it's also necessary to carry out some modelling to establish whether or not HF gas could pose a risk in the UK and if so under what conditions.

8.2.6 Acidic wet deposition has an effect on vegetation with the greatest impact due to acidified fog and cloud with solute concentrations up to 10 times higher than rain (Cape, 1993). Hilly areas exposed to orographic clouds or coastal fog may be worst affected.

8.2.7 Sustained additions of acidic compounds to soil may lead to soil acidification. In the case of volcanic activity, the fate of sulphur, chlorine and fluorine in soil is also of importance. If groundwater is derived largely from meteoric water this can also be affected.

8.2.8 The UK has greatly reduced anthropogenic concentrations of sulphur and levels of acidity in the atmosphere, soils and freshwater since the mid-twentieth century, but recovery in some areas is slow (RoTAP, 2012) so any further deposition of acids may add to legacy issues.

8.2.9 Elevated SO_2, HF and sulphate aerosols in ambient air are probably the main causative agents of vegetation damage downwind of volcanic gas sources. However more extensive fieldwork

and laboratory work is needed for detailed analysis of the combined effect of these pollutants on natural and cultivated vegetation (Delmelle, 2003).

8.2.10 Delmelle (2003) states that in order to understand the impacts of volcanic degassing on the terrestrial and atmospheric environment we need: 1) systematic 2D and 3D measurements of volcanic plumes, 2) development of general physical and chemical models to describe the fate of volcanic gases and aerosols during transport in the troposphere, and 3) investigation of the response of diverse ecosystems to volcanogenic air pollution.

8.2.11 Poisoning in sheep is likely to occur when the fluorine content of dried grass exceeds 250 ppm (IVHHN). Poisoning can occur where only 0.5mm of ash has been deposited. As stated in chapter two it is entirely possible that this eruption scenario becomes vigorously explosive resulting in volcanic ash which is a vehicle for volcanic HF. We propose some recommendations in Appendix F.

8.3 Aviation impacts

8.3.1 SO_2 and sulphate (in the form of sulphuric acid) can cause damage to airframes and sulphate deposits can accumulate in turbines blocking cooling holes and leading to overheating as observed after the eruption of Mount Pinatubo in the Phillippines in 1991 (Carn et al., 2009).

8.3.2 Sulphate aerosols also accelerate corrosion thus requiring increased maintenance and decreasing engine lifetime; helicopters flying routinely in volcanic areas (e.g. for volcano observatories) have thorough daily maintenance regimes.

8.3.3 Miller and Casadevall (2000) reported that an aircraft suffered engine power loss in 1992 due to sulphate deposition in the engines from the eruption of Mount Pinatubo the previous year.

8.3.4 There is also the possibility of crew and passengers being exposed to toxic gases on the plane/helicopter if SO_2 for example has not fully oxidised in the atmosphere (see section 4.3).

8.3.5 The International Volcanic Ash Task Force (IVATF) was established by the International Civil Aviation Organisation in May 2010 in response to the disruptions of civil aviation that resulted from the eruption of the Eyjafjallajokull volcano in April-May the same year. The airworthiness effects of sulphur dioxide and other constituents of a volcanic cloud was considered an area that requires more research.

8.4 Other sectors

8.4.1 A volcanic haze or 'vog' is likely to lead to reduced visibility and could impact different sectors including transport. Volcanic particulates and gases can penetrate into mechanical and computer equipment, systems and buildings, and potential effects on modern electronics, for instance, are not clearly understood.

8.4.2 There is little current understanding of the potential impacts of metals contained in volcanic plumes such as mercury, iridium, arsenic, and others. As stated above, these can catalyse reactions, and combined with acid gases and aerosols could have impacts in several sectors.

9. Summary of results

9.1 Key findings

Here we summarise key findings based on the objectives of the exercise, starting with a definition of, and parameters for, a 'Laki-type' eruption scenario.

1. **Characterise a 'Laki-type' eruption scenario in terms of a range of suitable 'source' parameters for modelling.**

The Laki-type eruption scenario is defined here as a sustained large-volume fissure eruption (>1km^3 erupted magma) in Iceland (see Chapter 2). It was assumed during this exercise that the duration of this scenario is fixed as for the Laki eruption in 1783-4 at eight months but with most volcanic activity in the first five months.

We have collated some published parameters (see Chapter 3) and the expert elicitation has generated distributions for various additional parameters as summarised in Table 10. Participants new to the expert elicitation process were asked to consider the likely range of parameters given '100 runs of a Laki-type scenario'.

The summary presents the mean of the weighted expert opinion – Table 9 contains details about any ambiguities and Appendix C should be consulted for a comparison with 'equal-weighted' expert opinion.

2. **Establish likely eruption location, duration and dynamic evolution.**

About 79% of magma erupted in historical time in Iceland (the last ~1100 years) has been produced in the Eastern Volcanic Zone. About 77% was erupted at just four volcanoes in the EVZ: Grímsvötn, Barðarbunga/Veidivötn, Hekla and Katla (see Chapter 2). On this basis, the Eastern Volcanic Zone is the most likely area to produce a future large-volume fissure eruption. Other volcanoes with potentially active fissure systems are located in the Northern Volcanic Zone and the Western Volcanic Zone, the Öræfi Volcanic Zone and the Snæfellsnes Volcanic Zone.

The duration of historical and Holocene (last 12,000 years) fissure eruptions is poorly constrained, except for the Laki eruption itself at eight months (Table 5).

Some aspects of the potential future dynamic evolution of a Laki-type eruption scenario were elicited (e.g. possible number of fissure-opening episodes, duration of vigorously explosive phases see above) and are shown in Tables 9 and 10. A reconstructed time-series representation of the actual eruption (Thordarson and Self, 2003) is presented in Fig. 3.

Table 10. Overleaf. Elicited source parameters for a future Laki scenario (large-volume basaltic fissure eruption) giving the median and 5% and 95% values based on weighted opinions.

Parameter	Median of weighted opinion distribution (with 5% and 95 % values)
Mean total lava volume:	(3.0) 12.6km^3 (19.9)
Maximum total lava volume:	(8.2) 24.1 km^3 (56.7)
Mean explosion column height (above vent):	(4.7) 10.2km (14.9)
Maximum explosion column height (above vent):	(8.0) 12.6km (19.0)
Average sustained height for gases during mainly effusive phase (above vent):	(0.51) 1.8km (8.5)
Maximum sustained height for gases during mainly effusive phase (above vent):	(0.65) 3.4km (12.2)
Average amount of SO_2 released from explosive vent per km^3 lava erupted:	(3.4) 8.2 Tg (14.3)
Upper limit of SO_2 released from explosive vent per km^3 lava erupted:	(5.3) 12.0 Tg (19.9)
Maximum magma extrusion rate in an explosive phase:	(850) 7900m^3/s (43000*)
Average magma extrusion rate in an explosive phase:	(70) 3100m^3/s (9800)
Upper limit for percentage total of SO_2 released at the vents:	(50) 76.8% (96.8)
Lower limit for percentage of total SO_2 released at the vents:	(42) 69.1% (84.1)
Likely maximum number of fissure opening episodes:	(6) 19 (99)
Likely average number of fissure opening episodes:	(3) 11 (34)
Likely minimum number of fissure opening episodes:	(1) 6 (12)
Likely duration of the vigorous explosive phase for a fissure opening episode	(0.3) 2.7 days (18)
Likely maximum eruption column height (above vent) for phreatomagmatic activity:	(2.6) 11.2km (16.6)
Typical e-folding time of SO_2 in troposphere in winter for a 'Laki-type' plume:	(1.5) 5.1 days (25)
Typical e-folding time of SO_2 in troposphere in summer for a 'Laki-type' plume:	(1) 2.2 days (17)
Typical e-folding time of SO_4 in troposphere in winter for a 'Laki-type' plume:	(2) 7.2 days (29)
Typical e-folding time of SO_4 in troposphere in summer for a 'Laki-type' plume:	(1.6) 4.2 days (75)
The reduction of concentration of S in plume by adsorption:	(1.1) 6.8% (10)
The reduction of concentration of F in plume by adsorption:	(3) 7.1% (23.9)

3. **Evaluate the eruptive gases, aerosols, and ash that may be produced and could ultimately lead to impacts in the UK.**

Volcanic degassing releases mainly H_2O, CO_2 (largely inert) and volatile acidic gas species such as sulphur dioxide (SO_2), hydrogen sulphide (H_2S) and hydrogen halides (hydrogen chloride -HCl, hydrogen fluoride - HF, hydrogen bromide - HBr) into the atmosphere. These gases will cool, mix with the ambient atmosphere and concentrations will be diluted downwind, they also undergo a range of physical and chemical processes (including gas-gas reactions, or gas-liquid-solid reactions) depending on conditions. These processes control rates of conversion of gases to aerosols and also deposition rates (removal from the atmosphere). Volcanic gases that could potentially be produced in sufficient quantities to reach the UK under certain meteorological conditions (ie rapid transport) might include SO_2 and HF. Aerosols would include sulphuric acid (H_2SO_4) particles formed by oxidation of SO_2, other particulates might include sulphates, chlorides, bromides, trace metals and fine ash (the latter formed only during vigorous explosive episodes). How this combination of gases and aerosols might chemically interact with anthropogenic pollutants in the UK ambient air is unclear. Precipitation may remove gases, fluoride, acids, and other aerosols from the atmosphere and deliver them to the Earth's surface (e.g. acid rain falling on soils, vegetation). There may also be dry deposition of gases and aerosols, in particular acids in the absence of precipitation. See Appendix F.

4. **Establish what chemical reactions, physical processes and meteorology should be included in modelling of plume transport.**

There is much we don't yet know about plume chemistry and the controls on it. It was agreed that simple dispersal models without chemistry have value because they can address the first order problem of getting toxic species to the UK at flight levels or into the atmospheric boundary layer (the lowest part of the atmosphere in contact with the Earth's surface). We need to better understand the role of important physical and chemical processes such as SO_2 oxidation, oxidant limitation, adsorption, coagulation, nucleation, and wet and dry deposition using suitable models. Species such as HF and HCl may act like tracers (for short time periods of minutes to a few hours under certain conditions) so simple models may be adequate for them, species such as SO_2 can be considered using a decay constant to represent oxidation for example. In general, further study of the reactions that might be involved in volcanic plumes and their kinetics is essential in order to assess residence times and deposition rates and thus to facilitate more detailed modelling and quantitative assessment of impacts. A variety of meteorological scenarios should be used when modelling to inform impact assessments.

5. **Establish what the wet and dry deposition rates might be**.

A much improved understanding of plume chemistry and reactions is needed to understand the residence times and deposition rates of gases and acid compounds. Hydrogen chloride and hydrogen fluoride are more soluble in water than sulphur dioxide, and hence wet deposition may cause major depletion of these species from the plume (especially during the night or in wet periods).Dry deposition velocities depend on the reactivity of the species, so in experiments hydrogen fluoride (with high ash absorptivity) is 1-4 cm/s and SO_2 0.1-2 cm/s (Seinfeld, 1986). Delmelle et al. (2001) showed that SO_2 and HCl (hydrogen chloride) had similar dry deposition rates of c. 1.6 cm/s at

Masaya volcano (in the tropics). Wet deposition is mainly about precipitation so in environments where there is much condensed water in the atmosphere (cloud), it is controlled by the rates of reaction of different species. For example, HCl and HF are likely to have higher wet deposition rates than SO_2, because SO_2 relies on chemical reaction in preference to physical dissolution (Oppenheimer et al., 2003). Much more research is needed on both dry and wet deposition.

6. **Characterise likely concentrations in the UK based on current knowledge.**

Much more research and modelling are needed to address this (see Chapter 5 for a review of published results). Chenet et al. (2005) suggested that a visible haze forms at 5 x 10^{-9} kg sulphate aerosol per kg of air (equivalent to 5ppb). Haze was present for prolonged periods in Europe during the Laki eruption. Based on modelling using GLOMAP, Schmidt et al. (2011) suggested that aerosol pollution ($PM_{2.5}$) would double in concentration across Western Europe during the first three months of a 'Laki-type' eruption. This equates to 36 more days above the WHO $PM_{2.5}$ guidelines during the eruption.

7. **Identify what the optimum monitoring and observation networks might look like from source to UK.**

In Iceland, a new EUFP7 'Supersite' project is focusing significant European scientific effort on monitoring the Eastern Volcanic Zone, magma tracking to improve eruption forecasting, early warning, eruption source characterisation in near real-time, and plume monitoring. Several UK institutions including BGS, UK Met. Office and Cambridge University are participating in this project. The UK government through BGS is also investing in real-time geophysical monitoring in Iceland. The NERC-funded Vanaheim consortium led by Leeds University is working on connecting the near-field and far-field observation capability. In the UK we need to coordinate our existing ground, air and space resources, develop new technologies, in particular to better understand the vertical structure of volcanic clouds or haze, address remote sensing limitations and improve the spatial and temporal resolution of real-time ground monitoring and subsequent analysis. Particular gaps include air quality monitoring and SO_2 monitoring in rural areas or in northwestern parts of the UK and any ability to monitor H_2S. This is discussed in Chapter 6 and Appendix F.

8. **Understand what data on concentrations and deposition are required by health, environment and infrastructure experts.**

Air quality guidelines are well-established in the UK and EU for SO_2 which would be the main constituent gas in the erupted plume and which in high enough concentrations would trigger acute respiratory symptoms in asthma sufferers and aggravate the condition of patients with chronic lung problems. To assess the effect on such individuals, peak concentrations measured over 15 minutes would be compared with existing guideline values, and therefore short duration peaks are the most important to model for health purposes. Sulphate aerosol, other volcanogenic aerosols and possible fine ash would add to the existing particle concentrations in the atmosphere and at ground level would be measured in routine monitoring networks as PM_{10} and $PM_{2.5}$ (hourly and 24 hr means). These would be compared with existing guideline values. Deposition maps can be produced using existing capability (Appendix F). Further planning for critical infrastructure, environment and health is recommended once some preliminary modelling has been carried out.

9.2 Knowledge gaps

9.2.1 Knowledge gaps were identified throughout the elicitation workshop and some of the main issues are identified below but this list is not exhaustive:

- We cannot measure HCl, HF and some other key species from satellite.

- More work is needed to develop databases of _satellite data_ for comparison and analysis to better understand processes and uncertainties in existing data.

- _Air and ground-based methods_ are needed for comparison/validation of satellite methods. Improved and coordinated remote sensing including ground-, air- and space-based resources would significantly help source characterisation. More data from known eruptions is needed.

- We're lacking _near-source observations_ near the ground to establish in-plume processes and could investigate specially designed spectrometers / radars to monitor in real-time.

- _Numerical modelling of different eruption types_ such as lava fountaining to capture the physics of eruptions other than Plinian explosions. This should help with assessment of eruption rates, particle size distribution etc.

- _Processes in the eruption column_ change what actually ends up in the distal cloud (in terms of gas and aerosol) but we have a poor understanding of them: adsorption, coating of particles, high T gas phase chemistry...

- How significant would the _lava heat source_ be in terms of local meteorology and the impact on entrainment of ambient air?

- _Processes in the dispersing plume_ including adsorption, aggregation and their impact on gas/aerosol content of the plume are poorly understood.

- _Trace metals_ are present in plumes but we don't understand much about them, their transformation, deposition or potential impact (e.g. mercury, iridium, arsenic).

- _Wet deposition coefficients_ are not sufficiently known.

- The numerical _modelling of ash fallout_ requires more sophistication.

- Identify a HF _scavenging co-efficient_ process and any techniques for dealing with this and HCl.

- Understand the role of _fine ash particles on the oxidation of SO_2_ and identify if this is important enough to take into account.

- Whether SO_2 reaches ground levels in the UK (or is first converted to SO_4 aerosol) is partly dependent on _oxidant limitation_ but we don't know enough about it or the controls on it.

- Research is needed to evaluate if a Laki-type scenario would increase the likelihood of _extreme weather_ in the UK (drought, heatwave, severe winter, severe storms as seen in 1783-4 but was this coincident)?

- We have not yet sufficiently understood the likely far-field _health impacts of the Laki eruption_ and more thorough assessment is needed.

- How do _volcanic and anthropogenic pollutants_ interact and what is their combined impact on health?

9.3 Research and monitoring needed

Source term

1. High resolution monitoring campaigns are needed of future eruptions, from proximal to distal environments using multiple techniques to build knowledge and datasets.
2. Detailed process modelling (alongside 1).
3. Conduct lab experiments and theoretical work to define source term processes (alongside 1 and 2).
4. Develop models to capture the physics of different eruption types (e.g. lava fountaining).
5. Evaluate the influence of lava flows on buoyancy and entrainment of the plume (linked to 4).
6. Characterise the processes active within the column for reactivity and uptake in the column to define the distal plume.
7. Evaluate the properties of the Laki tephra and compare what is in the explosive phase and the effusive phase – develop modelling of lava fountaining.

Dispersion models

8. Getting gas and particles to respirable level in the atmosphere is most important – transport is first order. Need to run multiple models under different conditions to establish probabilities. Try models with chemistry and without, with SO_2 and PM (Met Office and Leeds are working together to assess aspects of modelling for large SO_2 eruptions).
9. Establish a method for evaluating dispersion models to ensure that they are producing realistic and necessary data for impact studies.
10. Identify what is sufficient to inform the decision making and planning process.
11. Create forecasts of quantities and concentrations, although it should be noted that one cannot model health impacts directly from dispersion model outputs because we do not know who is at risk from PM (it is always multifactorial).
12. Models can produce concentrations of gases at the rate needed for health impacts (e.g. 15 minute WHO thresholds for SO_2) but crucially it is not known how accurate they may be.

UK environment impacts

13. Identify the species of sulphate being dispersed and the degree to which there may be some neutralisation and the timescale of this process.
14. Establish: the fate of fluoride and the combination of sulphate and fluoride that may influence reactivity and longevity and the impact on vegetation etc.
15. Understand the role of fine ash (produced for example during hydromagmatic explosions), catalysis of SO_2, impact on e-folding time etc.
16. Investigate interaction of plume constituents with anthropogenic pollution, also halogen impact on oxidant limitation, trace metals and toxicity, reaction of organics to create new compounds.
17. Conduct vegetation and crops resistivity work.
18. Constrain values for HF and fluoride (during Laki) and identify to what extent the impacts were due to these species. HF is possible given a 6 hour travel time from Iceland to UK.
19. Need better understanding of wet deposition coefficients.
20. Evaluate the potential for a Laki scenario to increase the possibility of having extreme weather events in the UK.

Health impacts

21. A full review of historical and modern knowledge to increase understanding of what happened in 1783 in the UK (including Scotland where no analysis has been carried out), Europe and

Iceland based on a modern understanding of air pollution. Negative reporting is as important as positive reporting but is not included in recent compilations.

22. Undertake a critical evaluation of published reports on mortality from Laki in 1783.

23. Evaluate what the role of mixing volcanic pollutants with anthropogenic pollutants would be to increasing pollution, reactivity and producing new polluting compounds.

24. Do volcanic particles (ash and sulphate aerosol) differ in their toxicity from particulate matter already present in the ambient air and derived from anthropogenic sources?

25. Can we estimate the mortality impacts in the UK from a future Laki-like eruption?

Monitoring

26. Fill in gaps in UK monitoring capability (see Chapter 6 and Appendix F).

27. Review UK remote sensing capabilities and the accuracy of the measurements that we can make for both gas and particle loads.

28. Establish a long-term strategy for sampling, ash collection and analyses including leachates (Appendices F and H, I).

