Volcanic gases: silent killers

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Abstract

Volcanic gases are insidious and often overlooked hazards. The effects of volcanic gases on life may be direct, such as asphyxiation, respiratory diseases and skin burns; or indirect, e.g. regional famine caused by the cooling that results from the presence of sulfate aerosols injected into the stratosphere during explosive eruptions. Although accounting for fewer fatalities overall than some other forms of volcanic hazards, history has shown that volcanic gases are implicated frequently in small-scale fatal events in diverse volcanic and geothermal regions. In order to mitigate risks due to volcanic gases, we must identify the challenges. The first relates to the difficulty of monitoring and hazard communication: gas concentrations may be elevated over large areas and may change rapidly with time. Developing alert and early warning systems that will be communicated in a timely fashion to the population is logistically difficult. The second challenge focuses on education and understanding risk. An effective response to warnings requires an educated population and a balanced weighing of conflicting cultural beliefs or economic interests with risk. In the case of gas hazards, this may also mean having the correct personal protection equipment, knowing where to go in case of evacuation and being aware of increased risk under certain sets of meteorological conditions. In this chapter we review several classes of gas hazard, the risks associated with them, potential risk mitigation strategies and ways of communicating risk. We discuss carbon dioxide flows and accumulations, including lake overturn events which have accounted for the greatest number of direct fatalities, the hazards arising from the injection of sulfate aerosol into the troposphere and into the stratosphere. A significant hazard facing the UK and northern Europe is a "Laki"-style eruption in Iceland, which will be associated with increased risk of respiratory illness and mortality due to poor air quality when gases and aerosols are dispersed over Europe. We discuss strategies for preparing for a future Laki style event and implications for society.

Volcanic gases have claimed directly the lives of >2000 people over the past 600 years (Auker et al., 2013). Millions more people have been impacted by volcanic gas, with effects ranging from respiratory irritation to neurological impacts, to crop failure and famine. Gas hazards contrast markedly with other volcanic hazards such as lahar, pyroclastic flows and ash fall; they are silent and invisible killers often prevailing over large areas of complex terrain. Volcanic gases may accumulate far from their source and flow down valleys as a gravity flow, engulfing and asphyxiating people as they sleep. Sometimes the hazard is visible in the form of a condensing plume emanating from a vent, with acidic gases capable of corroding buildings and aircraft, damaging crops and causing respiratory disease and skin burns. The trajectory and dispersal of such a plume is subject to local meteorology. The plume or gas cloud must be detected and tracked by sophisticated instrumentation. Designing a warning system that works in real time whilst incorporating both measurements and models tests the ingenuity of personnel at volcano observatories and meteorological agencies. Yet these hazard-warning systems are necessary if people are to live at close quarters with degassing volcanoes. The dissemination and communication of warnings associated with gas hazards requires effective alerts and systems in place to ensure that the warning gets to the part of the population at risk. The population must react to the warning in a way that mitigates risk; this is only possible if sufficient understanding of the hazard exists. The insidious hazard of volcanic gases is often poorly understood and overlooked. In this chapter, we review the challenges associated with monitoring, detecting and communicating gas hazards and managing risk associated with gases. We start by reviewing the types of hazard.

1. Volcanic gases, insidious hazards

A single event dominates the inventory of deaths due to volcanic gases: in August 1986 Lake Nyos (Cameroon, Africa) emitted a dense cloud of carbon dioxide (CO_2) gas in the middle of the night, which rapidly flowed down surrounding valleys, suffocating immediately 1700 sleeping people up to 20 kilometers away from the lake (Kling et al., 1987). Many other deaths have occurred as a result of people encountering accumulations of CO_2 or hydrogen sulfide (H_2S) gases in low-lying areas or in the form of flows and clouds. In a recent analysis volcanic gas inundation was recognized as the second most common cause of death in the most frequent, fatal volcanic events (Auker et al., 2013). The key characteristic of this hazard is that usually there is no warning and no visible sign of it. Gas concentrations may creep up unnoticed until it too late, or a sudden inundation may leave no time for escape.

Fatalities arising from the secondary effects of volcanic gases run into the millions over historical times (Rampino et al., 1988). Large explosive eruptions inject SO_2 directly into the stratosphere, which transforms rapidly (within hours to days) to sulfate aerosol (Robock, 2000). The aerosol scatters and reflects incoming visible and UV radiation from the sun, causing tropospheric cooling over the lifetime of the aerosol (typically a few years). Volcanic cooling has caused crop failure and famine for many years after large eruptions. Some recent eruptions (e.g. Pinatubo, Philippines, 1991 and El Chichon, Mexico, 1982) have allowed direct measurement of the reduction in direct radiative flux into the troposphere, total aerosol optical depth and tropospheric temperature (Dutton and Christy, 1992), which validated predictions of the effects of stratospheric sulfate aerosol on climate. Large historic eruptions such as that of Tambora Volcano in 1815 (Indonesia) were associated with global cooling, leading to famine, social unrest and epidemic typhus, leading to the "Year Without a Summer" (Oppenheimer, 2003). A dramatic European example is the Laki (Iceland) eruption of 1783, which was followed by several years of crop failure and cold winters, resulting in the deaths of >10,000, ~20% of the Icelandic population (Grattan et al., 2003; Thordarson and Self, 2003).

Another class of volcanic gas hazards is generally non-fatal, but gives rise to or exacerbates significant chronic and acute health conditions (**Table 1**). Persistent gas plumes at low levels in the atmosphere are common at many volcanoes worldwide. These plumes may be rich in sulfate aerosol, generating a pervasive, choking haze. At Kīlauea Volcano, Hawaiʻi, studies have shown a link between incidences of plume inundation and asthma attacks in children (Longo et al., 2010a). These plumes give rise to acid rain and their corrosive properties (arising from not just the SO_2 but also the acid halogen gases HCl and HF) leads to the damage of buildings, vehicles and infrastructure. These plumes may persist for decades or longer, making them a significant health hazard (Delmelle et al., 2002). In other areas, interception of magmatic gases by groundwater aquifers may lead to contamination of water supplies that are tapped by springs. In East Africa, for example, the high concentrations of fluorine in the spring water, once dissolved in magmas many kilometres below, have caused widespread dental fluorosis (D'Alessandro, 2006).