29. Enhance linkages between NERC facilities (ground, airborne and space monitoring).

30. Investigate new remote-sensing instruments with ability to detect HCl, HF and other species that we can't currently detect for satellite payloads.

31. Investigate possibility of a dedicated 'Laki-SAT' or several with small payloads on for example telecommunications satellites. The aim would be higher temporal and spatial resolution than the geostationary SEVIRI (for which Iceland is at high latitudes therefore very high angle).

9.4 Response needed

Emergency response

1. Establish an emergency response plan with timescales.

2. Establish a response plan and public advice to raise UK resilience to long-term impacts (much work has already been undertaken by the Health Protection Agency).

9.5 Recommendations

1. The research and monitoring recommendations described above should be encouraged and facilitated, inevitably funding opportunities are required. Some projects are now already underway as a result of the meeting at the Cabinet Office in May 2012 to establish some preliminary modelling results but a multi-disciplinary effort across the scientific community is needed for longer term progress. Impact studies on environment and infrastructure including aviation are particularly important.

2. Given the current limited evidence on which to base public health and environmental actions in the event of a future large-volume fissure eruption, it is recommended that a precautionary approach is taken and it is assumed that the toxicity of volcanic particulate air pollution (including ash and sulphate aerosol) is similar to ambient air particulate for monitoring and health surveillance purposes. In a scenario of the plume fumigating 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. It is suggested that UK impacts would be variable spatially and temporally. Improved near real-time monitoring of SO_2 and other gases is needed in the UK and guidance needs to be prepared in advance for the public and for those sensitive to air pollution (e.g. asthmatics).

3. Additional advice should be sought from an expert advisory group (perhaps specially convened for this purpose), including calculating estimates of short and long-term mortality for Laki-type episodes lasting over many months, with calculations for ambient air levels of $PM_{2.5}$, PM_{10} and SO_2 extrapolated beyond those adopted for the current air quality guidelines. The toxicity of the volcanic particles (ash and sulphate aerosols) would require specific evaluation by expert judgement by the Committee.

4. UK air quality guidelines are set on health criteria and provide a wide margin of safety in the population. In a natural event outside regulatory control, the guidelines for particulate matter and SO_2 could be temporarily relaxed and additional information provided to the public based on actual daily levels from the air monitoring network. Thus, advice for chest patients could include when to stay indoors, when to wear a suitable mask if going outdoors, or when asthma sufferers should increase their medication with their doctor's knowledge to control symptoms.

5. Special measures for the general population and patients, including the type of advice mentioned in the preceding paragraph, need to be planned for in advance and prepared for rapid dissemination by the media in the event of a fissure eruption which could grow into a Laki event. The small volcanic island of Myakejima, south of Tokyo, is instructive as an example of a population living on a volcano emitting large quantities of SO_2 from its summit. Warning systems (loudspeakers, flashing traffic lights) inform the people (issued with gas masks) if the gas levels are rising. Many houses and all public buildings, including schools, have been fitted with special ventilation systems which filter out SO_2 and can be switched on if required (Kajino et al., 2004; Ishigama et al., 2008). Above all, there is a high level of understanding about the hazard in the population.

6. Difficulties in predicting source terms before the fissure eruption and in the modelling of the dispersion of the plume, as well as the limits to our understanding of the chemical reactions in the plume during its transport, may lead to quite uncertain forecasts of exposure in the UK population. Order of magnitude levels of SO_2 from 0.02 ppm to 0.2 ppm to 2 ppm, for example, would mean different levels of acute response in susceptible people, and would be a broad but adequate basis for producing planning advice by emergency managers.

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APPENDIX A: Meeting and elicitation participants

List of Participants

Willy Aspinall	Aspinall and Associates / University of Bristol
Peter Baxter	University of Cambridge
Steve Blake	Open University
Christine Braban	Centre for Ecology and Hydrology (NERC)
Antonio Costa	University of Reading
Pierre Delmelle	Université Catholique de Louvain
Anjan Ghosh	Health Protection Agency[14]
Matthew Hort	UK Met Office
Robie Kamanyire	Health Protection Agency[13]
Ishani Kar-Purkayastha	Health Protection Agency[13]
Sue Loughlin	British Geological Survey (NERC)
Tamsin Mather	Oxford University
Virginia Murray	Health Protection Agency
Clive Oppenheimer	University of Cambridge
Anja Schmidt	Leeds University
David Stevenson	Edinburgh University
Thor Thordarson	Edinburgh University
Roland von Glasow	University of East Anglia
Charlotte Vye	British Geological Survey (NERC)
Geoff Wadge	University of Reading
Claire Witham	UK Met Office

Twenty one people attended the Workshop. Of these, fifteen were present throughout and fourteen took part in the elicitation and undertook the Classical Model calibration exercise and hence could participate as weighted contributors in the structured elicitation of selected questions ('Target Items'). The purpose of the elicitation exercise was to obtain quantified uncertainty distributions that could be ascribed to related inputs in any modelling intended to estimate potential volcanic effects and impacts on UK.

The fourteen Experts are tabulated here as A to N, but appear in various combinations and with varying numbered guises in Appendix C summarising the elicitation results. Two Experts (J and K) provided responses to all twenty-eight Target Items, and all Experts answered at least 18 questions. Ten Target Items were evaluated by all fourteen Experts, while the least subscribed Item (concerning the expected average rate of magma discharge in an explosive phase) surprisingly had just five legible, complete and valid appraisals.

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[14] From 1st April 2013, HPA became part of Public Health England.

Item Expert	A	B	C	D	E	F	G	H	I	J	K	L	M	N	No.by item
Q8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q9_1	1	1		1		1	1		1	1	1	1	1	1	11
Q9_2	1	1		1		1	1		1	1	1	1	1	1	11
Q10_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q10_2	1	1	1	1	1	1		1		1	1	1	1	1	12
Q10B_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q10B_2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q11_1			1	1	1	1	1		1	1	1	1	1	1	11
Q11_2			1	1	1	1	1		1	1	1	1	1	1	11
Q12_1				1			1		1	1	1	1	1		7
Q12_2							1		1	1	1	1			5
Q15_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q15_2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q16_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q16_2	1	1	1	1		1	1	1	1	1	1	1	1	1	13
Q16_3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Q19_1				1	1		1	1	1	1	1	1	1	1	10
Q19_3					1			1	1	1	1	1	1	1	8
Q24_1	1		1	1	1		1		1	1	1	1	1	1	11
Q24_2	1		1	1	1		1		1	1	1	1	1	1	11
Q42_1	1	1	1		1	1	1	1	1	1	1		1		11
Q42_2	1	1	1		1	1	1	1	1	1	1		1		11
Q43_1	1	1	1				1	1	1	1	1				8
Q43_2	1	1	1				1	1	1	1	1				8
Q45S			1		1	1	1	1	1	1	1		1		9
Q45F			1		1	1	1	1	1	1	1		1		9
No. by Expert	20	18	22	20	21	20	26	20	27	28	28	22	25	20	

Table 11 Summary of elicitation participation , by Expert (A-N) and by Item (questions answered).

APPENDIX B: Expert Judgment Elicitation – a briefing note

Prepared by Willy Aspinall[15], 8 May 2012

1 Preamble

This note is based on the author's experiences of facilitating expert judgment elicitations in several topic areas in science, engineering and medicine. Conduct of those elicitations has been strongly influenced by the guidance given in Cooke and Goossens (1999) and Cooke and Goossens (2000) – see Appendix for a reprint of the latter paper.

2 Essentials

Expert opinion is almost invariably sought when scientific uncertainty impacts on an important decision process. Because such uncertainty is ubiquitous in scientific knowledge – if it were not, a decision would be obvious – there is the inescapable corollary that the experts themselves cannot be absolutely certain, and thus total agreement with one another is unattainable. This is especially true where such uncertainty is substantial, or where the consequences of the decision are particularly serious or onerous.

In circumstances where scientific uncertainty impinges on the determination of an issue, soliciting expert advice is not new. Generally, however, this has been pursued on an informal basis, and an unstructured approach is rarely, if ever, found entirely satisfying to all parties. Neither is it likely to be immune to legitimate criticism, from one side or another. To counteract these shortcomings, a s*tructured* expert judgment elicitation refers to the deliberate effort to tie the whole process to transparent methodological rules, with the goal of treating expert judgments as scientific data in a formal decision process.

Various methods for assessing and combining expert uncertainty are described in the literature. Until recently, the most familiar approach has been one that advocates a group decision-conferencing framework for eliciting opinions, but other approaches now exist for carrying out this process more objectively. Prominent amongst the latter is the expert weighting procedure known as the Classical Model, formulated by Cooke (1991), which can be implemented with the computer package EXCALIBUR to analyse opinions obtained through a structured elicitation procedure. The unique feature of this particular approach is that it is the only one in which distinct and different weights are given to individual experts, based statistically on their ability to judge uncertainties. This skill is measured empirically by performance metrics derived from control questions. The theoretical basis and principles of the Classical Model are expounded in Cooke (1991), and a recent summary of case histories using the procedure is given in Cooke and Goossens (2008).

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2.1 The elicitation procedure

The main top-level steps in the procedure for applying the EXCALIBUR procedure in practice, most of which are common with other elicitation approaches, can be summarized as follows (but see Appendix for more detailed discussion by Cooke & Goossens, 2000):

- A group of experts are selected, usually by the 'problem-owner'; the latter sometimes takes additional external advice as to individual expert's qualifications, experience and suitability to act as a panel expert in the context of the problem.

- The selected experts will be elicited individually, strictly within their domain of expertise, regarding the uncertainty they would ascribe over the results of questions which, in theory, could be determined by possible measurements or observations that are not feasible for practical, time-constraint or ethical reasons.

- In the procedure, the selected experts also assess other variables within their field, the true values of which are known or become known post hoc – these are termed 'seed items'.

- The experts' opinion are treated as statistical hypotheses and are scored with regard to statistical likelihood (often called 'calibration') and informativeness.

- These scores are combined to form weights. These weights are constructed to be 'strictly proper scoring rules' in an appropriate asymptotic sense: experts receive their maximal expected long-run weight by, and only by, stating their true degrees of belief. With these weights, statistical accuracy strongly dominates informativeness – one cannot compensate poor statistical performance by very high information.

- Likelihood and informativeness scores are used to derive performance- based weighted combinations of the experts' uncertainty distributions.

The key feature of this method is the performance-based combination of expert uncertainty distributions. When it comes to attempting to resolve differences in expert judgments, people who seek to find a harmony of views by conciliation can be disconcerted by this approach, but extensive experience overwhelmingly confirms that experts grow to favour it because its performance-based measure is entirely objective and amenable to diagnostic examination.

This encourages experts wary of getting involved in policy advice to participate in important decision issues: the structured, neutral procedure and the collective, de-personalized nature of the result reassure experts. Key to achieving this is the facilitator, who needs to be impartial and able to deal with differences of opinion with tact, to prevent individual experts from hijacking the debate, and to avoid other pitfalls, such as asking misconstrued or leading questions, or prompting the experts. At the same time, the facilitator needs the knack of keeping all participants fully engaged and focused throughout the elicitation in order to achieve a balanced and justifiable outcome.

The facilitator also needs to be aware of certain practical expedients. For instance, asking people to provide their responses into a computerized form, such as Excel, makes life much easier for the facilitator when processing the responses, but experience shows that this actually discourages experts from reflecting on, or re-considering, whatever values they enter: with a computer form,

people tend just to enter a number and move on. Thus, a paper questionnaire and a pencil and eraser are valuable tools to provide to participants so that they can more easily update their entries as they progress the elicitation.

2.2 Combining expert assessments

A combination of expert assessments is often referred to as a "decision maker" (DM), in the sense of linear pooling. With a set of several seed items (usually about ten in number), a group of experts can be ranked according to the product of their individual calibration and information scores. With these latter weights to hand, it is then possible to elicit from the same group of experts their quantile-based distributions for items of interest to the problem-owner (i.e. for questions for which an expert consensus is sought), and these individual response distributions can be linearly pooled, applying the individual weights. It should be noted that a weighted combination distribution, obtained in this way, is seldom if ever identical to the distribution of any one contributing expert, but does represent a rational consensus of the information provided by members of the group as a whole, differentiated by their performance on the seed items.

In this context, "good expertise" corresponds to good calibration (high statistical likelihood the expert's distributions reflect true values) and superior information. Strong weights reward good expertise, and pass these virtues on to the decision maker. The reward aspect of weights is very important. An expert's influence on the outcome from the group should not appear haphazard, and he/she should be discouraged from attempting to game the system by trying to tilt assessments to achieve a desired outcome. Thus it is necessary to impose a strictly proper scoring rule constraint on the weighting scheme. This means that an expert achieves his maximal expected weight by, and only by, stating assessments in conformity with his/her true beliefs.

3 Remarks

In the Classical Model, calibration and information are combined to yield an overall or combined score ("performance-based weight") with the following attributes:

1. Individual expert assessments, realizations and scores can be recorded. This enables any reviewer to check the application of the method, in compliance with the principle of **accountability / scrutability.**
2. Performance is measured and hopefully validated, in compliance with the principle of **empirical control.** An expert's weight is determined by performance on seed items.
3. The score is a long run proper scoring rule for average probabilities, in compliance with the principle of **neutrality.**
4. Experts are treated equally, prior to the performance measurement, in compliance with the principle of **fairness.**

Whilst expert names and qualifications should be part of the documentation of every expert judgment study, they are not usually associated directly with identifiable individual assessments in the open literature. However, the experts' reasonings should be recorded along with their quantile

estimates, and these arguments are usually collated from the group and reported in supporting documentation as expert rationales.

There is no mathematical theorem which states that performance-based weights will out-perform equal weights or out-perform the best expert in any particular elicitation. Indeed, it is not difficult to construct artificial examples where this is not the case. Selecting which of weighting scheme to use is a matter of experience but, in practice, performance-based weights are found to be systematically better, statistically and in information terms, over the long run. Good performance on a one-off basis for a single individual data set is not convincing – what is convincing is good performance on a large diverse data set, such as the TU Delft expert judgment database (Cooke and Goossens, 2008).

In practice a method should be easy to apply, easy to explain, should do better than equal weighting, and should never do something ridiculous. Given the body of experience with structured expert judgment that has now accumulated, the performance-based Classical Model approach is well established: simply using traditional equal weights ("one man, one vote") for scientific uncertainty quantification no longer seems to be a convincing alternative.

Upon reflection, it should be evident that equal weighting has one very serious drawback. As the number of experts increases, the equal weight combination typically becomes increasingly diffuse, until it represents no one's belief and is useless for decision support (e.g. the PEGASOS Project for seismic hazard in Switzerland). This syndrome is frequently seen when the number of experts exceeds, say, ten. The viability of equal weighting is sustained only by sharply restricting the number of experts who will be treated equally, leaving others outside the process. It appeals to a 'democratic consensus' ideal – progress in science, however, is driven by rational consensus.

Ultimately, therefore, consensus is an equilibration of power: in science, more than any other endeavour, it is not the power of the ballot but the power of argument that counts (Kurowicka and Cooke, 2006), and this can be made manifest through the EXCALIBUR structured elicitation procedure. When scientists disagree, any attempt to impose agreement, other than through a rationalizing approach, will promote confusion between consensus and certainty. The goal should be to quantify uncertainty, not to remove it from the decision process. The Classical Model approach is most useful when there is no other sensible way to make risk-based decisions – apart from resorting to the precautionary principle, or, even less helpfully, evading an answer by simply agreeing to disagree.

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Kurowicka, D. and Cooke, R., 2006. *Uncertainty Analysis with High Dimensional Dependence Modelling*. Wiley, Series in Probability and Statistics, Chichester: 284pp

APPENDIX C: Elicitation Results

Elicited Target Items – range graphs and quantile solutions
Notes: Expert identity numbering changes from one item to another.
Some solution values are given to more precision than is justified, and should be rounded appropriately.

8. What is the likelihood that in the next Laki-like eruption there is an episode which releases 10 times more SO_2 on the same timescale as the peak eruption episode during Laki? [express as %age?]

Scenario modelling Item 8: Prob (%) episode with 10x Laki SO_2
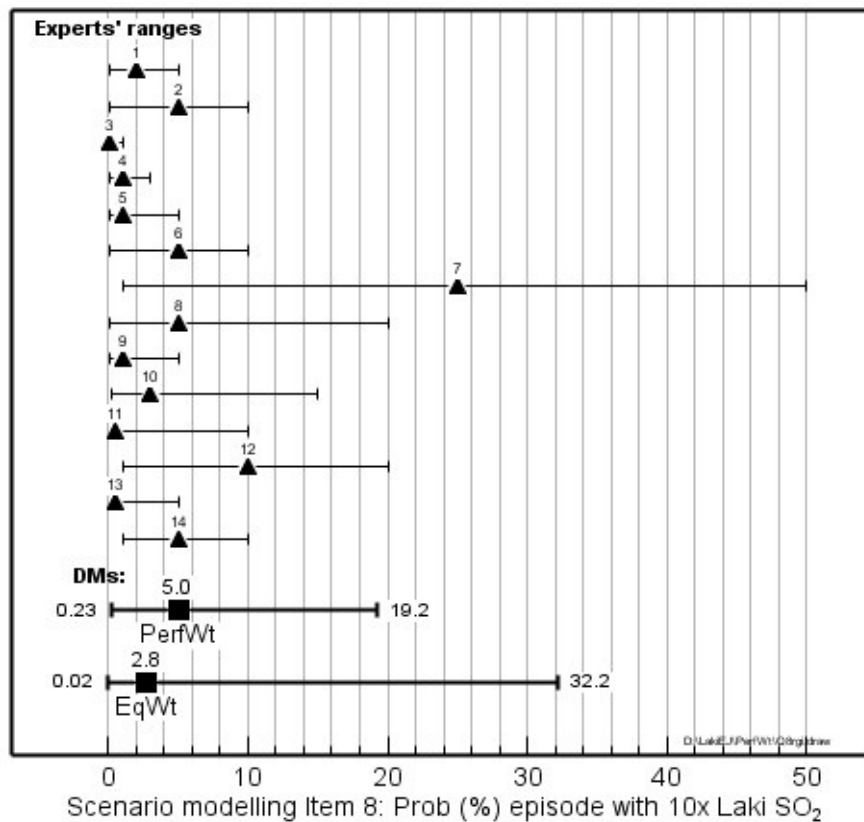
Performance-based DM solution:
5% quantile: 0.23%	median: 5.0%	95% quantile: 19.2%

Equal weights DM solution:
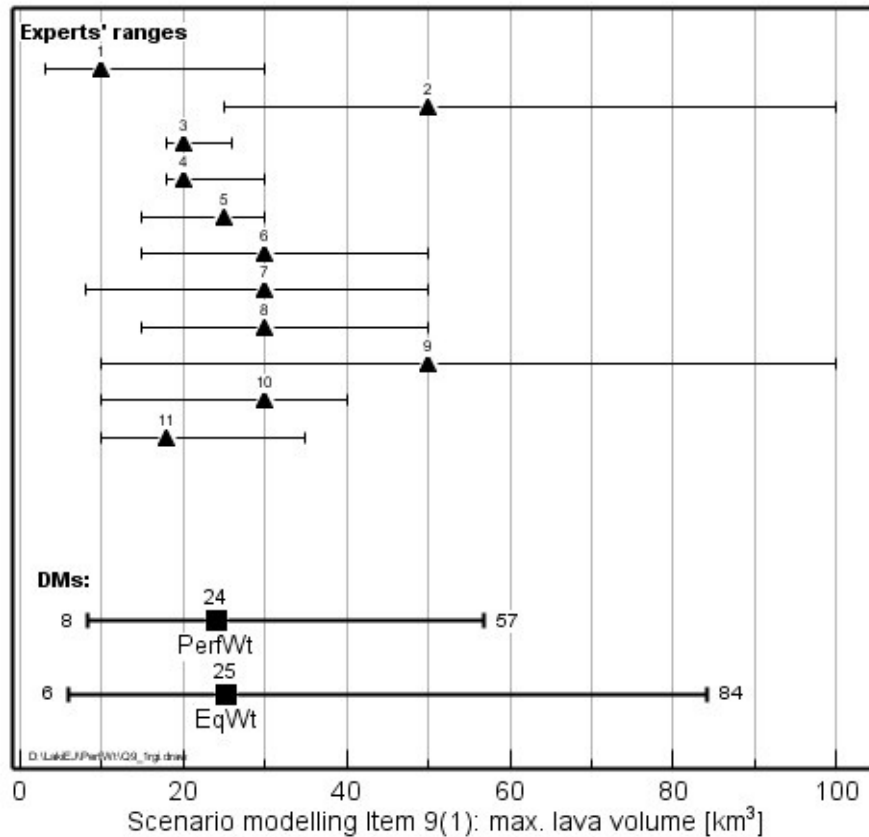|		
5% quantile: 0.02%	median: 2.8%	95% quantile: 32.2%

Comments: the two Decision Maker (DM) solutions appear reasonably consistent with one another – the Equal weights solution has wider uncertainty than the Performance-

based weights solution, as expected. Seemingly Expert 7 is not going to be surprised if the next Laki-like eruption entails a much greater amount of SO_2 than the 1783 event

9_1 Given an eruption like Laki 1783-4 (flood lava eruption), what maximum total lava volume should be used for scenario modelling (in km^3)?