What are volcanic gases?

Volcanic gases are mixtures of volatile compounds released from the ground's surface or directly from volcanic vents, into the atmosphere. They are generated when magmas exsolve volatiles at low pressures during their ascent to the surface and eruption. Volcanic gases may precede the arrival of lava at the surface by several weeks or even months. In some cases, persistent and diffuse emissions of gases may take place continuously between eruptions, even when the eruptions occur very infrequently. The gases have different compositions depending on: tectonic setting, how close to the surface the degassing magma is stored and whether the fluids are interacting with a wet hydrothermal system prior to reaching the atmosphere (Giggenbach, 1996). The gases that typically emanate from deep magma intrusions between and prior to eruptions are dominantly carbon dioxide (CO_2) and hydrogen sulfide (H_2S). When magma reaches the surface, the gas composition becomes dominated by the more melt-soluble components: water (which may make up >85 % by volume of the gas mixture), with lesser amounts of CO_2 and SO_2 (which make up 2-10%), halogen gases hydrogen fluoride (HF) and hydrogen chloride (HCl), and carbon monoxide (CO) and other minor components. If the gases interact with a hydrothermal system the acid gases SO_2 and HCl are removed, or “scrubbed” (Symonds et al., 2001); this is typical of the early stages of an eruption, or of “failed” eruptions (Werner et al., 2011). The components of volcanic gases that are of greatest concern for health are (**Table 1**), primarily CO_2, SO_2, H_2S, HCl, HF and metals such as mercury (Pyle and Mather, 2003) and short-lived radioactive isotopes such as radon (Baxter et al., 1999). These gases and aerosols are of course also produced in many industrial settings and the risk of accidents in these settings has prompted most of the studies on their effects on health. Some gases undergo chemical reactions in the plume, resulting in secondary products that can cause health and environmental effects. Sulfur dioxide reacts with water to form sulfuric acid aerosol droplets that leads to acid rain in the troposphere (Mather et al., 2003). When injected into the stratosphere, the aerosols may reflect and absorb radiation from the sun, resulting in the cooling of the Earth’s surface for up to a few years for the largest eruptions over the past few decades, perhaps longer for larger classes of historic eruptions (Robock, 2000).

There are multiple factors governing the magnitude of the volcanic gas health hazard and consequently, risk: the concentrations of gases (a function of both gas flux and composition), the mode of delivery to the atmosphere (e.g. from a point-source or over large areas; tropospheric or stratospheric) and the longevity or duration of the event. Monitoring networks should fulfill several functions in order to produce a realistic picture of the hazard: instrumentation coverage, precision (both spatial and temporal) and timeliness are critical. Once the hazard is identified and assessed, the nature of it must be communicated effectively to the communities at risk via an alert or warning system. The reaction and response of the community to the risk communication must be appropriate and prompt, otherwise delays in evacuations and other risk mitigation procedures might occur. Preparing for future events requires an understanding of the hazard and its recurrence interval, robust monitoring networks and alarm systems, sophisticated models to simulate possible outcomes and risk mitigation plans to reduce or prevent fatalities. Whilst this sequence is well-developed for a subset of hazards in some localities, such as lahar, ash fall and lava flow inundation, there are very few examples of successful alert systems for gas hazards and even fewer that have been tested in extremely hazardous scenarios which might allow us to evaluate the effectiveness of hazard communication and risk mitigation. Challenges specific to gas hazards relate to: (1) the difficulty of achieving adequate coverage with regard to monitoring (e.g. gas concentrations may be low across most of an area, but there may be localized regions of high concentrations, so dense networks of instrumentation are required); (2) developing alert and early warning systems that will be communicated in a timely fashion to the population. Gas hazards may develop rapidly and be highly dispersed, making communication of warnings problematic. (3) Ensuring that an educated population will respond in a timely and appropriate way. An amenable response to warnings or evacuation orders requires an educated population and a balanced weighing of conflicting cultural beliefs or economic interests with risk. In the case of gas hazards, this may also mean having the correct personal protection equipment, such as gas masks; knowing where to go in case of evacuation (e.g. high ground); and being aware of increased risk under certain sets of meteorological conditions (e.g. on still days with no wind). Different hazards require vastly different responses. Large eruptions which inject gas (and ash, see chapter XXX) into the upper atmosphere for example, give rise to regional, or global hazards that have their own unique set of challenges that focus on dealing with both immediate health effects and longer term impacts (social and economic) resulting from climate forcing. In this chapter we review some key case studies and discuss the monitoring, alert and risk mitigation schemes that were in place or could be implemented for future events. We discuss the particular challenges inherent in dealing with gas hazards on all temporal and spatial scales and suggest profitable approaches for future development.

2. Developing risk mitigation strategies for CO_2 flows and accumulations

Over the course of a decade beginning in 1979, our understanding of gas hazards was to take a dramatic turn. Events served as a stark reminder that volcanic gas hazards were capable of causing significant loss of life. Hazards from atmospheric CO_2 are usually limited, because atmospheric dispersion tends to dilute volcanic or hydrothermal gas emissions to the extent that concentrations become non-lethal rapidly away from a vent or degassing area. If however, geological, geographical, hydrological or meteorological factors bring about the accumulation of CO_2, or its concentration into a flow, the effects are life-threatening. Within the Dieng Volcanic Complex in central Java, on 20 February 1979, a sequence of earthquakes was followed by a phreatic eruption and sudden release of CO_2 (Allard et al., 1989; Le Guern et al., 1982). The area was known for its hydrothermal manifestations, with boiling mud pools, hot springs and areas of tree kill indicative of CO_2; local people are aware of “death valleys” in which vegetation is dead up to a certain level on the valley walls, and animals are often killed. People lived (and still do) in the low areas adjacent to grabens and phreatic craters known to have been sites of explosions and gas emissions in the past. After three large earthquakes between 2 and 4 am, a phreatic explosion at 5:15 was associated with the ejection of large blocks and a lahar that reached the outskirts of the village Kepucukan (Allard et al., 1989). Frightened by the activity, people attempted to escape from the village, walking west along the road to Batur, another village just 2 km away. Halfway there, 142 people were engulfed in “gas sheets” that emanated from the erupting crater, which killed them instantly. Gas emissions, dominated by CO_2, continued for another 8 months (Allard et al., 1989) and may have reached a total volume of 0.1 km^3 (Allard et al., 1989).

Today, more than 500,000 people live in an area at high risk of hazardous CO_2 flows in Dieng caldera. Gas emission events occur frequently, heralded by seismicity (every few years with large events every few decades). A recent survey showed that 42% of the people are aware of the risk of "poisonous gas" but only 16% link this hazard to volcanic activity (Lavigne et al., 2008). Most people show a reluctance to accept the risk and a greater reluctance to leave the area due to a combination of religious and cultural beliefs (the area has been a sacred Hindu site since the 7th century) and economic factors (Dieng is agriculturally rich and in addition attracts many tourists). Farmers work within metres of dangerous mofettes (cold CO_2-producing fumaroles) and mark them with mounds of earth. Villages are situated at the mouths of valleys that connect phreatic craters on high ground with the caldera floor and which channel cold CO_2 flows. Monitoring the hazards is therefore of utmost importance and takes place using a network of in situ logging geochemical sensors and seismometers, maintained by the Indonesian volcanological agencies. Monitoring is not easy: the sensors are difficult to maintain, have short lifetimes and do not have the spatial coverage required to monitor all of the gas-producing vents and areas. Since 1979, there have been six phreatic eruptions accompanied by elevated CO_2 emissions. Degassing crises in 2011 and in 2013, however, were successfully managed using the existing system, with CO_2 concentration levels used to assign alert levels. Gas emission forced the evacuation of 1200 residents following a phreatic eruption at Timbang crater on 29 May 2011, and people were advised to remain at least 1 km away from the crater, where dead birds and animals were found (CVGHM report, 2011). An improved network of telemetered arrays of sensors, webcams and linked siren warning systems for the surrounding villages was approved for USAID/USGS funding in 2013. For future events, it is widely assumed that phreatic eruptions will be preceded by significant seismicity (Le Guern et al., 1980). Evacuations of far larger areas will be necessary to protect the population from the gas hazard and Early Warning Systems are needed to communicate encroaching hazards.

It was not until 1986 that the wider public was exposed to the idea of volcanic gas hazards, when the 8th largest volcanic disaster in historical times occurred near to Lake Nyos in Cameroon. A landslide triggered the overturn of a density-stratified lake, within which CO_2 had concentrated in its lower levels. The sudden depressurization of the lake water upon overturn caused an outpouring of CO_2 from the lake and into a valley, killing 1746 people by asphyxiation, up to 25 km from the lake, as well as thousands of cattle (Kling et al., 1987). Around 15,000 people fled the area and survived but developed respiratory problems, lesions and paralysis as a result of their exposure to the gas cloud (Baxter et al., 1989). There were no monitoring systems in place, no warning system and no assessment of risk before the event; scientists had no idea that this kind of event was possible prior to 1986.

It transpired, from isotopic analysis of the CO_2, that the gas had a magmatic origin, and had entered the lake from fault systems channeling gases from deep in the crust, derived ultimately from the mantle (Kling et al., 1989). There was no direct volcanic activity associated with the disaster. Gas sensor networks linked to siren systems were immediately set up at the edges of the lake and at the heads of the valleys to warn of future gas flow events. A unique hazard mitigation system was set up in 1999, funded by the United States and supplemented by the governments of Cameroon, France and Japan, with the aim of artificially degassing Lake Nyos by decompressing deep lake waters using three pipes, which work in a self-sustaining way, initially pumping deep water towards the surface but thereafter driven by the degassing of CO_2 (Kling et al., 1994). The scheme has reduced gas pressures in the lake substantially, reducing the risk of future overturn and gas flow events, which would otherwise have occurred every few decades. A new hazard has been identified however, in the shape of a weak dam, raising the possibility that dam breach and removal of water from Lake Nyos could be a potential future trigger for a gas emission event, regardless of the degassing pipes. Added to this is the increasing risk to people, as they gradually resettle the area.

The Lake Nyos event was not unique; two years before the disaster a similar limnic eruption occurred at Lake Monoun, killing 38 people. Other lakes are associated with significant risks of similar events: at Lake Kivu, on the border of the Democratic Republic of Congo and Rwanda, recent measurements have shown that ~300 km^3 of CO_2 (at standard temperature and pressure) are present in the lake's permanently stratified deep water (Schmid et al., 2005). Release of these gases by limnic overturn would have deadly consequences for the two million people living along the lake shore. It has been suggested that limnic eruptions in the Holocene have been responsible for local extinction events (Haberyan and Hecky, 1987). Elsewhere, limnic eruptions have been implicated in the deaths of a wide range of Eocene vertebrates, which were subsequently preserved to an exceptional degree, at the Messel Pit (Germany), which was, in Eocene times, a crater lake over a maar (Franzen and Köster, 1994). Limnic eruptions remain, however, a rare, if extremely hazardous, event.