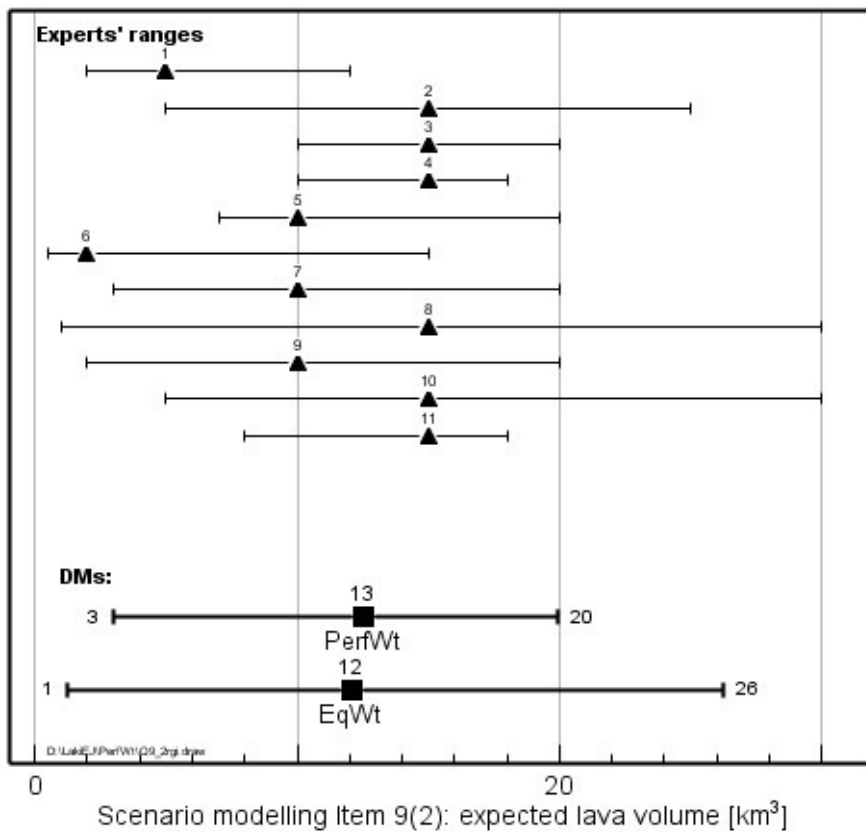Scenario modelling Item 9(1): max. lava volume [km^3]

Performance-based DM solution:
5% quantile: 8.2 km^3 median: 24.1 km^3 95% quantile: 56.7 km^3
Equal weights DM solution:
5% quantile: 5.9 km^3 median: 25.3 km^3 95% quantile: 84.1 km^3

Comments: the two DM solutions appear reasonably consistent with one another – the Equal weights solution has wider uncertainty than the Performance-based weights solution, as expected. The credible intervals of Experts 2 and 9 are greater and displaced relative to the rest of the group, suggesting that they hold the view any scenario modelling should accommodate this possibility.

9_2 Given an eruption like Laki 1783-4 (flood lava eruption), what expected (i.e. mean) total lava volume should be used for scenario modelling (in km^3)?
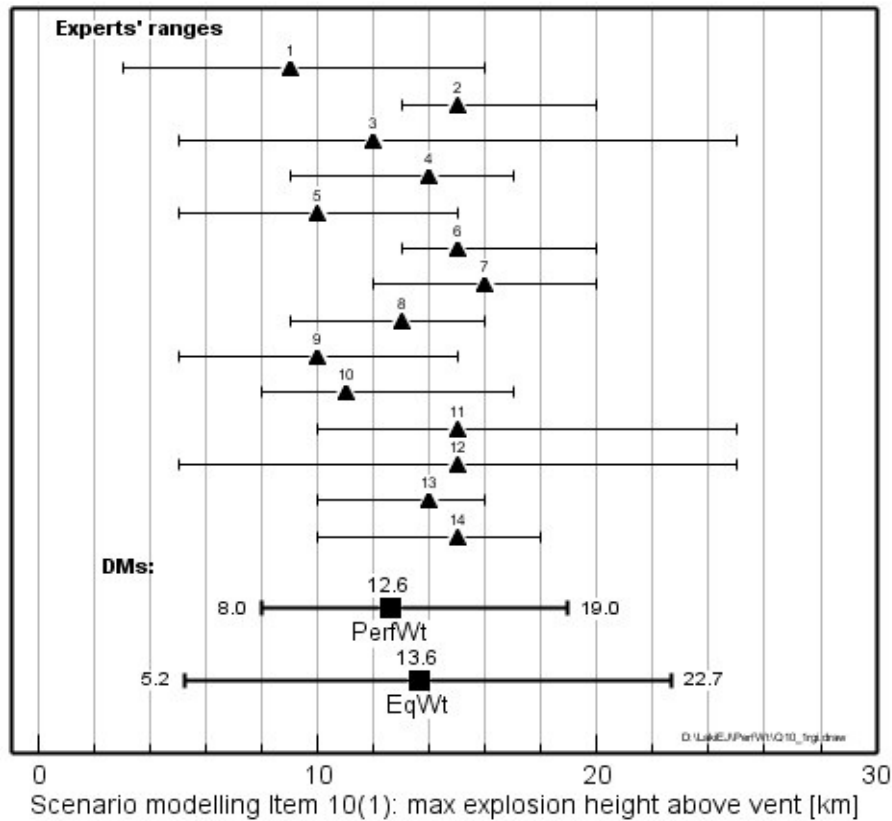

Performance-based DM solution:
5% quantile: 3.0 km^3 median: 12.6 km^3 95% quantile: 19.9 km^3
Equal weights DM solution:
5% quantile: 1.2 km^3 median: 12.1 km^3 95% quantile: 26.3 km^3

Comments: the two DM solutions appear consistent with one another – the Equal weights solution has wider uncertainty than the Performance-based weights solution, as expected. The low medians of the distributions of Experts 1and 6 may indicate a possible knowledge gap issue, or that scenario modelling should include this eventuality.

10_1 What is the likely maximum explosion column height above vent during individual eruptive episodes (fissure opening)?

Performance-based DM solution:
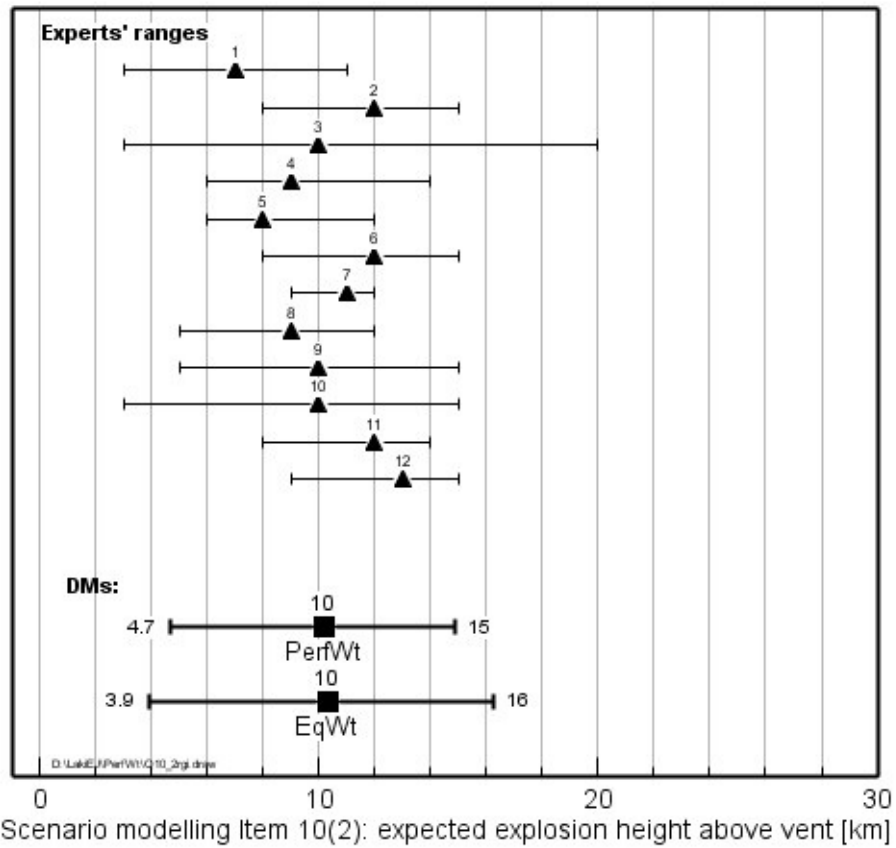5% quantile: 8.0km   median: 12.6km   95% quantile: 19.0km
Equal weights DM solution:
5% quantile: 5.2km   median: 13.6km   95% quantile: 22.7km

Comments: the two solutions appear consistent with one another – the Equal weights solution has wider uncertainty than the Performance-based weights solution, as expected.

10_2 What is the likely mean explosion column height above vent during individual eruptive episodes (fissure opening)?

Scenario modelling Item 10(2): expected explosion height above vent [km]

Performance-based DM solution:
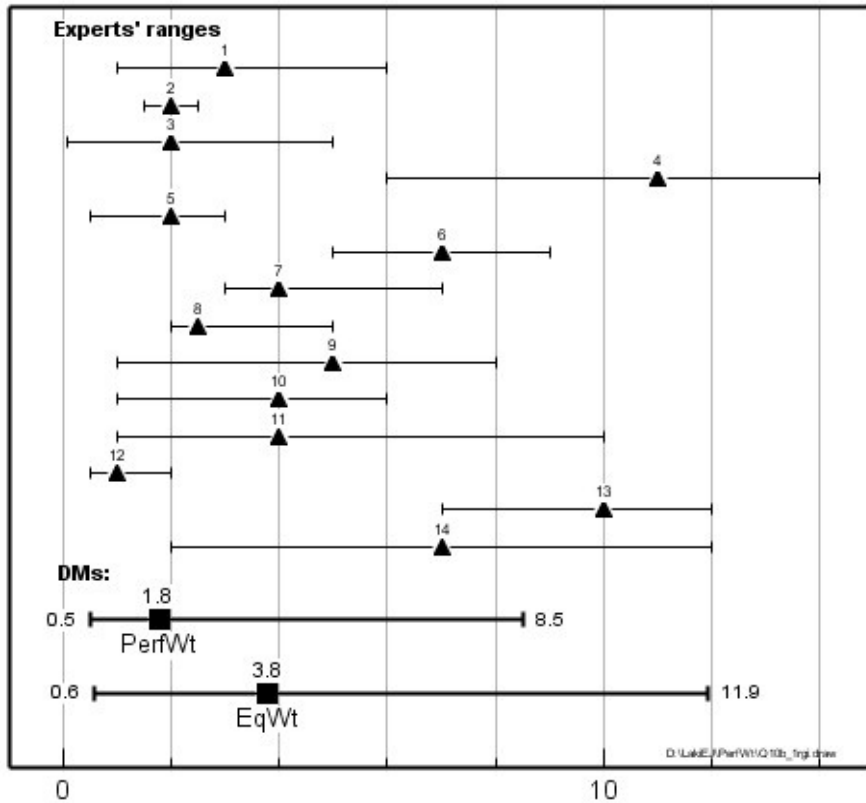5% quantile: 4.7km   median: 10.2km   95% quantile: 14.9km
Equal weights DM solution:
5% quantile: 3.9km   median: 10.3km   95% quantile: 16.3km

Comments: the two solutions appear very consistent with one another – the Equal weights solution has marginally wider uncertainty than the Performance-based weights solution.

10b_1 After the initial explosive phase (ie first days), what is the likely average sustained plume height for gases above the vent for the remainder of the active episode?

Scenario modelling Item 10b(1): expected fountaining gas plume height [km]

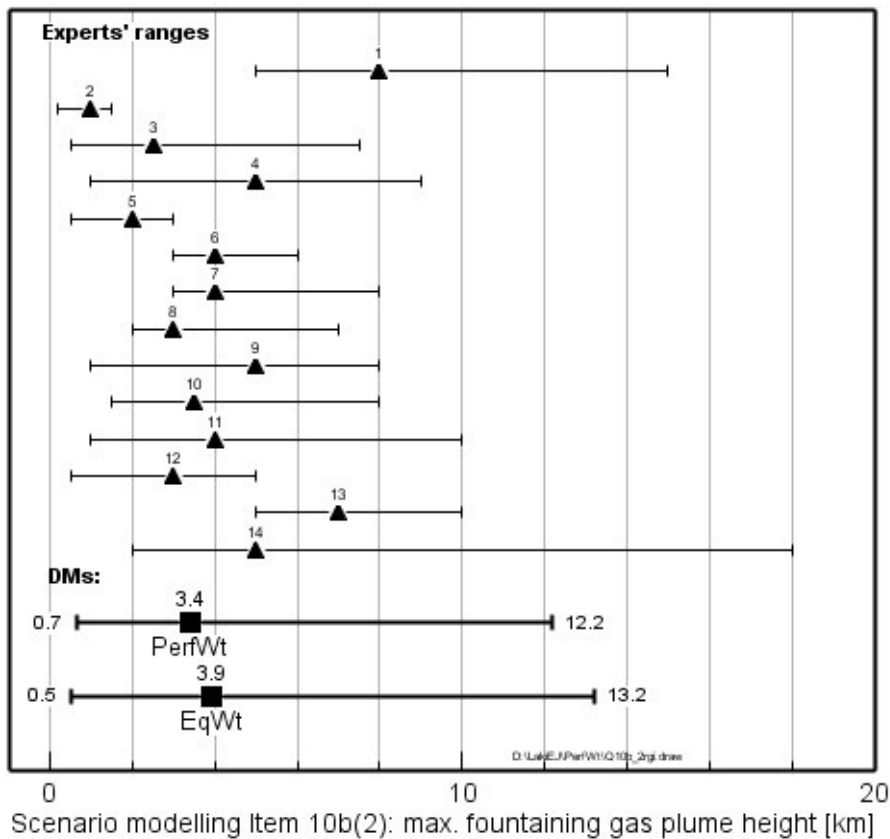Performance-based DM solution:
5% quantile: 0.51km   median: 1.8km   95% quantile: 8.5km
Equal weights DM solution:
5% quantile: 0.60km   median: 3.8km   95% quantile: 11.9km

Comments: the two solutions appear reasonably consistent with one another – the Equal weights solution has wider uncertainty than the Performance-based weights solution, as expected. However, there is wide scatter across different individual's credible ranges and quantiles, suggesting a possible knowledge issue and a parameter that is difficult to constrain for scenario modelling purposes.

10b_2 After the initial explosive phase (ie first days), what is the likely maximum sustained plume height for gases above the vent for the remainder of the active episode?

Scenario modelling Item 10b(2): max. fountaining gas plume height [km]

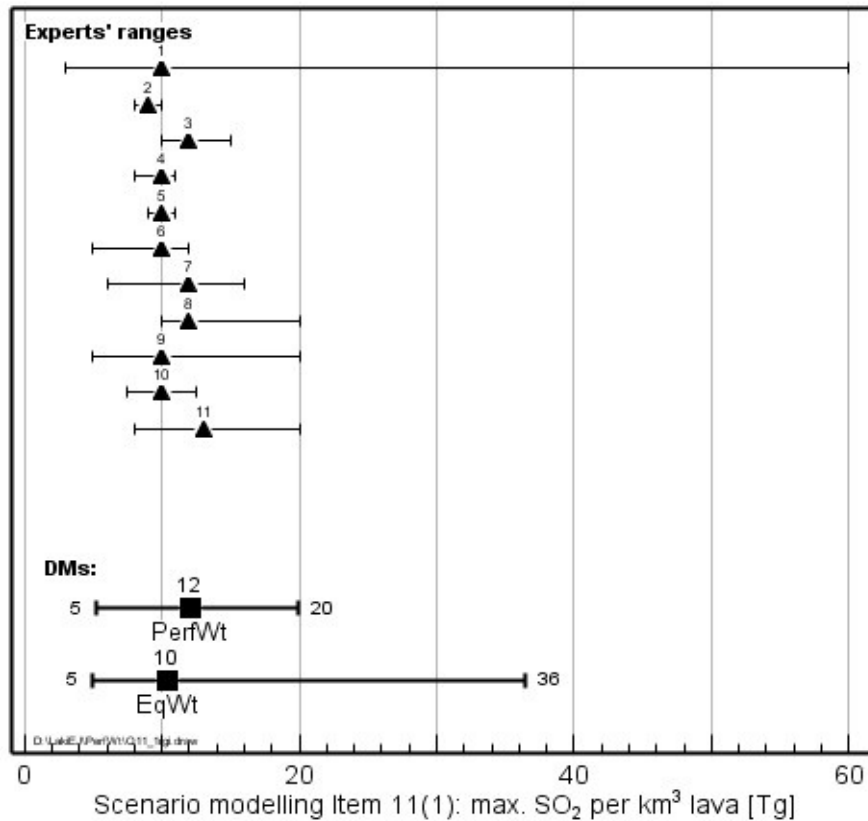Performance-based DM solution:
5% quantile: 0.65km   median: 3.4km   95% quantile: 12.2km
Equal weights DM solution:
5% quantile: 0.53km   median: 3.9km   95% quantile: 13.2km

Comments: the two solutions appear consistent with one another – the Equal weights solution has marginally wider uncertainty than the Performance-based weights solution. This said, both DM credible ranges are very wide, and both long-tailed to higher height values, reflecting mainly the views of Experts 1, 13 and 14. These results suggest further consideration needs to be given to the way this is parameterized for scenario modelling, as it is important in relation to the likelihood of large amounts of gas being transportable to UK.

11_1 What is the likely upper limit amount of SO$_2$ released from the explosive vents per unit of lava volume (Tg of SO$_2$ per km^3 of lava erupted)?

Scenario modelling Item 11(1): max. SO$_2$ per km^3 lava [Tg]

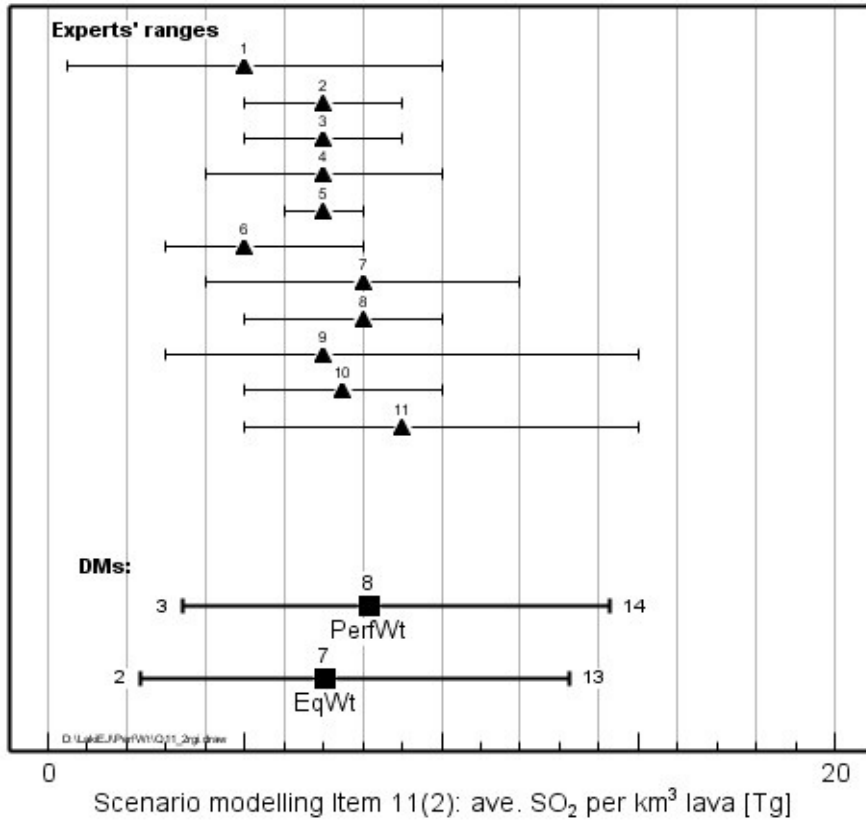Performance-based DM solution:
5% quantile: 5.3 Tg   median: 12.0 Tg   95% quantile: 19.9 Tg
Equal weights DM solution:
5% quantile: 4.9 Tg   median: 10.4 Tg   95% quantile: 36.5 Tg

Comments: the two solutions appear reasonably consistent with one another – the Equal weights solution has much wider uncertainty than the Performance-based weights solution, due to the opinion of Expert 1. Quantification of uncertainty on this factor may benefit from further discussion with Expert 1, to establish whether they have strong reasoning for their upper tail uncertainty.

11_2 What are the likely average amount of SO$_2$ released from the explosive vents per unit of lava volume (Tg of SO$_2$ per km^3 of lava erupted)?

Scenario modelling Item 11(2): ave. SO$_2$ per km^3 lava [Tg]

Performance-based DM solution:
5% quantile: 3.4 Tg   median: 8.2 Tg   95% quantile: 14.3 Tg
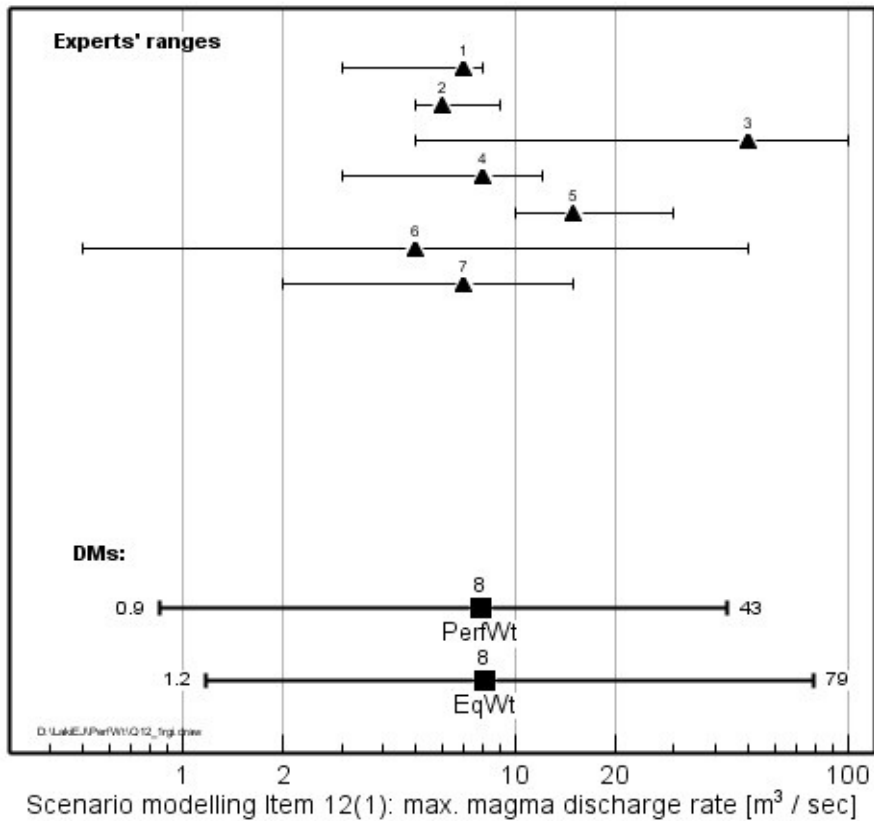Equal weights DM solution:
5% quantile: 2.4 Tg   median: 7.1 Tg   95% quantile: 13.2 Tg

Comments: the two solutions appear very consistent with one another, although the Performance weights DM unusually exhibits the same uncertainty range as the Equal weights distribution, rather than less. Otherwise, differences are not meaningful.

12_1 What is the maximum rate of magma discharge in an explosive phase? (cubic metres / second)

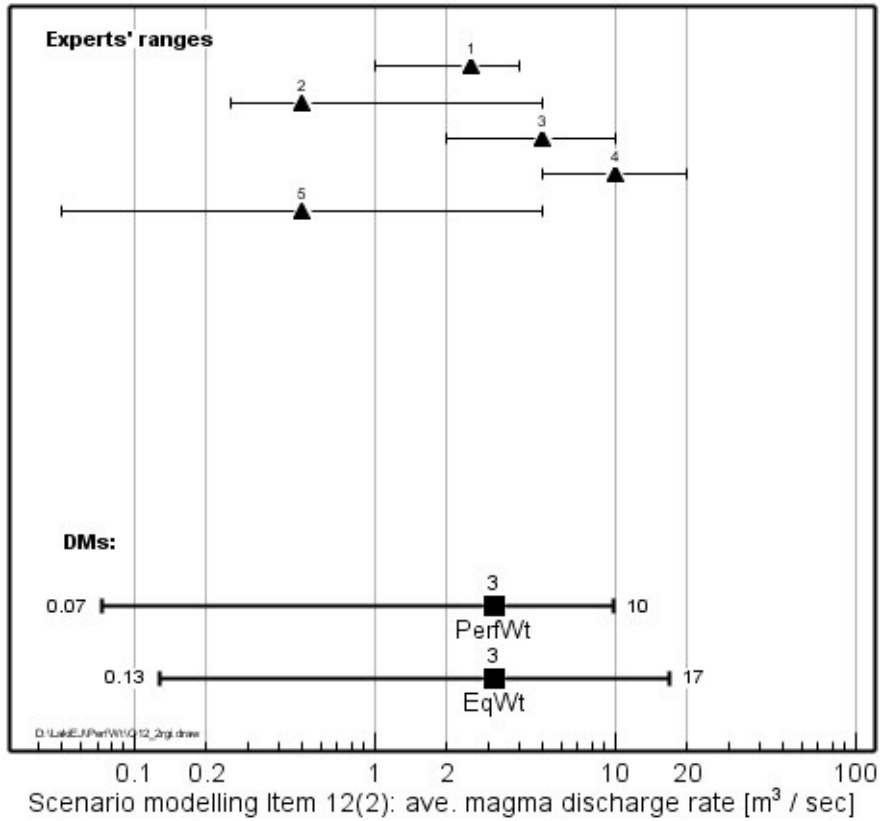Performance-based DM solution:
5% quantile: 0.85 m³/s   median: 7.9 m³/s   95% quantile: 43 m³/s
Equal weights DM solution:
5% quantile: 1.2 m³/s   median: 8.1 m³/s   95% quantile: 79 m³/s

Comments: note log scale for x-axis and only seven experts' responses. The two DM solutions appear reasonably consistent with one another – the Equal weights solution has wider uncertainty than the Performance-based weights solution, as expected (partly masked by log scale plotting). Expert 3 provides a credible interval and median value implying a much higher maximum discharge rate than the rest of the group; ideally, this would be explored further for reasoning.

12_2 What is the expected average rate of magma discharge in an explosive phase? (cubic metres / second)

Scenario modelling Item 12(2): ave. magma discharge rate [m³ / sec]

Performance-based DM solution:
5% quantile: 0.07 m³/s   median: 3.1 m³/s   95% quantile: 9.8 m³/s
Equal weights DM solution:
5% quantile: 0.13 m³/s   median: 3.2 m³/s   95% quantile: 17.0 m³/s

Comments: note log scale plotting, and only five respondents. The solutions suggest that in any modelling large uncertainty should be associated with this parameter.

15_1 What is the likely upper limit for the percentage of total SO_2 emissions that is released from vents?

Scenario modelling Item 15(1): SO_2 from vents [upper bound % of total]
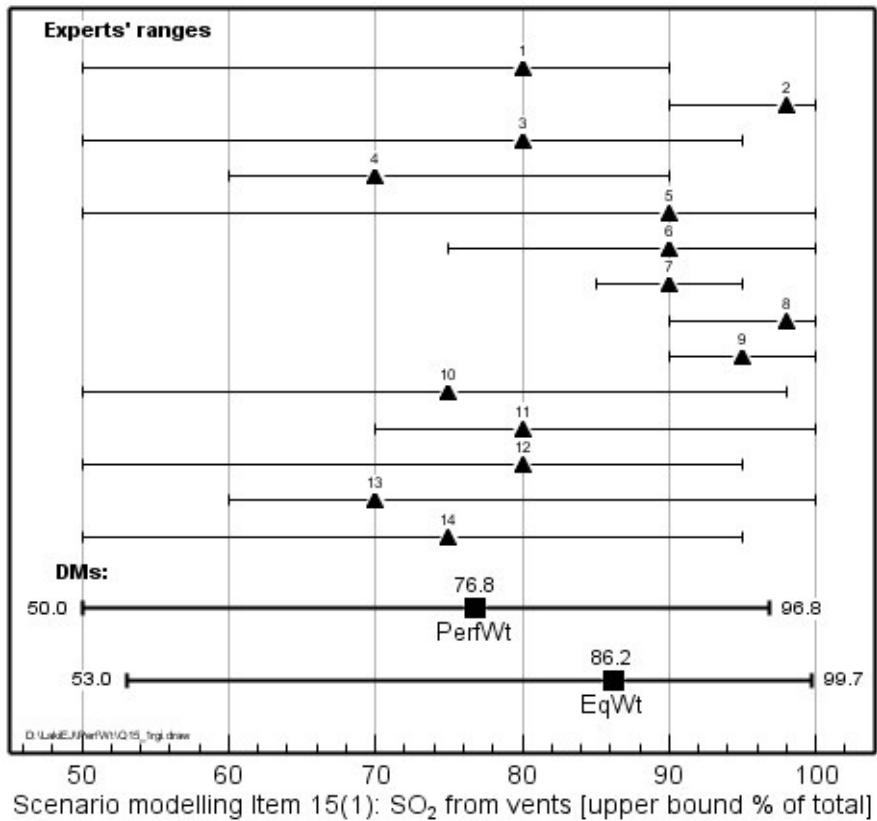
Performance-based DM solution:
5% quantile: 50.0%   median: 76.8%   95% quantile: 96.8%
Equal weights DM solution:
5% quantile: 53.0%   median: 86.2%   95% quantile: 99.7%

Comments: there is significant uncertainty associated with ascribing an upper bound to this variable for modelling purposes, as evinced by the spreads on the two DM solutions, and the difference in medians. Some Experts (i.e. 2, 7, 8 and 9, with weaker support from 5 and 7) favour much higher values than the rest of their colleagues. There may be a knowledge topic to address here.

15_2 What is the likely lower limit for the percentage of total SO$_2$ emissions that is released from vents?

Scenario modelling Item 15(2): SO$_2$ from vents [expected % of total]

Performance-based DM solution:
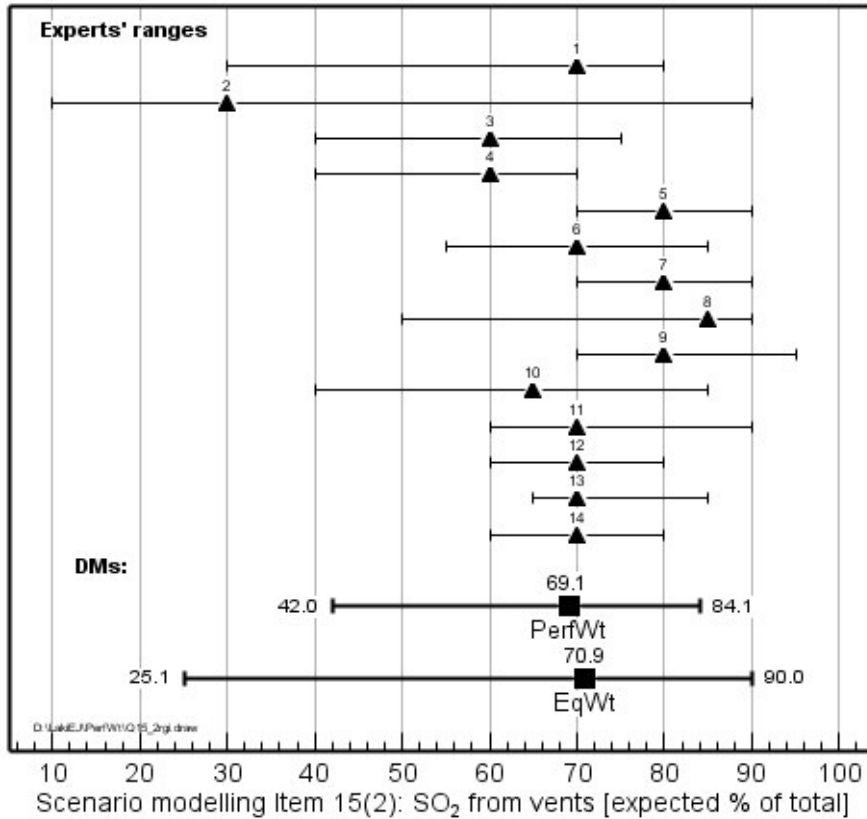5% quantile: 42.0%   median: 69.1%   95% quantile: 84.1%
Equal weights DM solution:
5% quantile: 25.1%   median: 70.9%   95% quantile: 90.0%

Comments: the two solutions appear reasonably consistent with one another – the Equal weights solution has wider uncertainty than the Performance-based weights solution, mainly due to the influence of Expert 2. The latter, however, has a very wide credible range that has little net effect on the Performance-based weights DM solution.

16_1 What is the likely maximum number of fissure opening explosive phases during an eruption on the scale of Laki?

Scenario modelling Item 16(1): max. no. explosive phases
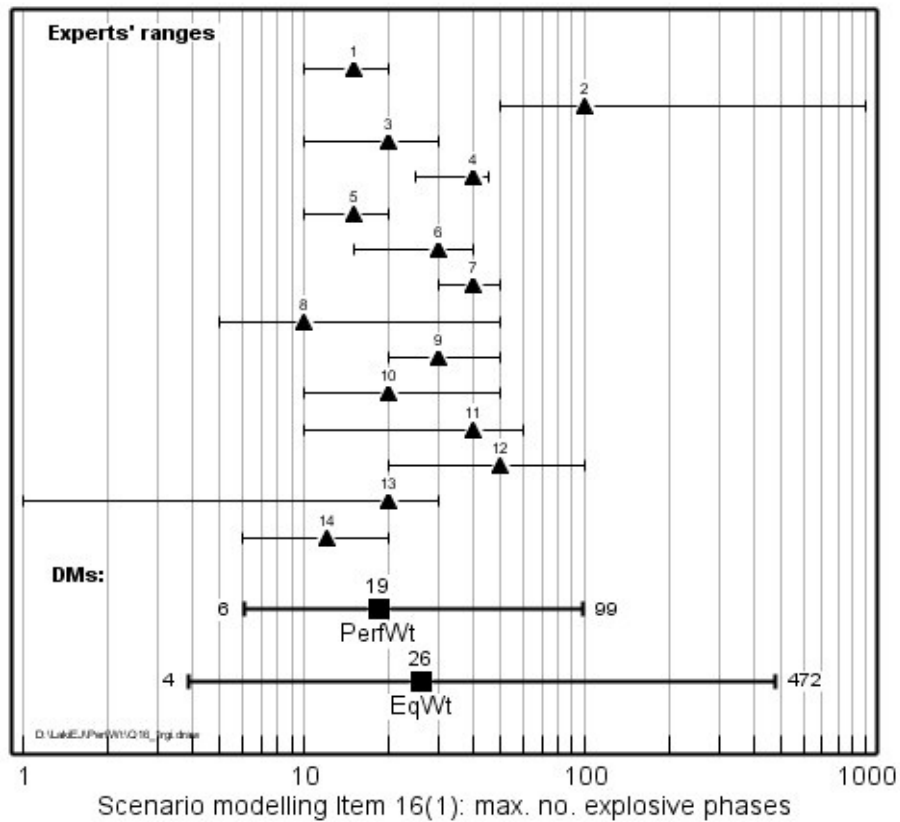
Performance-based DM solution:
5% quantile: 6   median: 19   95% quantile: 99
Equal weights DM solution:
5% quantile: 4   median: 26   95% quantile: 472

Comments: note log scale. The two DM solutions appear consistent with one another – the Equal weights solution has wider uncertainty than the Performance-based weights solution, due mostly to the distribution of Expert 2. The credible ranges of Experts 2 and 13 are very incongruous, and could suggest an issue with the definition of "explosive phases" in the question.

16_2 What is the likely average number of fissure opening explosive phases during an eruption on the scale of Laki?