Outstanding questions are those concerning how to mitigate hazard and manage early warning systems and how to reduce risk associated with these silent, yet deadly hazards. Considerable interest in modeling gas flow over topography has arisen from recent developments in CO_2 transport as a supercritical fluid through long-range pipelines for carbon sequestration (Duncan and Wang, 2014). The possibility of a breach in a pipeline and associated gas flow has prompted investment in gas hazard assessment. At Mefite D'Ansanto in central Italy, a near-pure CO_2 gas flows down a channel at a rate of ~1000 tonnes per day (Chiodini et al., 2010). The flow reaches a height (defined by a gas concentration of 5 vol%) of 3 meters above the valley floor (far higher than a typical human). Using measurements of CO_2 concentration at various heights and distances in the valley to constrain the model and a local wind field, a gas transport model (TWODEE-2; Folch et al., 2009) was used to simulate the gas flow and to predict the zones of potential hazard for humans in terms of dangerous (>5 vol%), very dangerous (>10 vol%) and lethal (>15 vol%) concentrations, which has been used successfully for risk mitigation in the area. Gas transport models will have great utility in areas subject to dense, cold gas flows and are relatively inexpensive to implement, given appropriate constraints and calibrations provided by field measurements. Their unique advantage is that they provide a means to convert discrete measurements of gas concentrations using sensors into a fully 3-D continuous model of gas concentration and hazard that can be straightforwardly incorporated into warning systems.

The gas flows described above are extreme; there are numerous examples of smaller scale gas accumulation hazards that have caused loss of life. These kinds of manifestations have been shown to be the most frequently associated with deaths in the record (Auker et al., 2013) and as such, require robust monitoring, alert systems and risk assessment. Areas of tree kill and asphyxiated animals were reported at Mammoth Mountain, inside Long Valley Caldera, beginning in 1990 and caused by the diffuse emission of CO_2 over 0.5 km^2 that reached up to 1200 tons/day at its peak (Farrar et al., 1995), following a swarm of earthquakes and an intrusion in 1989. The emissions have caused fatalities: in 2006 three ski patrollers died after falling close to a fumarole. The gas hazards occur in a recreational area visited by 1.3 million skiers in the winter and 1.5 million hikers in the summer. Monitoring has been undertaken since 1990 in the form of campaign-style measurements using soil gas chamber spectrometers, and then through three permanently installed soil gas instruments, operated and monitored by United States Geological Survey scientists (Gerlach et al., 2001). Risk mitigation measures include the posting of signs in prominent areas warning of the hazards associated with gas accumulations in topographic lows. For this lower level of hazard, this communication method is effective and has resulted in a largely safe enjoyment of the area by a largely educated public, despite the gas emissions.

In the Azores, in the mid-Atlantic, the situation is rather more precarious. On Sao Miguel Island, villages are situated within the Furnas volcanic caldera (Baxter et al., 1999; Viveiros et al., 2010). This is the site of numerous gas manifestations such as boiling fumaroles, diffuse emissions and cold CO_2-rich springs. It is an area popular with tourists, who enjoy the thermal spas. Up to 98% of the houses, however, are situated over CO_2 degassing sites (Viveiros et al., 2010). A study in 1999, which has been repeated many times subsequently, showed that lethal concentrations of CO_2 (>15 vol%) existed in non-ventilated confined spaces in the houses (Baxter et al., 1999). There have been no confirmed cases of deaths in the area from CO_2 asphyxia but there exist frequent anecdotal records of people being “overcome” by gases (Baxter et al., 1999). No formal early warning or alert system exists, but there are soil gas flux spectrometers and soil temperature sensors located in the village that telemeter data back to the Azores Monitoring Centre for Volcanology and Geothermal Energy in real time. A survey of the population of the village of Furnas carried out in 1999 showed that, astonishingly, not a single one of 50 random adult respondents had any knowledge about the existence of gas hazards in the area. Upon closer questioning of the wider population only a very small fraction, mainly civil defense and medical workers, were aware of the hazard (Dibben and Chester, 1999). This shows a profound lack of education of the general population by the scientific establishment at the time of the survey. Whilst a more recent survey has not been carried out, it is likely that this has improved in recent years with the enhancement of monitoring and the responsibility to safeguard tourists. But this situation raises some thorny issues concerned with risk mitigation (Dibben and Chester, 1999). Highlighting the most vulnerable areas in the village is likely to reduce the value of property in those areas and so the public will likely be averse to accepting such information. Gas hazard alerts might affect tourism and hence the economic status of the area. Building regulations to prevent the build up of CO_2 in basements might be harder for the poor to comply with, resulting in a socially divisive vulnerability structure. Lastly, installation of a high spatial coverage, precise and reliable monitoring and early warning system might lead the population to believe that they are no longer threatened, encouraging risky behaviors.

3. Monitoring and communicating “vog” hazards

When magma is close to the Earth’s surface (and when the gases do not interact with extensive wet hydrothermal systems), the gas hazards fall into a different category to those described above. In this case, acidic gases such as sulfur dioxide, hydrogen chlorine and hydrogen fluoride become important hazards. Active volcanism is therefore associated with thick plumes containing a mixture of these acid gases, as well as water, CO_2 and minor carbon monoxide (CO) and hydrogen sulfide (H_2S). Under these conditions, volcanic smog or “vog” may cause acute respiratory difficulties and skin, noise and throat irritation. Vog, which is made up of sulfate aerosol particles, has been linked to asthma and other respiratory diseases (Hansell and Oppenheimer, 2004). Some volcanoes degas prodigious fluxes of gases quasi-continuously. Mount Etna, in Italy, for example, produces several thousand tons of SO_2 and significant quantities of other acidic gases every day and activity has persisted at this level for decades (Allard et al., 1991). Other prodigious producers of tropospheric volcanic gas plumes are Nyiragongo (Democratic Republic of Congo), Ambrym (Vanuatu), Kīlauea (USA), Erebus (Antarctica), Masaya (Nicaragua), Erta Ale (Ethiopia) and Villarica (Chile). Some of these volcanoes are sparsely populated; others have major urban centres within range of their plumes.

Kīlauea Volcano, Hawai'i, has been in continuous eruption since 1983. At Kīlauea, magma is outgassing at both the summit (since 2008) and from eruption sites and active lava fields on the east rift zone (Longo et al., 2010a), giving rise to multiple sources of gases. The emissions affect not only the 2 million visitors to Hawai'i Volcanoes National Park every year, but also wider areas of Big Island and the other Hawaiian islands via dispersal by the trade winds (**figure 4**). It has been shown that indoor SO_2 concentrations regularly exceed the World Health Organisation guidelines in the affected areas of Big Island (Longo et al., 2010b) and that during periods of enhanced volcanic outgassing there are synchronous increases in the occurrence of acute respiratory conditions requiring treatment on the island (Longo et al., 2010a). In response to the clear need for a system of monitoring and early warning, SO_2 concentration sensor data from inside the park and around the island are combined with SO_2 emission rates and a model for plume dispersion to produce a vog model that forecasts air quality for the Hawaiian Islands (**figure 5**). These warnings have proven to be a very successful way of mitigating risks due to vog; statistical analysis has shown that the predictions lie within one standard deviation of the data for forecasts up to 24 hours ahead (Reikard, 2012). Advice to residents to minimize their exposure to vog once a forecast or warning for high aerosol concentrations has been issued include closing windows and doors, limiting outdoor activities and exertion and having medications on hand. Communication of vog warnings takes place via the web, radio, field units and road signs. This style of monitoring, modeling, forecasting, warning and communication might profitably be applied to many other volcanic centres facing similar tropospheric volcanic aerosol pollution in the future.

4. The great dry fog: preparing for a future Laki-style event

The Laki (Lakigigar) eruption 1783–1784 is known to be the largest air pollution incident in recorded history and its effects were felt throughout the northern hemisphere (Grattan, 1998). Activity in this area of southern Iceland began in mid-May 1783 with weak earthquakes which intensified into June. On the 8th of June, the 27 km long fissure opened up with more than 140 vents (Thordarson and Hoskuldsson, 2002; Thordarson et al., 1996). The eruption pumped 100 million tonnes of SO_2 into the westerly jet stream, producing sulfur-rich plumes that were dispersed eastwards over the Eurasian continent and north to the Arctic. The reaction of SO_2 with atmospheric vapour produced 200 million tonnes of sulfate aerosol, of which 175 million tonnes were removed during the summer and autumn of 1783 via subsiding air masses within high pressure systems (Thordarson and Hoskuldsson, 2002; Thordarson and Self, 2003). At its peak, this mechanism may have been delivering up to six million tonnes of sulfate aerosol to the boundary layer of the atmosphere over Europe each day (Stothers, 1996). The explosive activity from the eruption produced a tephra layer that covered over 8,000 km^2 and is estimated to have produced 12 km^3 of tholeiitic lava flows. Ten eruption episodes occurred during the first five months of activity at Laki, each with a few days of explosive eruptions followed by a longer phase of lava emissions. Volcanic activity began to decrease in December 1783 and ceased on the 7th of February 1784 (Steingrímsson, 1998; Thordarson and Hoskuldsson, 2002; Thordarson and Self, 2003).

The consequences of the eruption were catastrophic. In Iceland, acid rains destroyed grazing and more than half of the livestock died from starvation or in combination with skeletal fluorosis (bone deformation resulting from the ingestion of high levels of fluorine) precipitated from erupted fluorine gases. More than a quarter of Iceland's population subsequently died from starvation and the survivors suffered from growths, scurvy, dysentery, and ailments of the heart and lungs (Steingrímsson, 1998). The aerosol produced in the atmosphere resulted in a "dry fog" which hung over Britain, Scandinavia, France, Belgium, the Netherlands, Germany and Italy during the summer of 1783, affecting human health and withering vegetation (Durand and Grattan, 2001). The aerosol also caused severe climatic perturbations. In the UK, August temperatures in 1783 were 2.5°C to 3°C higher than the decadal average, creating the hottest summer on record for 200 years. A bitterly cold winter followed, with temperatures 2°C below average (Luterbacher et al., 2004). Coincidentally, in England, the death rate doubled during July 1783–June 1784 with 30,000 additional deaths recorded (Federation of Family History Societies, 2010; Grattan et al., 2007; Witham and Oppenheimer, 2004b). This period is classified as a 'mortality crisis' because the annual national mortality rate was 10-20% above the 51-year moving mean (Wrigley and Schofield, 1989). Two discrete periods of crisis mortality occurred: August-September 1783 and January-February 1784, which in combination accounted for around 20,000 additional deaths, with the East of England the most affected region (Witham and Oppenheimer, 2004a). Crisis years are not unusual however, during the period 1541-1870 there were 22 crises where the death rate was 20-30% higher, which is greater than the 1783-84 crisis of 16.7% (Grattan et al., 2003). Whilst it is difficult to prove a direct causal link between the eruption and the mortality crisis the connection between temperature extremes and mortality of the elderly or vulnerable is well established ((Keatinge and Donaldson, 2004; Kovats, 2008; Royal Society, 2014; Wilkinson et al., 2004). The effects of the Laki volcanic cloud are implicated in the climatic anomalies of 1783–4 and it is therefore likely that the Laki Craters eruption did contribute to the crises (Grattan et al., 2003; Witham and Oppenheimer, 2004a).