Scenario modelling Item 16(2): expected no. explosive phases

Performance-based DM solution:
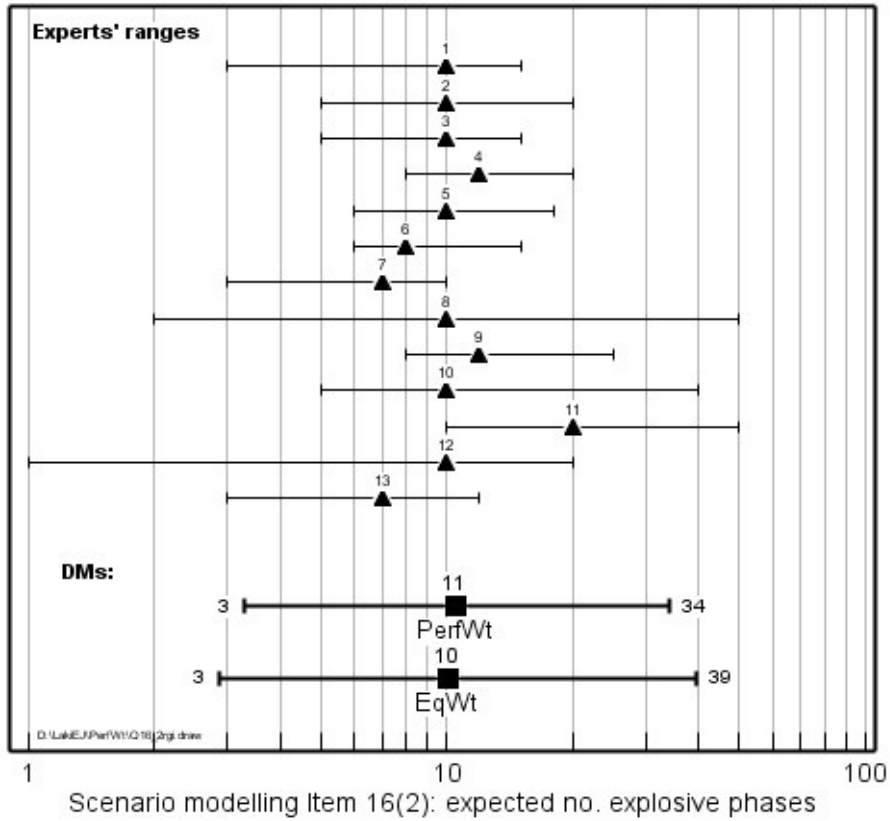5% quantile: 3   median: 11   95% quantile: 34
Equal weights DM solution:
5% quantile: 3   median: 10   95% quantile: 39

Comments: the two DM solutions appear reasonably consistent with one another – the Equal weights solution has wider uncertainty than the Performance-based weights solution. Note log scale compresses appearance of individual uncertainty spreads.

16_3 What is the likely minimum number of fissure opening explosive phases during an eruption on the scale of Laki?

Scenario modelling Item 16(3): minimum no. explosive phases

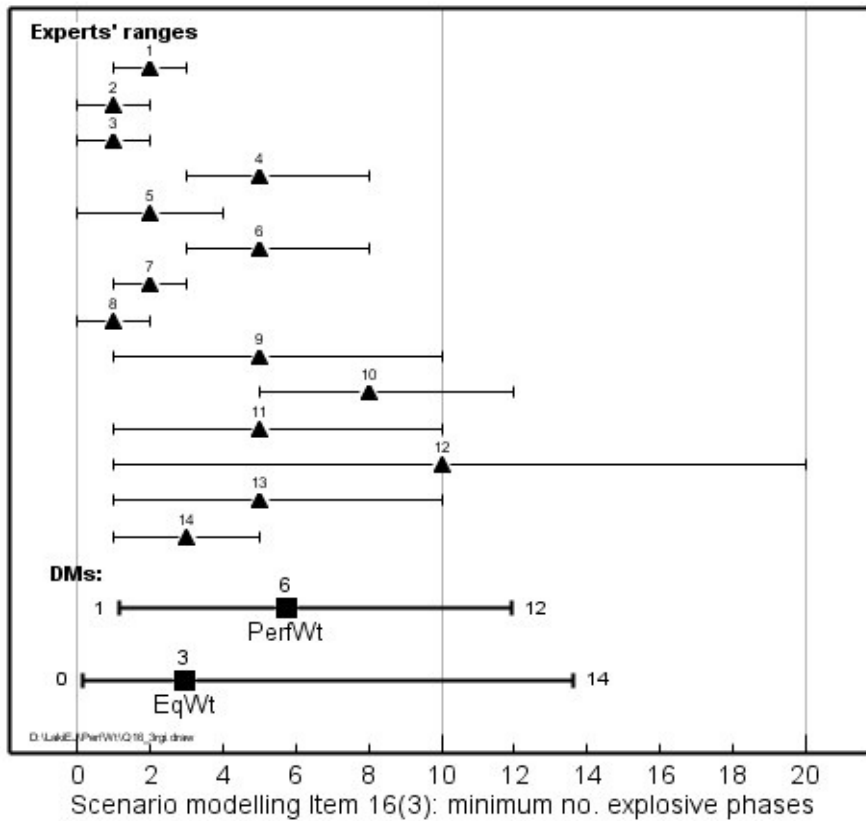Performance-based DM solution:
5% quantile: 1   median: 6   95% quantile: 12
Equal weights DM solution:
5% quantile: 0   median: 3   95% quantile: 14

Comments: the two DM solutions appear reasonably consistent with one another – the Equal weights solution has wider uncertainty than the Performance-based weights solution. Across the expert group there is a hint of a three-way split, in terms of the number of explosive phases to adopt for modelling purposes. Again, this may stem from issues with question definitions, and might benefit from further consideration.

17. What is the likely duration of the explosive phase of a fissure-opening episode?

Scenario modelling Item 17: fissure-opening explosive phase duration [days]
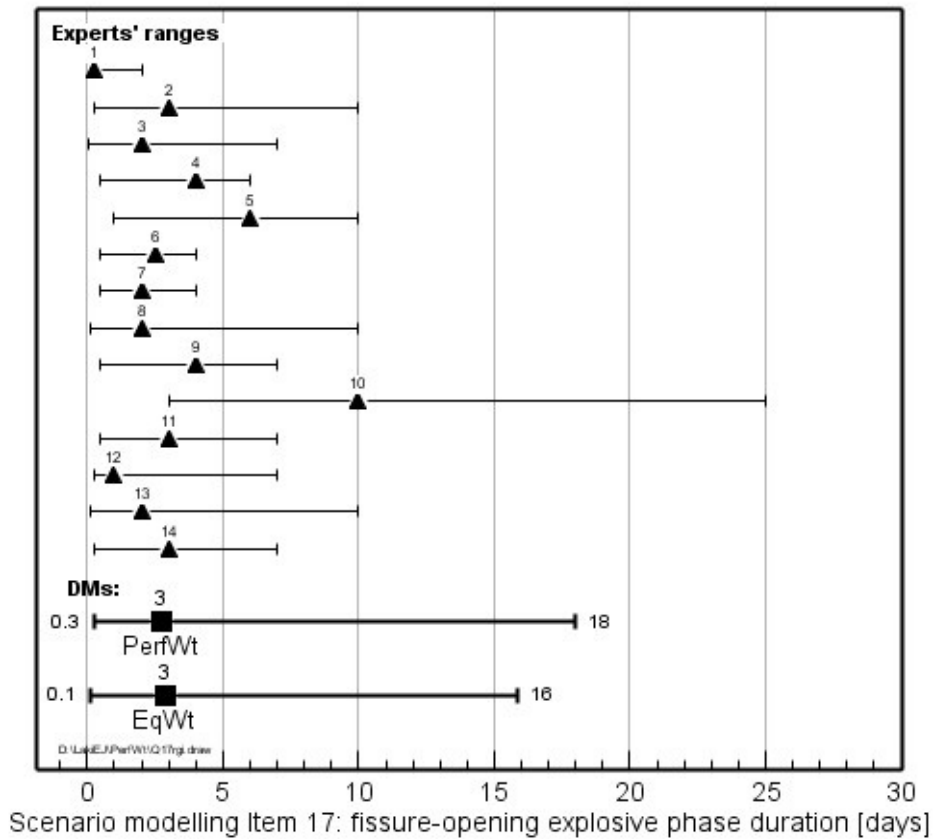
Performance-based DM solution:
5% quantile: 0.3 days   median: 2.7 days   95% quantile: 18.0 days
Equal weights DM solution:
5% quantile: 0.1 days   median: 2.9 days   95% quantile: 15.8 days

Comments: this Item is unusual in that the performance-based weights DM solution has a slightly greater uncertainty spread than the Equal weights counterpart, due to the distribution provided by Expert 10. This excepted, the two DM solutions are very similar.

18. What is the typical gap between major gas outburst episodes?

Scenario modelling Item 18: typical gap between major gas episodes [days]

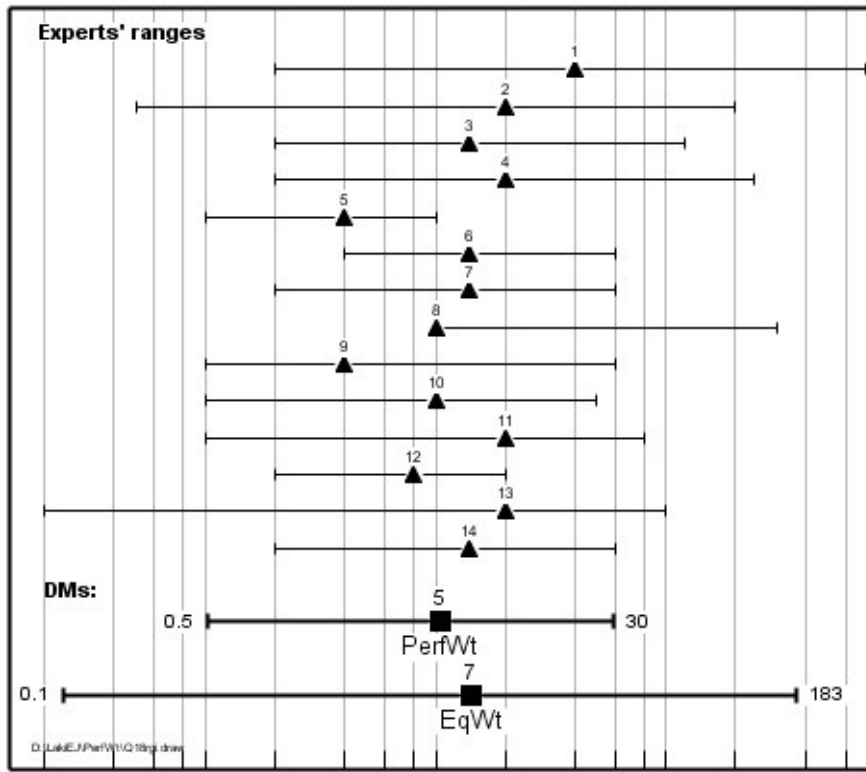Performance-based DM solution:
5% quantile: 0.5 days   median: 5.2 days   95% quantile: 30 days
Equal weights DM solution:
5% quantile: 0.1 days   median: 7.2 days   95% quantile: 183 days

Comments: note log scale. There are very wide uncertainties expressed in relation to this
factor. The performance weights DM solution suggests the typical (i.e. average)
duration would be about 5 days, with a 90% confidence range spanning half-a-day to
30 days for the variety of durations. The Equal weights DM solution encompasses a
much wider range, but with similar median value (7 days).

19_1 <u>For phreatomagmatic</u> activity, what is the likely % of total erupted volume?

Scenario modelling Item 19(1): expected proportion total erupted volume from phreatomagmatic activity [%]
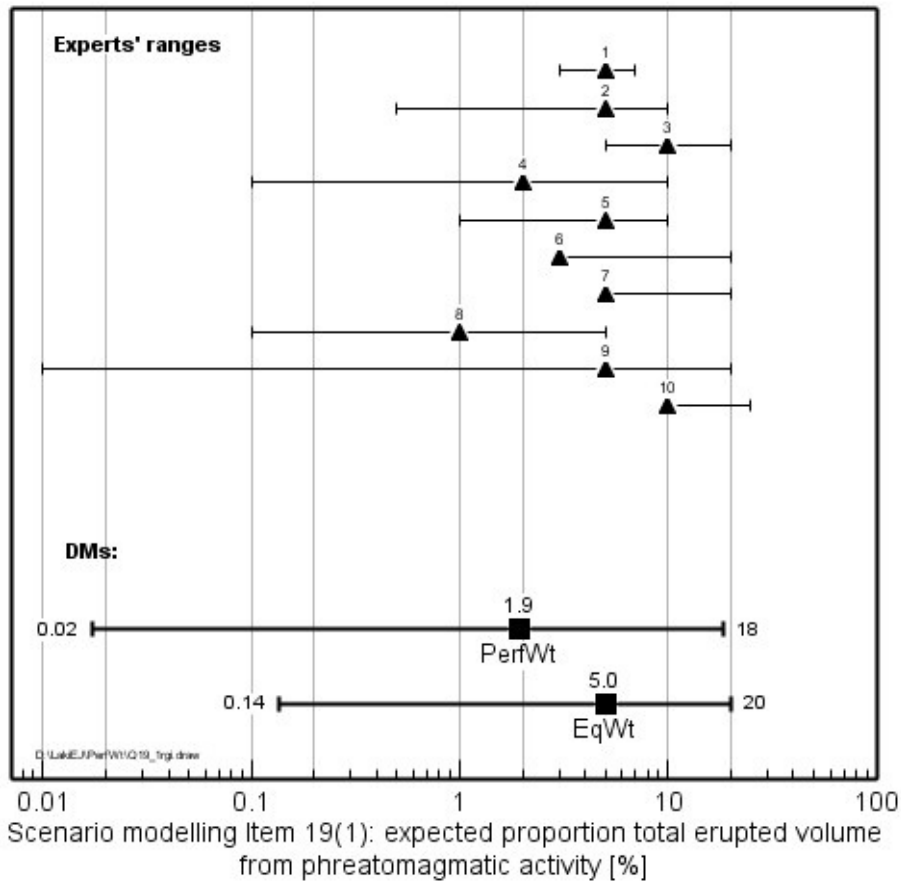
Performance-based DM solution:
5% quantile: 0.02%   median: 1.9%   95% quantile: 18.4%
Equal weights DM solution:
5% quantile: 0.14%   median: 5.0%   95% quantile: 20.0%

Comments: note log scale. The Performance-based DM solution is strongly influenced in this case by Expert 9 – in particular with regard to a long tail to low percentage values. This does not seem irrational if the possibility exists that, under certain circumstances, there may be little or no phreatomagmatic activity during the scenario eruption; other experts may not have considered this, or may have reasons for arguing it is extremely unlikely. Thus, there is a knowledge/judgement issue here.

19_3 <u>For phreatomagmatic</u> activity, what is likely maximum eruption column height?

Scenario modelling Item 19(3): max. column height
in phreatomagmatic activity[km]
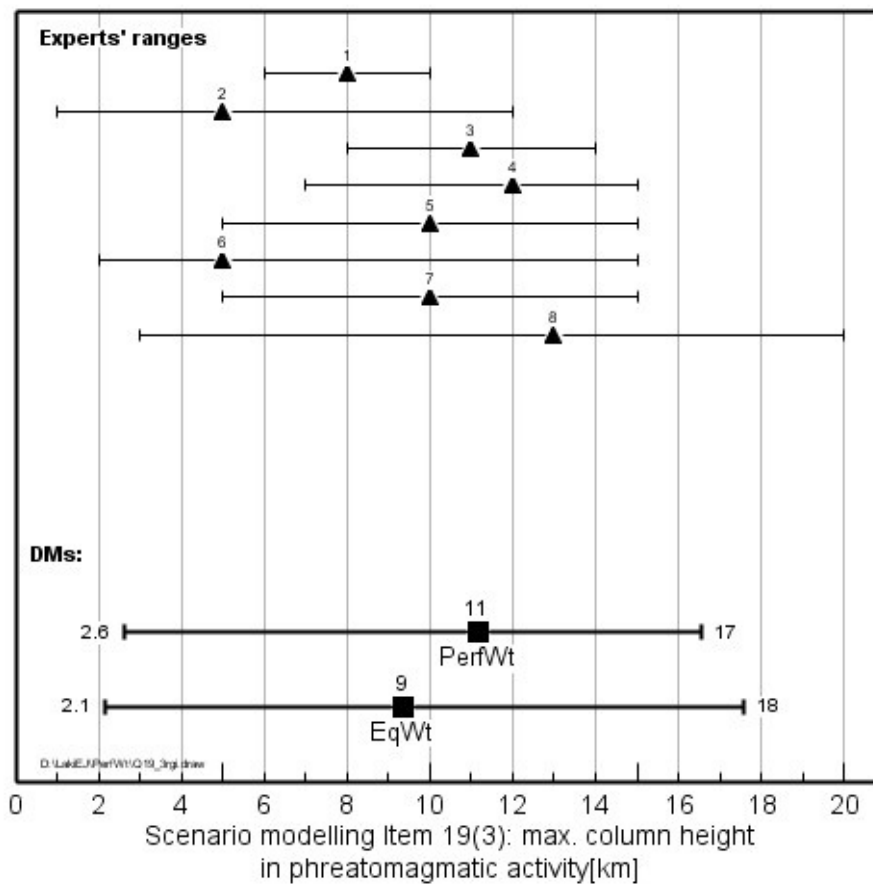
Performance-based DM solution:
5% quantile: 2.6km   median: 11.2km   95% quantile: 16.6km
Equal weights DM solution:
5% quantile: 2.1km   median: 9.3km   95% quantile: 17.6km

Comments: the two solutions appear reasonably consistent with one another – the Equal
    weights solution has fractionally wider uncertainty than the Performance-based weights
    solution, as is usual. The individual medians suggest a hint of a "two schools of
    thought" issue here for phreatomagmatic activity column height expectations.

24_1 What is the expected minimum ash volume produced w.r.t. the total erupted tephra volume (answer in % of the total erupted tephra volume)?

Performance-based DM solution:
5% quantile: 0.02%   median: 0.7%   95% quantile: 10.8%
Equal weights DM solution:
5% quantile: 0.09%   median: 6.7%   95% quantile: 19.7%

Comments: note log scale. This is clearly a very uncertain and debatable aspect for scenario modelling, and may benefit from discussion and clarification of controlling factors.

24_2 What are the expected maximum ash volume produced w.r.t. the total erupted tephra volume (answer in % of the total erupted tephra volume)?
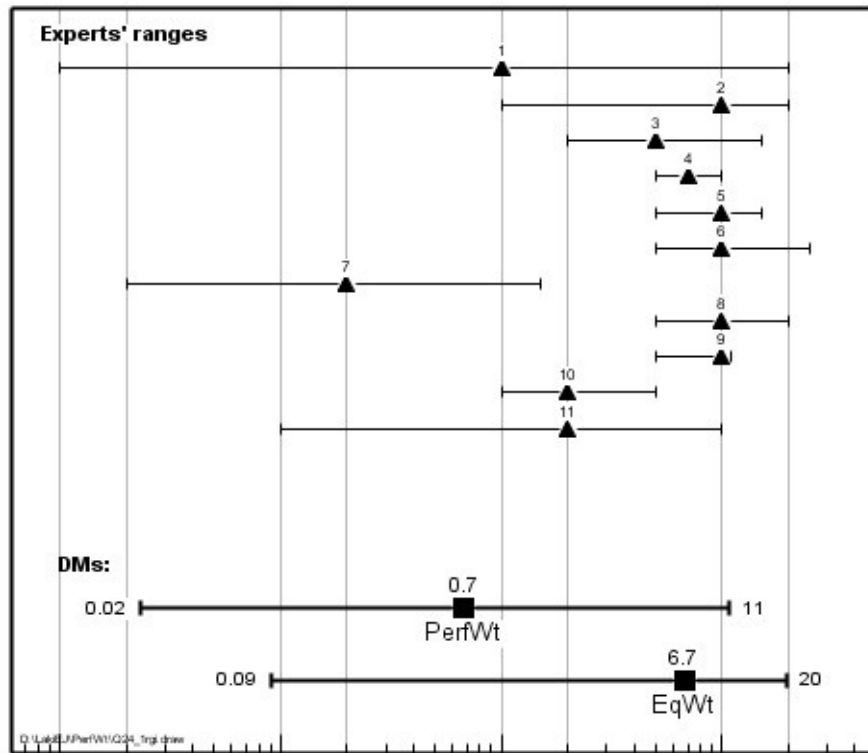
Scenario modelling Item 24(2): max. volume proportion ash to tephra [%]

Performance-based DM solution:
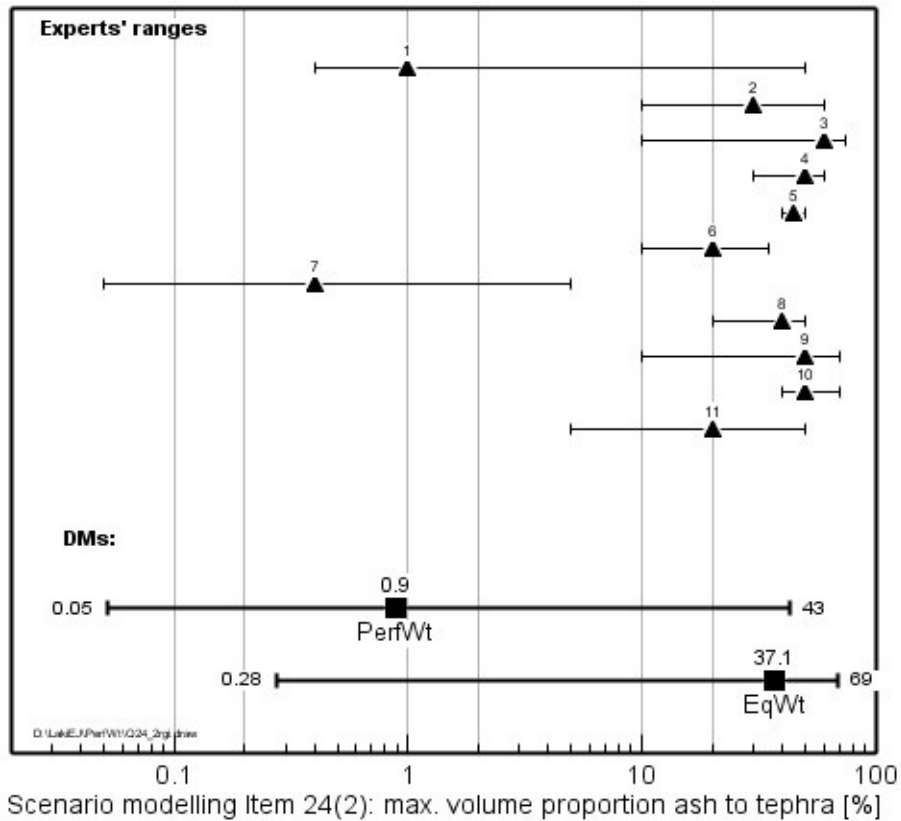5% quantile: 0.05%   median: 0.9%   95% quantile: 43.0%
Equal weights DM solution:
5% quantile: 0.3%   median: 37.1%   95% quantile: 68.9%

Comments: note log scale. As with the minimum volume proportion of ash to tephra Item (24_1) above, this is clearly a very uncertain and debatable aspect for scenario modelling, and may benefit from clarification of controlling factors.

42_1 What is the typical e-folding time of SO₂ in the atmosphere (troposphere) in the winter within a Laki-like plume?
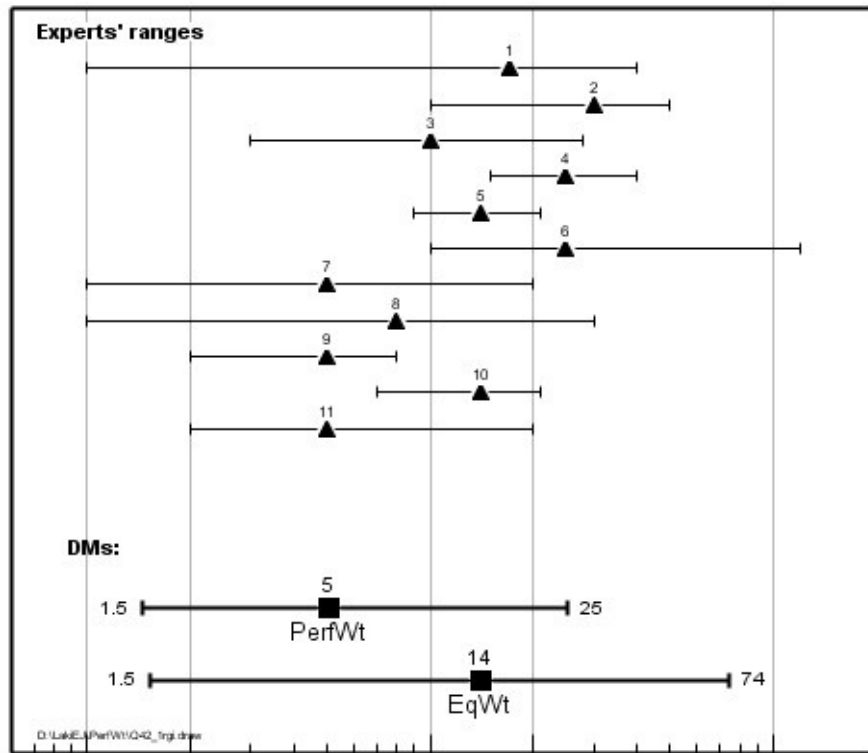
Scenario modelling Item 42(1): e-folding time SO₂ in winter atmosphere [days]

Performance-based DM solution:
5% quantile: 1.5 days   median: 5.1 days   95% quantile: 25 days
Equal weights DM solution:
5% quantile: 1.5 days   median: 14 days   95% quantile: 74 days

Comments: note log scale. The two DM solutions differ somewhat from one another; the Equal weights solution has a higher median and much wider uncertainty than the Performance-based weights solution.

42_2 What is the typical e-folding time of SO_2 in the atmosphere (troposphere) in the summer within a Laki-like plume?

Scenario modelling Item 42(2): e-folding time SO_2 in summer atmosphere [days]

Performance-based DM solution:
5% quantile: 1.0 days   median: 2.2 days   95% quantile: 17 days
Equal weights DM solution:
5% quantile: 1.0 days   median: 8.4 days   95% quantile: 38 days

Comments: : note log scale. Again, as with the previous Item, the two DM solutions differ from one another; the Equal weights solution has a higher median and wider uncertainty than the Performance-based weights solution

43_1 What is the e-folding time of SO_4 in the atmosphere (troposphere) in winter within a Laki-like plume?

Scenario modelling Item 43(1): e-folding time SO_4 in winter atmosphere [days]
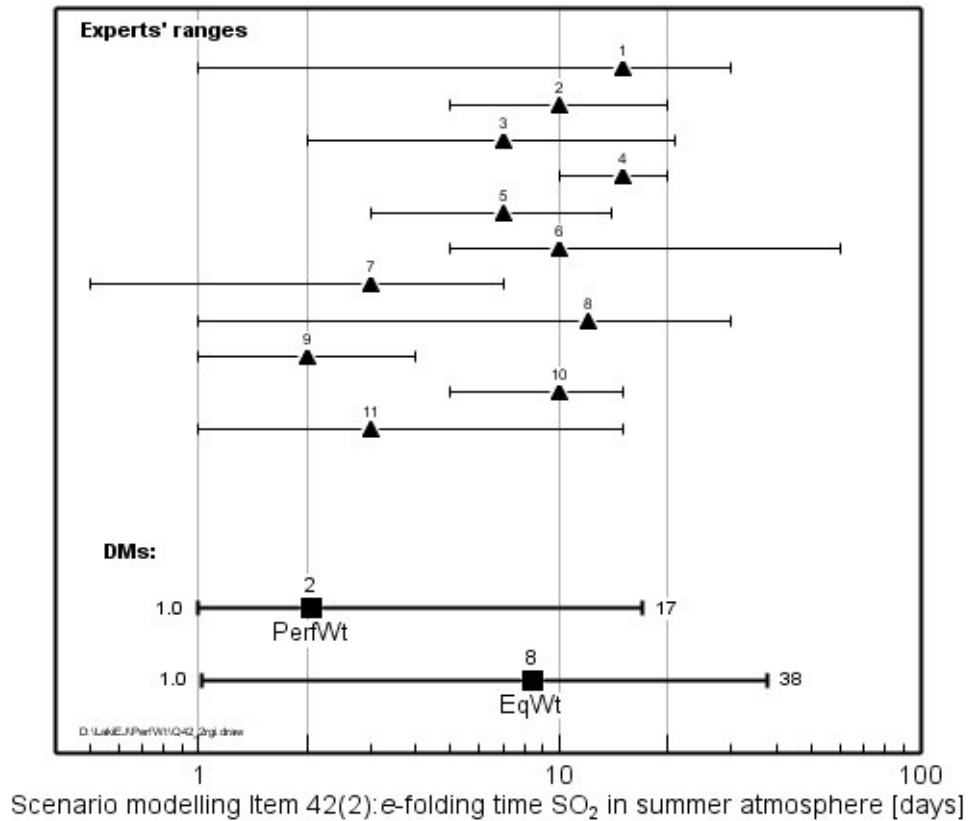
Performance-based DM solution:
5% quantile: 2.0 days   median: 7.2 days   95% quantile: 29 days
Equal weights DM solution:
5% quantile: 0.6 days   median: 8.4 days   95% quantile: 270 days

Comments: note log scale. Here, the two DM solutions differ from one another significantly in terms of uncertainty spreads, even though the medians are similar. Expert 4 may have grounds for believing SO4 is long-lived, and this apparent knowledge gap might be explored.

43_2 What is the e-folding time of SO_4 in the atmosphere (troposphere) in summer within a Laki-like plume?

Scenario modelling Item 43(2): e-folding time SO_4 in summer atmosphere [days]
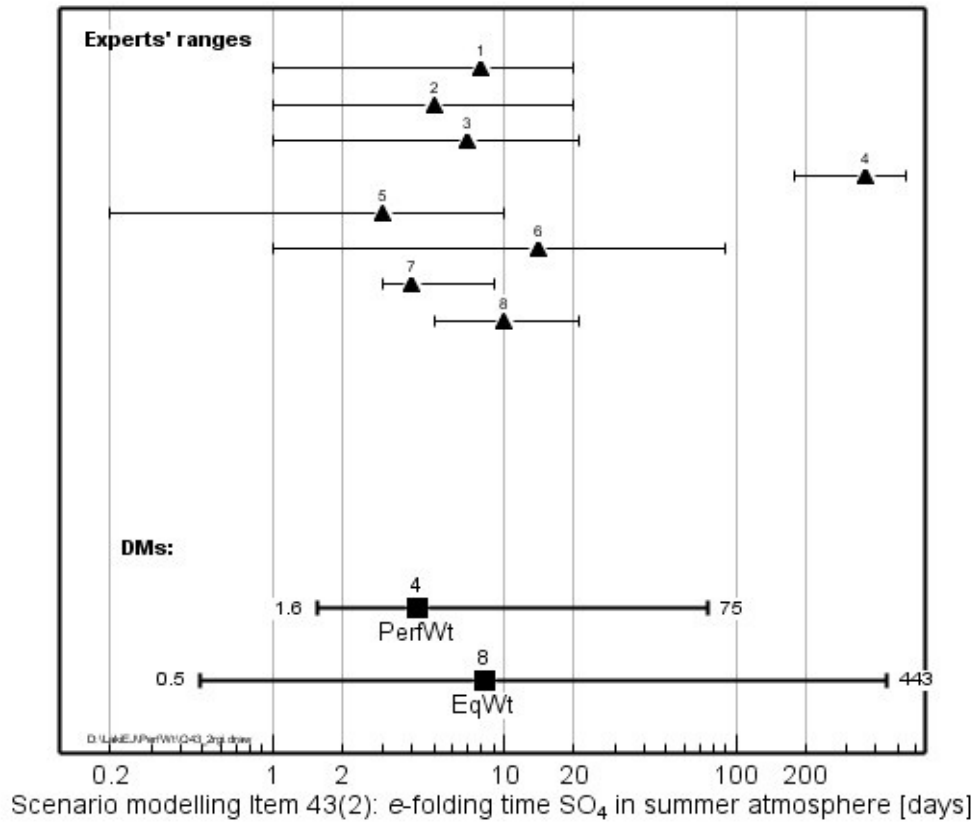
Performance-based DM solution:
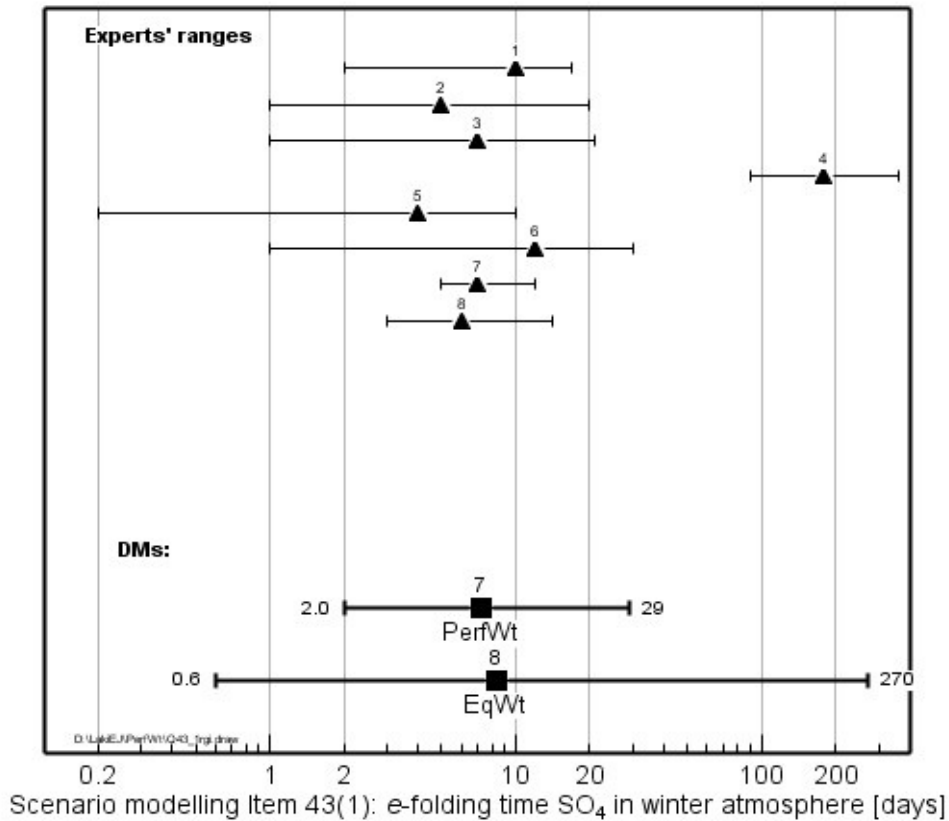5% quantile: 1.6 days   median: 4.2 days   95% quantile: 75 days
Equal weights DM solution:
5% quantile: 0.5 days   median: 8.2 days   95% quantile: 443 days

Comments: same comments as for previous Item.

45S By how much [expressed as %] does proximal adsorption on ash reduce the volcanic gas
   concentrations of S in the plume?

Scenario modelling Item 45S: reduction of S by ash adsorption [%]
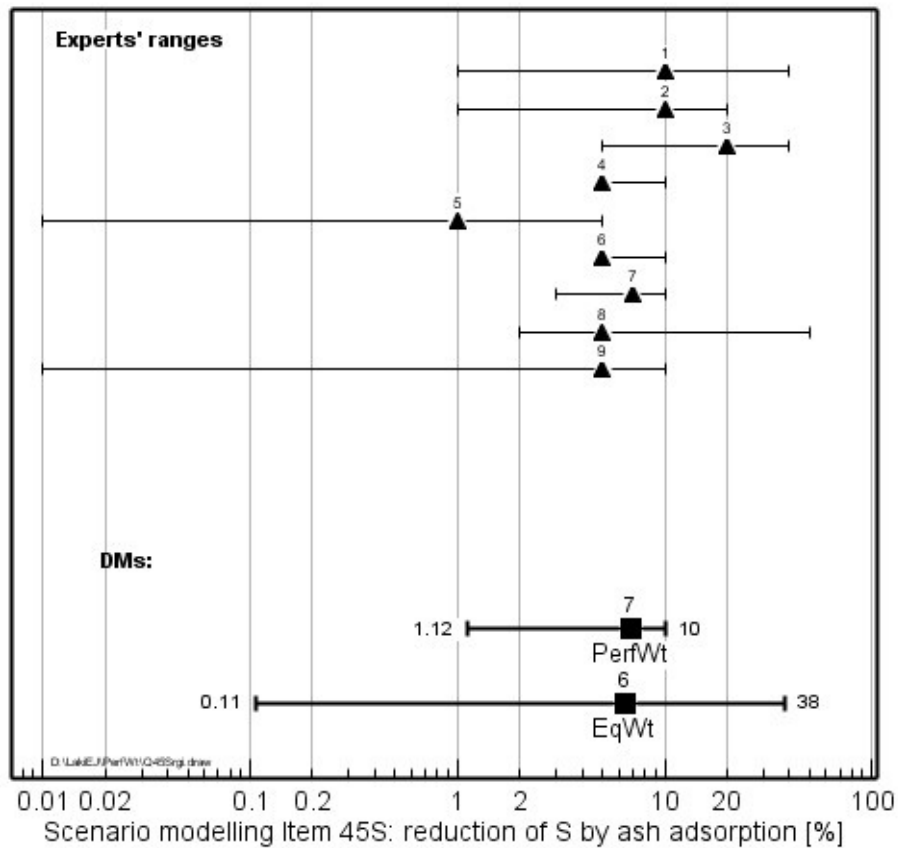
Performance-based DM solution:
5% quantile: 1.1%   median: 6.8%   95% quantile: 10.0%
Equal weights DM solution:
5% quantile: 0.1%   median: 6.4%   95% quantile: 38.2%

Comments: in this Item, two Experts (5, 9) with relatively low individual weights provide
   distributions which encompass a prospective situation in which there might be
   negligible adsorption of S onto ash in the initial conduit/plume phase; this suggests
   some clarification of the circumstances, and perhaps also the question definition, would
   be helpful.

45F By how much [expressed as %] does proximal adsorption on ash reduce the volcanic gas
concentrations of F in the plume?

Scenario modelling Item 45F: reduction of F by ash adsorption [%]
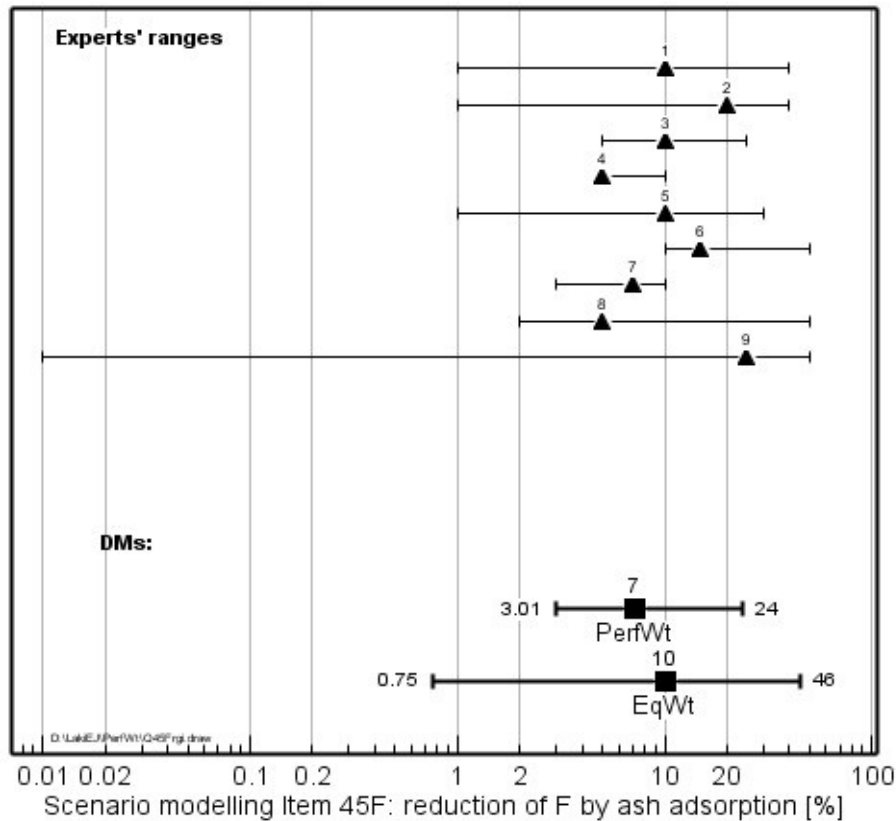
Performance-based DM solution:
5% quantile: 3.0%   median: 7.1%   95% quantile: 23.9%
Equal weights DM solution:
5% quantile: 0.8%   median: 10.0%   95% quantile: 45.6%

Comments: in this Item, Expert 5 offers a different judgement compared to his/her view on
Item 45S above, whereas Expert 9 persists with a distribution which encompasses
negligible adsorption of F onto ash in the initial conduit/plume phase (albeit with a much
higher median value).   Again, this suggests some clarification of the circumstances,
and perhaps also the question definition, would be helpful.