Current levels of particulate air pollution in many parts of the UK exert considerable impact upon public health (Public Health England, 2014). Epidemiological studies have linked premature mortality with exposure to air pollution, particularly to particles smaller than 2.5 µm in diameter (PM2.5) (Pope and Dockery, 2006). During a 14 day period in March and April 2014, air pollution was 'very high' (based on government monitoring of PM10 and PM2.5) across the UK, which resulted in 3500 additional healthcare visits for acute respiratory symptoms and approximately 500 for severe asthma (Smith et al., 2015). The air pollution episode was due to anticyclonic atmospheric conditions which brought together local air pollution emissions, pollution from continental Europe and dust transported atmospherically from the Sahara (Smith et al., 2015). Air pollution levels resulting solely from local emissions also regularly breach European Union directives; NO_2 is of particular concern and in April 2015 the UK Supreme Court ruled that the government must submit new air quality plans to the European Commission by the end of the calendar year (Supreme Court Press Office, 2015).

Given that air pollution in parts of the UK is regularly at (or in breach of) permissible levels, even a modest-sized eruption in Iceland could push UK cities over the threshold into very high levels of pollution. Over the last 1130 years, there have been four fissure eruptions in Iceland that caused environmental and climatic perturbation, of which Laki was the second largest and the occurrence of a contemporary Laki-style eruption poses a serious threat to the health of European populations. The need for preparedness for such an event was raised by a Geological Society working group in 2005 (Sparks et al., 2005) and subsequently added to the National Risk Register of Civil Emergencies (Loughlin et al., 2014).

Recent modelling of likely excess mortality resulting from a modern Laki reveals that a similar-sized eruption would produce, on average, 120% more PM2.5 over background levels, which would result in 142,000 additional deaths, an increase of 3.5% in the mortality rate (Schmidt et al., 2011). This rate of mortality is much lower than actually occurred during the 1780s, which could be due to several factors, including the assumption that modern populations are more resilient to air pollution and environmental stress (which may not be the case), and that the concentration response functions in the model do not account for all adverse health effects (i.e. asthma caused by elevated SO_2) (Schmidt et al., 2011).

The link between elevated mortality and extremes of temperature is also well-established and therefore volcanically-induced anomalous weather could also contribute to a post-eruptive death toll. The European heatwave of 2003 was a three week period of abnormally hot weather which resulted in over 52,000 deaths across Europe with cities particularly affected (Royal Society, 2014). There were over 14,800 fatalities in France, with excess mortality greater than 78% in Paris, Dijon, Poitiers, Le Mans and Lyon. In the UK there were 2091 fatalities of which 616 occurred in London alone (Kovats and Kristie, 2006; Royal Society, 2014). There was a resultant increase in heat health warning systems across Europe (heat surveillance systems with associated risk warnings and awareness raising) with 16 active by 2006, which resulted in a reduction in the mortality following the 2006 heatwave (Royal Society, 2014). The World Health Organisation's

EuroHEAT project researches heat health effects in European cities, preparedness and public health system responses. It has highlighted that the health burdens fall disproportionately on those living in urban areas, particularly if they are also physiologically susceptible, socio-economically disadvantaged and live in degraded environments; a variety of practical measures to increase resilience have been suggested alongside legislation, national plans and social capital-building (World Health Organization, 2007).

A future eruption similar to Laki would likely be forecast days to weeks in advance using the sophisticated volcano monitoring networks that are in place (Sigmundsson et al., 2014). The eruption itself would likely be accompanied by prolonged high fluxes of gases and ash, producing an aerosol-laden plume in the troposphere, as observed in recent Icelandic eruptions. During some prolonged or particularly intense periods of eruption the plume may even reach the stratosphere (Thordarson and Self, 2003). The plume will be modifed physically and chemically as it moves away from the vent. Dispersal largely depends on wind direction and shear, meteorological conditions, synoptic-scale features (Dacre et al., 2013) and the stability of the atmosphere. Reactions take place in the gas phase and on the surfaces of ash and aerosol particles, where SO_2 is transformed to sulfate aerosol as well as other chemical reactions involving halogen radicals and ozone and NO_x species (von Glasow et al., 2009). Chemical transformations of the plume will depend on the availability of surfaces for reactions and will be affected by particle aggregation and sedimentation. The lifetime of sulphate aerosols and SO_2 in the troposphere depends on altitude and season and is of the order of 5-10 days at the low altitudes between UK and Iceland (Stevenson et al., 2003). The source parameters and associated uncertainties for modelling of a Laki eruption scenario were developed by the British Geological Survey who determined that once an eruption was underway and assuming the least favourable meteorological conditions for the UK (a strong north-westerly wind), there would be a minimum lead time of approximately six hours (Loughlin et al., 2013). A sustained supply of gas and aerosol from the source and unfavourable meteorology might maintain long-term (months) direct impacts in the UK (Loughlin et al., 2014).

Most of the risks associated with the eruption could be mitigated, given sufficient time to prepare for them, but there is work to be done in preparing guidelines to deal with hazards such as acid rain, increased levels of atmospheric pollutants, contaminated water, and the effect of aerosol on aviation (Loughlin et al., 2014). An effective response to an impending crisis will also require a much better understanding of plume chemistry and dispersion and its effects on the environment and on climate; there is a clear need to make these a research priority. Tracking volcanic clouds using satellites is now possible for eruptions in most parts of the world (**figure 6**), but there is clearly scope to improve coverage in both time and space (including depth resolution in the atmosphere). Air quality monitoring networks would require augmentation and coordination to be used as input to forecasting models. There are many examples of smaller scale gas and aerosol monitoring and alert systems that have been successful (e.g. Kīlauea, USA; Mijakejima, Japan), but there are particular challenges applying these kinds of strategies to large regions potentially to include the whole of northern Europe. A major breakthrough has been the development of sophisticated modelling of aerosol formation, transport and loss. Early models used Global Circulation Models to simulate aerosol formation and its effects on climate (Chenet et al., 2005; Highwood and Stevenson, 2003) but it was recognised that fully coupled chemistry and microphysics models were required in order to simulate aerosol size distributions (Schmidt et al., 2010). Recently, the atmospheric chemistry and metereology model NAME (Jones et al., 2007) has shown promise for modelling the physical dispersion and transformation of volcanic SO_2 to aerosol. Current modelling is exploring the likelihood of near-surface concentrations of sulfur and halogen species exceeding health thresholds and the effects of acid deposition on ecosystems (Witham et al., 2014). Whilst these models are sophisticated, it is important to note that all models inherently involve uncertainties; particularly significant here are the estimated volcanic ash emission rates (Witham et al., 2012). A striking new finding from modelling the effects of tropospheric SO_2 emissions from the 2014 Holuhraun eruption has been that the sulfate aerosol increases the albedo of liquid clouds, causing a radiative forcing that might have been observable, had the eruption continued into summer 2015 (Gettelman et al., 2015). Radiative forcing of this magnitude is sufficient to cause changes in atmospheric circulation and might be a feasible mechanism to explain the far-reaching climatic effects of the 1783 Laki eruption (Gettelman et al., 2015). Understanding how dominantly tropospheric SO_2 emissions from large Icelandic flood basalt eruptions may affect climate and ultimately European air quality is a critical component of mitigating risk from a future eruption. The recent eruptions of Eyjafjallajökull (2010), Grímsvötn (2011) and Holuhraun (2014) illustrate well that Icelandic eruptions have potential to disrupt aviation, our economy and air quality; the impacts of an even larger future eruption will undoubtedly extend into the realms of human health, agriculture and the structure of our society.