APPENDIX D. Qualitative questions

These questions were posed during a qualitative session where participants discussed the questions and completed a form with written answers. The feedback from this session is incorporated into the report, especially Chapter 6 and the recommendations.

1. **How can air concentrations of gas/aerosol a) at the source and b) in the far-field be effectively monitored using research or other aircraft, sondes, lidars etc?**

2. **What is UK capability to monitor far-field concentrations of SO_2, SO_4 and other species, with a sufficiently fast repeat sampling rate?**

3. **Is there always a relationship between erupted magma volume and gas emission for flood lavas or is excess sulphur possible (eg from degassed, unerupted shallow intrusions)?**

4. **What are the upper and lower standard errors on the SO_2 estimates when using different methods for historic eruptions (eg petrological)?**

5. **What is the time variation by species in the rate of emission of gases throughout a fissure-opening episode and through an entire flood lava sequence?**

6. **Which species [H_2O, CO_2, SO_2, H_2S, HBr, HI, Hg, HNO_3, HCl, HF, NH_3, H_2, He, N_2, Ar, *others* ….] can actually be monitored?**

7. **In terms of the numerical modelling of the far-field impacts of a Laki-type eruption, for (a) degassing and (b) ash production, what geometry in terms of shape/dimensions best represents the (i) fissure; (ii) lava flows; (iii) explosive vent (e.g., area source, line source, point source)?**

8. **What chemical reactions are most relevant in the near-field plume/far-field plume for modelling*? Supplementary question 'What species can be modelled effectively without considering the chemical reactions or by considering them in some greatly simplified way?***

9. **What mechanisms are important for vertical (up and down) transport and which removal processes dominate for individual species (SO_2, SO_4 aerosol, H_2S, HCl, HF, NH_3, etc,)? Alternative wording: *What model processes, other than chemistry and deposition which are dealt with separately, are important?***

10. **Is it important to account for the physical and chemical interactions (e.g., adsorption) between volcanic gases and volcanic ash when using numerical models in order to correctly predict deposition/airborne concentrations in the UK during Laki-type events?**

11. **What is the role of processes such as aggregation during explosive phases of Laki-type events in comparison to say Eyjafjallajokull 2010?**

12. **Is it important to account for aerosol microphysical processes such as nucleation, coagulation and condensation when using numerical models in order to correctly predict volcanic sulphate aerosol concentrations/SO_2 mixing ratios?**

13. **What is air pollution in the UK going to 'look like', will it be patchy temporally and spatially, or persistent and what would be the main control on this?**

14. **Is eruption season/time of day important for atmospheric dispersion/in-plume and far-field plume chemistry?**

15. **How many meteorological situations need to be considered to give a plausible range of model outcomes?**

16. **How do we validate models for species added to chemistry schemes?**

17.   **What influence would the lava heat source have on local meteorology?**

18. **Can these local impacts be incorporated into the source term information?**
19.   **For considering long-range impacts, what temporal/spatial resolution of the source characteristics is required to accurately simulate concentrations of sulphur species/halogens in (i) the near-field, and (ii) a far-field plume?**

20.   **For considering long-range impacts, what temporal/spatial model resolution is required to accurately simulate SO_2 and SO_4 aerosol concentrations in the near-field/far-field plume?**

21.   **What level of modelling is required and is it possible to answer some/certain questions with more 'limited' modelling?** For example: performing non chemically reactive simulations is much faster and easier. These results would: inform regarding the probability of UK impact; allow some concentrations to be evaluated; etc.

22.   **While this is not perfect it may be adequate and stimulates the further question: Is it practicable to consider some of the chemical species without using chemical reactions?**

APPENDIX E: Glossary

Acid rain   Rain with a pH ranging from 2 to 4. Pure water in equilibrium with atmospheric CO_2 has a pH of 5.6.

Aerosol   Suspension of solid or liquid particles in the air ranging in size from a few nanometres (nm) to around 100 micrometres (μm) in diameter.

Albedo   The term 'surface albedo' refers to the reflectivity of the surface, ranging from 0 (perfectly absorbing) to 1 (perfectly reflecting), which is important in determining surface temperature. The Earth's planetary albedo is the fraction of the Sun's incoming radiation that reflects off the Earth and back into space.

Ash (volcanic)   Fine fragments of volcanic rock smaller than 2mm in diameter produced during explosive eruptions.

Basalt/Basaltic   Volcanic rock or magma with relatively low total SiO_2 content (45 – 52 wt%), relatively low Na_2O and K_2O and relatively high FeO and MgO.

Central volcano   A volcanic edifice constructed over time by the eruption of lava flows and fragmental pyroclastic material. There may be considerable variation in the composition of erupted magmas.

Cloud Condensation Nuclei (CCN)   Hygroscopic aerosol particles onto which water vapour can condense to form cloud drops.

Conduit   A subsurface passage followed by magma in a volcanic system.

Continental flood basalt (CFB) provinces   Large volumes of basalts of predominantly tholeiitic *(Tholeiite)* composition forming extensive sheet flows with a few intervening sedimentary deposits. CFBs are thought to have been erupted in geologically short periods of time at high extrusion rates.

Degassing   The process by which magma loses its dissolved volatile species and gases are released to the atmosphere. A volcano can degas with no ongoing extrusion of magma (passive degassing).

Dense Rock Equivalent (DRE) Erupted magmas vary substantially in terms of bubble content, so erupted magma volumes are often calculated assuming no bubble content to enable comparison. See Eruption size (volume).

Dry deposition   The removal of particles or molecules by settling on or sticking to ground-level surfaces (e.g. soils, vegetation, water, vehicles, infrastructure).

Dyke   A dyke is a sheet-like body of magma that rises through an existing fracture or creates a new crack as it rises to the surface.

Effusive eruption   An eruption dominated by the outpouring of lava onto the ground is sometimes referred to as an effusive eruption. Here we use the definition of Thordarson and Larsen, 2007 (>95% of the erupted magma is lava). See also 'explosive eruption'.

Eruption size (magnitude)   A very good way to compare different types of eruption is to use the formula   Magnitude = $\log_{10}$ (erupted mass, kg) – 7   (Pyle, 2000).

Eruption size (volume)   A widely accepted measure of the size of an eruption is the volume of magma ejected as pumice and ash (tephra) during an explosive phase or the volume of lava extruded during an effusive phase. Eruption volumes are commonly expressed in cubic kilometers (km^3). One km^3 is roughly equivalent to 0.24 cubic miles. Estimates of the tephra volumes are usually obtained by mapping the distribution and thickness of the tephra deposits on the ground after the eruption is over. Tephra volumes measured in this way must then be corrected for void spaces (bubbles within the pumice, empty spaces between individual chunks of pumice or ash) to get an estimate of the original volume of lava erupted. This correction can be made by comparing the bulk density of the tephra deposit with the known density of the rock-type that makes up the tephra. The result is referred to as the "dense rock equivalent" or DRE of the erupted volume.

Explosive eruption   Any eruption in which the magma is torn into fragments (fragmentation) by gas pressure or interaction with water as it leaves the vent. A definition used in this report assumes >95% of the erupted magma is tephra in order for the eruption to be described as explosive.

Fire fountain/Lava fountain   A jet of lava sprayed into the air by the rapid expansion of gas bubbles and fragmentation of magma. Lava fountains typically range from about 10 to 100 m in height, but occasionally reach more than 500 m.

Fissure   A fissure is an elongate fracture or crack at the Earth's surface from which an eruption occurs. Multiple parallel eruption fissures produced by multiple eruptions or eruption episodes form an elongate **fissure swarm**.

Fissure eruption   An eruption from an elongate fissure rather than a central vent that commonly comprises lava flows and fire fountains (small magnitude explosions). After a period of hours or days activity tends to focus at a number of central vents along the fissure.

Flood lava/basalt   Very large-volume eruptions of basaltic lava flows linked to some extinction events(see also continental flood basalt provinces).

Fragmentation   Magma may be fragmented within the eruptive conduit and during eruption by a rapidly expanding gas phase. At depth the gas is dissolved in the magma, during decompression as the magma rises, the gas exsolves to form bubbles. If the magma is low viscosity (e.g. basalts) and rising slowly, the gas may escape before eruption leading to only minor fragmentation during eruption (e.g. fire fountains). However, if magma is viscous (silicic), or rising quickly, the bubbles remain in-situ and continue to expand and blast the magma apart during eruption. If magma interacts with ground or surface water this also results in explosions that effectively fragment the magma/lava.

Holocene   Geological epoch which commenced ~ 11,700 years before present.

Hydromagmatic eruption   An eruption involving the interaction of water and magma.

Lava Molten rock expelled at the Earth's surface by volcanic processes.

Lava fountain/fire fountain   A jet of lava sprayed into the air by the rapid expansion of gas bubbles and fragmentation of magma. Lava fountains typically range from about 10 to 100 m in height, but occasionally reach more than 500 m.

Mafic rocks   Contain high proportions of minerals rich in MgO, FeO, and CaO, i.e. olivine, pyroxene, amphibole and biotite. Basalt is a mafic rock.

Magma   Natural silicate melt with or without suspended crystals and bubbles.

Mortality rate   A measure of the frequency of occurrence of death in a defined population during a specified time interval (Centre for Disease Control and Prevention, 2011).

Orographic clouds   Clouds that develop in response to the forced lifting of air by the earth's topography causing cooling of air and condensation of water vapour.

Petrological studies (SO_2 calculation) A method that uses the difference between the volatile component in a pre-eruptive melt (glassy melt inclusion) and in a post-eruptive melt (matrix glass) used to determine the amount of a volatile component released per kg of erupted magma.

Phreatomagmatic   Explosive volcanic activity resulting from e interaction between magma/lava and groundwater, surface water or ice meltwater. The original definition referred only to the interaction of magma and groundwater but it is now widely used for any explosive activity caused by water-magma/lava interaction.

Pyroclastic   Pyroclastic rocks (consolidated) or deposits (unconsolidated) are fragmentary or 'clastic' and made entirely of volcanic material. The size of the fragments is important for classification: 'volcanic ash' (<2mm), 'lapilli' (2-64mm) and 'volcanic bombs' (>64mm) are the specific terms for fragments of different sizes. See also 'tephra'.

Rift zone   A rift zone is an elongate system of crustal fractures associated with an area that has undergone extension (ground has spread apart). A rift zone consists of many different features associated with the rise and eruption of magma from narrow dykes, including eruptive fissures, cinder and spatter cones, spatter ramparts, pit craters, lava flows, ground cracks, and normal faults.

Scoria   Pyroclasts containing bubbles which are typically several millimetres in diameter.

Spatter cones / rampart   Lava fountains that erupt from an elongate fissure will build broad embankments of spatter, called spatter ramparts, along both sides of the fissure.

Stratosphere The region of the atmosphere above the troposphere between 10–17 km and 50 km.

Strombolian eruption Eruption with a low-viscosity basaltic magma featuring a series (often rhythmical) of moderate explosions and/or fountaining of lava above a vent or crater.

Subaerial Volcanism that occurs at the Earth's surface with no water or ice present.

(Sub-)Plinian activity A type of explosive eruption that typically generates sustained high convective ash plumes.

Tephra When magma is erupted explosively it breaks up into fragments of various sizes, the collective term for fragments that have fallen to the ground from the air and are unconsolidated is tephra, regardless of the size of the fragments.

Troposphere The lowermost portion of the atmosphere from the Earth's surface to the tropopause. The troposphere is the portion of the atmosphere where most the clouds and weather occurs.

Tropopause Boundary between the troposphere and stratosphere ranging from 9 km at high latitudes to around 16 km in the tropics.

Volatile An element or compound such as H_2O or CO_2 that forms a gas at relatively low pressure and magmatic temperatures. Volatiles can be dissolved in silicate melts and can occur as bubbles of exsolved gas.

Volcano The definition of "volcano" has varied widely, with "volcano" applied to individual vents, measured in meters, through volcanic edifices measured in tens of kilometers, to volcanic fields measured in hundreds of kilometers. In Iceland, 'volcanic system' is commonly used to describe both central volcanoes and their associated fissure swarms.

Volcanic activity Includes *the* transport of magma through the Earth's crust and its expulsion in the form of lava and/or pyroclasts at the surface of a planet.

Volcanism Processes linked to volcanic activity.

Vent Surface opening from which volcanogenic material is erupted.

Volcanic sulphate aerosol Small droplets of sulphuric acid (H_2SO_4) formed in the atmosphere from oxidation of sulphur-rich gases. A composition of 75wt% of H_2SO_4 and 25wt% of H_2O is commonly assumed for volcanic sulphate aerosol in the stratosphere. It is assumed that the volcanic aerosol exists as $H_2SO_4.2H_2O$ which is equivalent to 73wt% of H_2SO_4 and 27wt% of H_2O.

Wet deposition Removal of aerosols, particles and gases present in the atmosphere through precipitation such as rainfall.

APPENDIX F: Volcanic Gas and Ash UK Ground level Monitoring Capability

1. Introduction

In the event of a volcanic eruption there are certain information prerequisites which should allow the UK to forecast the impact on the UK surface environment and to monitor the actual impact of the volcano plume as an eruption event proceeds, specifically to allow the risks to humans, agriculture, animals and ecosystems to be assessed in a timely fashion. One way the prerequisites categorised is the following:

1.   The" initial" plume chemical composition (gas and particulate)
2.   Physical plume transport to the UK
3.   Chemical transformation processes in the volcano plume during plume transport and as it mixes with background air
4.   the background composition of the UK air and surface constituents(including vegetation and surface waters)
5.   Prepared plan for obtaining the relevant environmental information as the volcano plume (or its ash fallout) reach the UK ground level.

This appendix outlines the current capabilities and some issues which need to be addressed for prerequisite 1, 4 and 5 to be sufficient to enable the UK to respond to a future volcanic eruption. For the purposes of this report, the plume is understood to consist of gases, refractory particulate (volcanic ash), and other non-refractory aerosol (such as primary sulphuric acid aerosol, often referred to in the literature as sulphate aerosol).

2. Initial plume composition

The plume composition can potentially be measured at any point from when the plume enters the atmosphere, i.e. at the vent of the volcano, through when the plume is at the height at which the plume hast neutral buoyancy and begins to be entrained in the atmospheric circulation, anywhere downwind, including grounding points in the UK. These measurements are not the primary focus of this report.

The major potential constituents of a volcano plume, a range approximate near field concentrations and relevant measurement techniques are summarised in Table 1. The capability to initialise models by using direct measurements from the Icelandic volcanoes which were accurate would allow a better understanding of the chemical evolution of the plume downwind.

3. Normal UK atmospheric composition and current environment monitoring activities relevant to volcano plume constituents.

3.1 Atmosphere

The major potential constituents of a volcano plume, a range approximate far field (i.e. UK surface) concentrations and relevant measurement techniques are summarised in Table 2. There is a considerable uncertainty as to which chemical species may reach the UK at sufficient concentrations

to cause local effects. The three constituents which are most likely to have measureable levels and impacts are SO_2, ash particulate and sulphate particulate. It is also likely that HF whether in the gas phase or adsorbed onto the ash is of primary concern given the potential health and environmental impacts. Several species are likely to be present and of concern but the understanding of these are less certain, these include HCl, HBr, H_2S and Hg.

In the UK Defra, the Devolved Administration and various UK Governmental Agencies fund air quality monitoring activities. This report does not attempt to summarise all of these activities, but notes the major UK wide monitoring networks whose data would be of use in the event of a volcano plume affecting the UK surface environment. These can be separated into two types of monitoring site – those with high resolution (hourly or daily information) and more time average information (weekly – monthly measurements).

3.1.1 High time resolution measurement: UK capabilities

The AURN is the UK's largest automatic monitoring network and is the main network used for compliance reporting against the Ambient Air Quality Directives. The AURN sites provide hourly concentration information which is available in real time. The AURN monitoring stations measure oxides of nitrogen (NOx), sulphur dioxide (SO_2), ozone (O_3), carbon monoxide (CO) and particles (PM_{10}, $PM_{2.5}$). The AURN site classifications and number of sites are summarised in Table 12. Further information on the AURN can be obtained from http://uk-air.Defra.gov.uk/networks/network-info?view=aurn and Bureau Veritas who operate the network.

In the event of a volcano plume grounding in the UK the SO_2 signal would be the clearest observable atmospheric chemical change, particularly if the increase was not accompanied by a significant increase in NO_x concentrations (which may indicate a polluted air mass rather than a volcanic signal). One may expect in addition that PM levels would increase however the relative change to background may be highly dependent on the type of monitoring site, for example the urban traffic sites would be the most difficult sites at which to interpret an increase in PM. There is also a small network of particle focussed measurements in the Particle Numbers and Concentrations Network

Table 12: AURN sites

Site Classification	Number of sites
Rural Background	13
Rural Background Agricultural	3
Rural Background Natural	7
Suburban Background	8
Urban Background	57
Urban Background Residential & Industrial	1
Urban Industrial	6
Urban traffic	36

The UK contributes to the European Monitoring and Evaluation Programme, which is a programme under the Convention on Long-range Transboundary Air Pollution for international co-operation to solve transboundary air pollution problems. The UK has two Level II EMEP sites, located at Auchencorth Moss (SE Scotland) and Harwell (Central England) which are funded via the Defra UKEAP project (http://pollutantdeposition.Defra.gov.uk/ukeap) and make a large suite of measurements, including being part of the AURN networks.

Table 13: Relevant high frequency measurements made at UK EMEP Supersites

Measurement	Method	Frequency
Water-soluble gases and particles at PM2.5 and PM10	IC	Hourly
Mercury (elemental) in air	CVAF	hourly
Mercury (speciated) in air (Auchencorth only)	CVAF	hourly
Ions in precipitation *Including fluoride*	Daily wet-only collector: I.C., pH, conductance	Daily
Particle size distribution (Auchencorth and Harwell)	SMPS	hourly
http://uk-air.defra.gov.uk/networks/network-info?view=particle		

3.1.2 Low time resolution measurement: UK capabilities

The major UK monitoring networks which make measurements relevant to volcano plume constituents are listed in Table 14. In particular UKEAP monitors the fortnightly inorganic ion composition of rain (though not fluoride) and the monthly average concentrations of HCl, SO_2 and particulate sulphate and chloride. The ECN network (http://www.ecn.ac.uk/) has measured the fluoride concentration in precipitation in addition to the standard ion suite since 2010.