5. Perspectives for the future

We have shown that the hazards due to volcanic gases are diverse in terms of not only their chemical nature but also their impacts. Monitoring and modeling the hazards, producing effective warning or forecast systems and risk mitigation strategies are all associated with unique challenges not shared with other volcanic hazards. Gas hazards may be diffuse and affect a large area. While there have been examples of successful monitoring strategies that integrate observations into sophisticated models describing gas behavior, these are few and far between.

Future work requires innovative and far-reaching solutions to these monitoring challenges that can be applied in developing countries with minimal maintenance. Arguably the greatest strides are being made in modelling, with sophisticated models that couple chemistry with particle microphysics showing great promise as a monitoring and risk mitigation tool when combined with high quality ground- and satellite-based observations of volcanic emissions. Overcoming the challenges associated with educating populations with regard to gas hazards and maintaining effective communications is critical for future risk mitigation. Our greatest challenge may be a future large fissure eruption in Iceland, which may have significant consequences for air quality, our economy and environment in Europe and in North America.

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Figures

Figure 1: Cartoon to show the range of gas hazards and the scale of their impacts. A: Diffuse degassing through fractures and faults. These gases are sourced from deep magma reservoirs. They may persist for long periods between and during eruptions. They typically affect local areas only but present significant hazards to people when gases accumulate in basements and topographic lows. B: Acidic tropospheric plumes from active volcanic vents contain SO_2 and halogen gases. They lead to pervasive vog (sulfate aerosol) that may cause or exacerbate respiratory diseases. They may persist for many years during non-eruptive activity at some volcanoes and the plumes are dispersed over 10s of km. C: Sudden flows of cold CO_2-rich gases occur as a consequence of lake overturn or phreatic explosions. They may last only minutes but may travel many 10s of km in that time, flowing close to the ground with lethal concentrations of CO_2. D: Large explosive eruptions inject SO_2 directly into the upper troposphere or stratosphere. The resulting sulfate aerosol has potential to cause significant regional and/or global environmental and climatic effects that may lead to cooling and crop failure, acid rain, increased mortality and crop failure over years timescales.

Figure 2: Volcanic plume from the summit of Kīlauea Volcano, Hawai‘i. This plume contains acid gases and condensed water droplets, conducive to the formation of “vog” (volcanic smog, or sulfate aerosol). Photograph credit United States Geological Survey.

Figure 3: Condensed steam and CO_2 accumulating in a valley close to Timbang Crater, Dieng Plateau, Indonesia in 2011. Note the dead vegetation below the level of the gas as a result of the high CO_2 concentrations. Photgraph credit Andy Rosati, Volcano Discovery.

Figure 4: Hawaiian Islands, December 3, 2008, showing a pervasive tropospheric vog plume carried westwards from Kīlauea Volcano by the Trade winds. Image acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA’s Aqua satellite.

Figure 5: Model to forecast “vog” and communicate vog hazard warnings for the Hawaiian Islands. The model uses estimates of volcanic gas emissions along with forecast winds to predict the concentrations of sulfur dioxide gas (SO_2, left) and sulfate aerosol particles (SO_4, right) downwind of the ongoing Kīlauea Volcano eruption. Images from the Vog Measurement and Prediction Website (VMAP; http://weather.hawaii.edu/vmap), hosted by the School of Ocean and Earth Science and Technology, University of Hawai‘i at Manoa.

Figure 6: Risk mitigation during a future large eruption in Iceland will depend on effective monitoring and hazard forecasting, which will be possible with a new generation of satellite-based sensors e.g. ESA's Sentinal 5 Precursor mission. Here we show data from existing satellite-based sensors. The OMI instrument on Nasa's Aura satellite can image the spatial distribution (in x-y) of A: sulfur dioxide and B. sulfate aerosol in the atmosphere from volcanic eruptions. These simultaneous traces were recorded on 8 May 2010 during the Eyjafjallajökull eruption. (NASA). C: on April 17, 2010, during the same eruption, NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite captured this image of the Eyjafjallajökull Volcano ash and aerosol cloud, providing a vertical profile of a slice of the atmosphere.