Although weekly and fortnightly average measurements are not useful in an first phase response, in the case of a longer term Laki type eruption, these measurements will be the core measurement networks which would be sued to assess the national impact of concentrations and dry and wet deposition of volcanic constituents, from which impacts on ecosystems and agricultural land could be derived.

Table 14. Relevant high frequency measurements made in the UK

Network	Measurement	Frequency
UKEAP	Ions in precipitation	Fortnightly
	Acid gases and aerosol composition	monthly
ECN	Ions in precipitation including fluoride	weekly
Heavy Metals	Hg in air	weekly
	Heavy metals in particulates	monthly
	Heavy metals in precipitation	monthly

3.1.3 Mobile atmospheric measurement response capability

Though mobile atmospheric measurement capabilities are not deployed for routine monitoring, there are capabilities both within the Environment Agency , NERC, and other government sectors and the University to deploy mobile platforms.

3.1.4 Atmospheric Deposition

From all precipitation measurements it is possible to calculate a wet deposition value. With dry particulate and gas phase chemicals a deposition velocity is required to calculate the rate of deposition to a particular surface, and in particular the surface resistance varies significantly between vegetation, rock, soil etc.

3.2 Fresh water, Vegetation and Soils

CEH (NERC) has an analytical facility which in addition to other chemical species has a validated method to determine F$^-$ by ion chromatography in aqueous media (http://www.ceh.ac.uk/products/analyticalcapabilities.html). This method is susceptible to interferences from low molecular weight organic acids but it has an LOD of 15ug/L.

There are methods to determine fluoride in soil and plant material although these have not been used for 20 years since analysis of samples from aluminium smelters. CEH has reference samples in store and the method for F analysis was validated in 2010 as part of vegetation analysis during the Eyjafjallajökull eruption.

Detection limit would be in the region of 1 ug/g- this is based on the lowest standard and taking a sample mass of 10g air dried herbage sample.

- Throughput is of the order of 25 samples / day – it is a relatively slow and labour intensive process.
- Turnaround time based on giving this work top priority over other work is 5-10 working days – assuming receipt of a dried and ground sample ready for processing.

3.2.1 Soil and Herbage samples

- CEH have a range of vegetation samples archived from various long term field sites and monitoring programmes which cover different habitat types. These could be used as baseline for a re-sampling programme however many protocols demand washing of the vegetation prior to analysis which would remove particulates and therefore their value here is unknown at present.

  There are a >3000 archived topsoil samples from Countryside Survey 2007 which could be analysed for total fluoride (http://www.ceh.ac.uk/collaboration/countrysidesurvey.html).

  There are ca. 300 current-year shoot vegetation samples for heather and moss from the 2007 Countryside Survey archived which could be used as a baseline with open-access squares used for re-sampling.

Unfortunately vegetation samples are not routinely stored in ECN but soil samples are available and ECN staff are already sampling all grassland vegetation when present.

- BGS holds a dataset of soil samples collected on a systematic grid across a large portion of the country at a sample density of 1 per 2 km^2 in rural areas and 1 per 500m in urban areas. To date 27 urban areas have been sampled. Soil data are available from Yorkshire southwards in England except for the very far south of England that will be surveyed in the next 2 years; for the whole of Northern Ireland and for the Clyde Basin in Scotland. These samples are not analysed for fluoride or sulphate but the sample archive is available for reanalysis for these parameters.

  For information about the BGS G-BASE survey and data holdings see:
  http://www.bgs.ac.uk/gbase/

- National Soil Inventory datasets– these are held by the Soil Survey at Cranfield for England and Wales and by the James Hutton Institute for Scotland. They have been collected at a sample density of 1 per 25 km^2 across both countries.
  Scotland: http://www.hutton.ac.uk/about/facilities/national-soils-archive
 England and Wales:
  http://www.cranfield.ac.uk/sas/nsri/information/information_holdings.html

3.2.2 Freshwaters

Intensive sampling is underway for a range of catchments to identify potential acidification episodes in freshwaters. The Acid Waters Monitoring Network (http://awmn.defra.gov.uk/) is coordinated by ENSIS/Environmental Change Research Centre at University College London. CEH have 20-30 year records for a number of lakes and rivers in acid sensitive areas plus intensive 7 hourly sampling in some catchments (e.g. Plynlimon which illustrate the dynamism of the signal http://www.ceh.ac.uk/sci_programmes/plynlimonchemistry.html) which should provide a good baseline record.

BGS also has a validated method to determine F$^-$ by ion chromatography in aqueous media with a LOD of 10 µg/L and has been analysing fluoride in stream water samples across the UK for the last 40 years as part of the Geochemical Baseline Survey of the Environment (G-BASE) project, which is the national geochemical survey of the UK. Sulphate concentrations have also been determined in the waters for about the last 25 years. Stream water samples are collected from every 2 km of first and second order stream length across the country. This is a systematic spatial survey that will complete coverage of the whole country in two years time. To date, all but the far south of England has been surveyed. The data provide a national baseline showing the variation in fluoride and sulphate concentrations in surface waters across the country. The variation is controlled by factors such as the underlying geology, climate, prevailing environmental conditions and pollution. Any assessment of the impact of volcanic deposition from Iceland would have to take account of this pre-existing variability in concentration. G-BASE is not a time-series monitoring survey but samples sites could be re-sampled and analysed to assess the impact compared to the known baseline conditions.

4. Obtaining the relevant environmental information
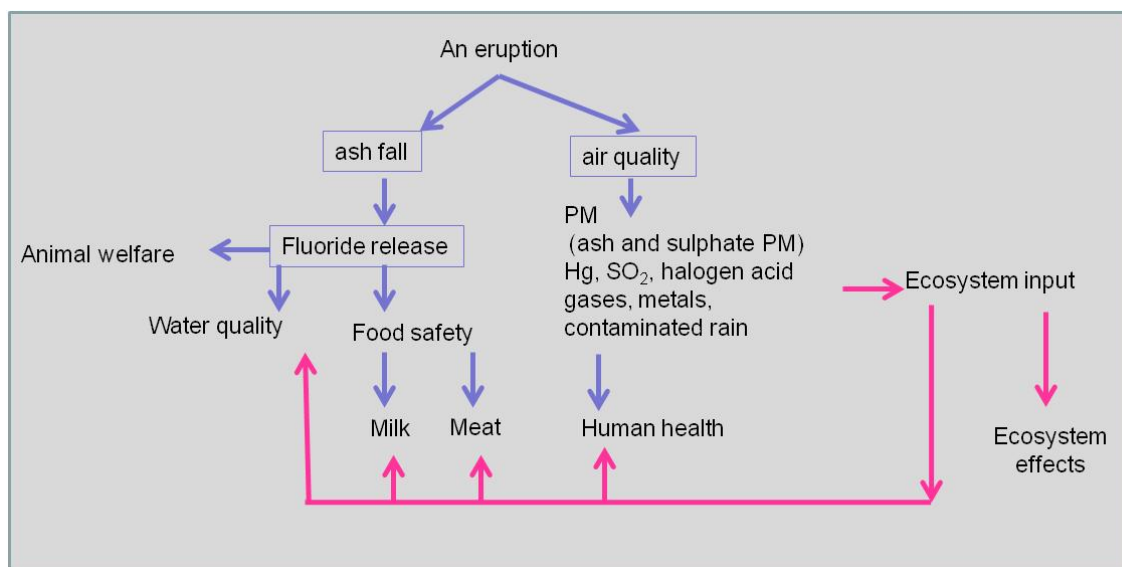
Schematic of effects of a volcano plume on the UK ground level

A simple coordinated sampling and analysis strategy is needed after the information is received that an Icelandic volcano plume is going to affect the UK. See Appendix H for the recommended IVHHN ash and leachate analysis protocol.

Level 1 : Ash fall/sedimentation

Require:
1. Fluoride content of the ash (mg/kg)[A,B]
2. Mass of ash fall/m^2 at key sites[B]
3. Forecasting of ash fall across the UK.
4. Guidance on locations of maximum deposition.
5. Use land use maps as to where ash fall areas co-locate with sensitive agricultural activities, in particular the UK dairy herd and N. Scotland sheep.
6. Provide ashfall prediction maps to DA's and Defra for agricultural response plan.
7. Information websites, such as APIS, widely publicised, for up to date information on acid deposition and effects.

Notes
A.   First measurements of fluoride content of ash would be likely to come from the Icelandic authorities with fresh ash.
B.   Pre-identified UK atmospheric monitoring stations deploy ash collection equipment supplied by BGS, and courier to designated laboratories (e.g. CEH Lancaster who have UKAS accredited fluoride measurement, BGS labs for crystallographic/ identification capabilities etc).

4.1 Recommendations:

For the UK to be correctly prepared for a future volcanic eruption some further work would be useful:

a. Method and network put in place and test for efficient enacting of (1) and (2).

Suggestion:

20 sites to be identified at which the AURN monitors SO_2, PM and are co-located or close to a Precipitation monitoring site, allowed enhanced levels of sulphur to be observed and deposition quantified . Currently the AURN is co-located at 7 UKEAP Precip-Net sites: Auchencorth Moss, Eskdalemuir, Harwell, High Muffles, Lough Navar, Strathvaich Dam, Yarner Wood. Further work would be needed to added further sites, with a distrubition which would allow a deposition map of the UK to be produced from the measurements. It is suggested that one important site would be Shetland, which is an AURN site, but not a Precip-Net site.

Once sites are identified, an SOP should be developed and communicated to the LSOs for those sites to allow them to be prepared. A practice exercise as suggested in (b) below should be carried out.

b. Methodology development and background mineral dust deposition rate characterisation.

Suggestion: Once sites for first response ash collection network are identified, sampling equipment should be designed, prepared and tested in a trial for 3 - 6 month, to check method and response SOP. This exercise would also be useful to characterise background deposition of mineral particulate at these sites for both mineralogy and leachate.

c. Development of EMEP4UK model (Defra and CEH funded model) to complement Met Office modelling activites.

In the event of a Laki type eruption there will be significant pressures on the NAME model. It would be prudent to have an established model used for UK deposition experiments to be available for forecasting plume deposition. It is suggested that the EMEP4UK model would be appropriate for this: EMEP4UK is a development of the EMEP UM to enable application at 5 km resolution over a British Isles inner domain (nested within the main EMEP UM 50 km domain (Vieno et al., 2010;Vieno et al., 2009). A small amount of work would allow this model to be used in forecast mode.

The EMEP Unified Model (www.emep.int/OpenSource/) is a grid-based chemistry-transport model comprising a collection of model pre-processors and post-processors that work together to produce a detailed representation of the physical and chemical state of the atmosphere at 50 km × 50 km horizontal resolution over a region encompassing Europe, the north Atlantic, North Africa, the Caucasus and parts of Russia (Simpson et al., 2012).

d. Ensure information resources for UK are in place:

i) Update fluoride sections of APIS to include volcano plume related literature.

ii) Ensure fact sheets are available to stakeholders including DAs, Defra vets, farm advisors etc. Website directing should be clear.

e. Impact on the freshwaters of the UK for a Laki type eruption: Model assessment.

This exercise would need to identify the UK models available for (i) assessing the input of volcanic acids into the UK waters over an 8 month period, (ii) identifying where the highest risks are (both to human water supply, and to agricultural water supplies (iii) quantifying the response time for information needs.

f. Plan for freshwater sampling

Measurement plan for Laki type eruption to focus water sampling on catchments and freshwater systems where there is a good baseline record (e.g. Pymlimon). Again, identification of networks where sampling is on-going should be used, and SOP setup for LSOs. This is important so that sampling is focussed and relevant, rather than an over sampling leading to redundant information.

g. Risk assessment of food security with respect to UK dairy herd and arable sector activites.

i. Method developed and disseminated for grass/crop sampling

ii. Laboratories identified for sampling and analysis. If Laki type eruption there would need to be sufficient lab capacity identified.
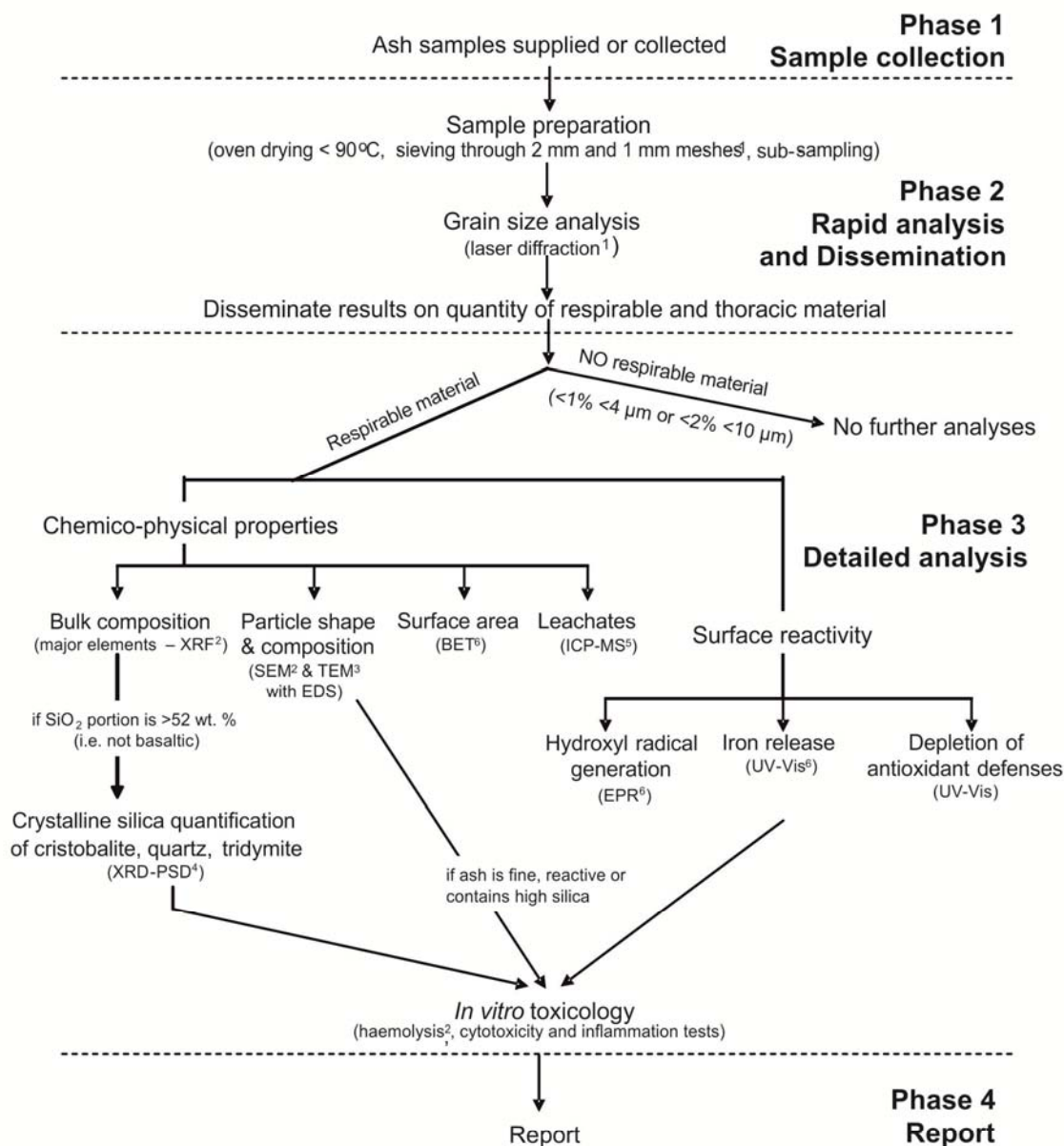
APPENDIX G: Gas Guidelines

See http://www.ivhhn.org/images/pdf/gas_guidelines.pdf

APPENDIX H: IVHHN Ash analysis protocol

Protocol for analysis of bulk ash samples for health hazard assessment

Durham University / **IVHHN**

Phase 1 – Sample collection
Ash samples supplied or collected

Phase 2 – Rapid analysis and Dissemination
Sample preparation (oven drying < 90°C, sieving through 2 mm and 1 mm meshes[1], sub-sampling)
Grain size analysis (laser diffraction[1])
Disseminate results on quantity of respirable and thoracic material

Respirable material / NO respirable material (<1% <4 µm or <2% <10 µm) → No further analyses

Phase 3 – Detailed analysis
Chemico-physical properties
- Bulk composition (major elements – XRF[2])
  - if SiO₂ portion is >52 wt. % (i.e. not basaltic)
  - Crystalline silica quantification of cristobalite, quartz, tridymite (XRD-PSD[4])
- Particle shape & composition (SEM[2] & TEM[3] with EDS)
- Surface area (BET[6])
- Leachates (ICP-MS[5])
- Surface reactivity
  - Hydroxyl radical generation (EPR[6])
  - Iron release (UV-Vis[6])
  - Depletion of antioxidant defenses (UV-Vis)

if ash is fine, reactive or contains high silica

In vitro toxicology (haemolysis[2], cytotoxicity and inflammation tests)

Phase 4 – Report
Report

References for methods
[1] C.J. Horwell, J. Environmental Monitoring, 9 (10), 1107-1145, 2007.
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[5] C.S. Witham, C. Oppenheimer and C.J. Horwell, Journal of Volcanology and Geothermal Research 141, 299-236, 2005.
[6] C.J. Horwell, I. Fenoglio and B. Fubini, Earth and Planetary Letters 261 (3-4), 662-669, 2007.

For full references and method summaries please visit www.ivhhn.org or contact Dr Claire Horwell (claire.horwell@durham.ac.uk)

APPENDIX I: Some ongoing relevant research projects

1. **FUTUREVOLC**
   An EU FP7 funded research consortium project to develop a 'volcano supersite' in Iceland. It is led by Freysteinn Sigmundsson at the University of Iceland with the Icelandic Meteorological Office. UK partners include the British Geological Survey, the Met Office, Cambridge University and Bristol University.

   The project objectives are:

   PO1. Establish an **innovative volcano monitoring system** and strategy, integrating multidisciplinary knowledge.
   PO2. Develop new methods for **near real-time integration of multi-parametric datasets** and the development of innovative instrumentation.
   PO3. Apply a seamless **transdisciplinary approach** to further scientific understanding of physical processes.
   PO4. Improve **delivery, quality and timeliness of information** from monitoring scientists to civil protection and governing authorities, locally and internationally.

   www.futurevolc.hi.is

2. **VANAHEIM**
   A NERC-funded research consortium to characterise volcanic plumes in the near to far-field. It is led by Leeds University (NCAS) and includes many UK institutes and universities as well as stakeholders. BGS and the Met Office are both partners.

   The project aims to improve monitoring, modelling and ash/aerosol characterisation for remote sensing both in Iceland and the UK. The main impact objectives are:

   1. Work with the Icelandic Meteorological Office in building capacity for future volcanic observations.
   This will be achieved working with the Met Office under the 2010 4-way MoU between IMO, Met Office, NCAS and BGS.
   2. Feed into the continued development of the UK Met Office's volcanic ash dispersion forecasting and other international developments.
   3. Tailor our research to address the Met Office requirements for development of algorithms for operational data assimilation schemes.

   http://www.ncas.ac.uk/index.php/en/vanaheim-introduction

3. **European Volcano Observatory Space Services (EVOSS)**

   An EU FP7 funded project that has developed an operational system that provides close to real-time volcanic ash, SO_2, thermal and deformation products to volcano observatories and Volcanic Ash Advisory Centres (e.g. the UK Met Office).

   It is currently led by IPGP, France.

   The operational system was developed in this research project but discussions are underway on how to make this service sustainable and develop it further – it operates across Europe, the Caribbean and Africa.

   www.evoss.eu