Gas species	*Mode of dispersal*	*Type of hazard*	*In what quantity?*	*Acute effects*	*Chronic effects*
Sulfur dioxide, sulfate aerosol	Tropospheric gas plumes from vents or lava lakes Stratospheric injection during explosive eruption	Acidic irritant Climate-forcing, particularly in tropics	 More than a few Mt.	Upper airway irritation, pulmonary edema, nose, throat, skin irritation Tropospheric cooling lasting 10^0-10^1 years	Exacerbation of respiratory disease
Hydrogen sulfide	Diffuse degassing from the ground or from vents prior to or during eruptions	Irritant, asphyxiant, inhibitor of metabolic enzymes	Prolonged exposure > 50 ppm may cause death	Headache, nausea, vomiting, confusion, paralysis, diarrhea. Cough, shortness of breath, pulmonary edema. Eye and throat irritation.	
Fluoride compounds (HF, fluoride dissolved in water)	Tropospheric plumes during eruptions. Groundwaters and acid rain (through dissolution and/or leaching of ash particles)	Acidic irritant		Hypocalcemia, coughing, bronchitis, pneumonitis, pulmonary edema. Nausea, vomiting. Eye and throat irritation. Slow healing skin burns.	Permanent lung injury. Mottling or pitting of dental enamel. Osteoporosis, kyphosis spine.
Chloride compounds (HCl, other chlorides in gaseous and aqueous form)	Tropospheric plumes during eruptions. Groundwaters and acid rain. Plumes arising from the contact of lava and seawater.	Acidic irritant		Coughing, bronchitis, pneumonitis, pulmonary edema. Eye and throat irritation.	Permanent lung injury.
Carbon dioxide	Diffuse/vent degassing pre- or syn-eruption. Overturn CO_2-saturated lakes.	Inert asphyxiant		Asphyxia, collapse.	Paralysis, neurological damage.
Carbon monoxide	Diffuse/vent degassing between or prior to eruptions.	Noxious asphyxiant, binds to haemoglobin		Collapse, coma.	Paralysis, neurological damage.
Metals e.g. mercury Hg	Tropospheric plumes during eruptions, groundwater and diffuse degassing.	Oxidant irritant		Bronchitis, pneumonitis, pulmonary edema. Neurotoxicity.	Neurotoxicity.

Table 1: health effects of volcanic gases (Hansell and Oppenheimer, 2004).

Figure 1

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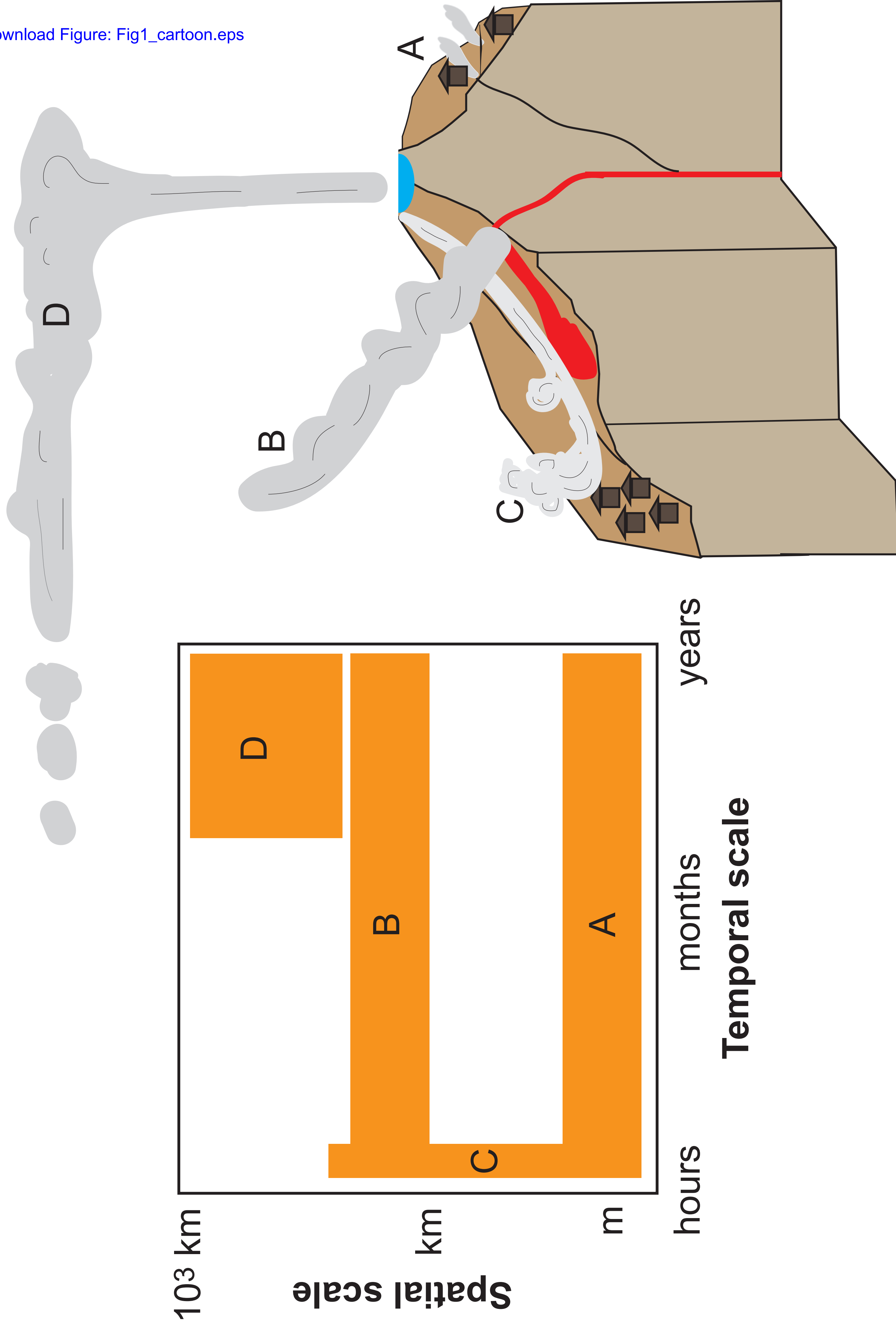

Figure 2

Click here to download Figure: Fig2_vog_Kilauea.jpg

Figure 3
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Figure 4

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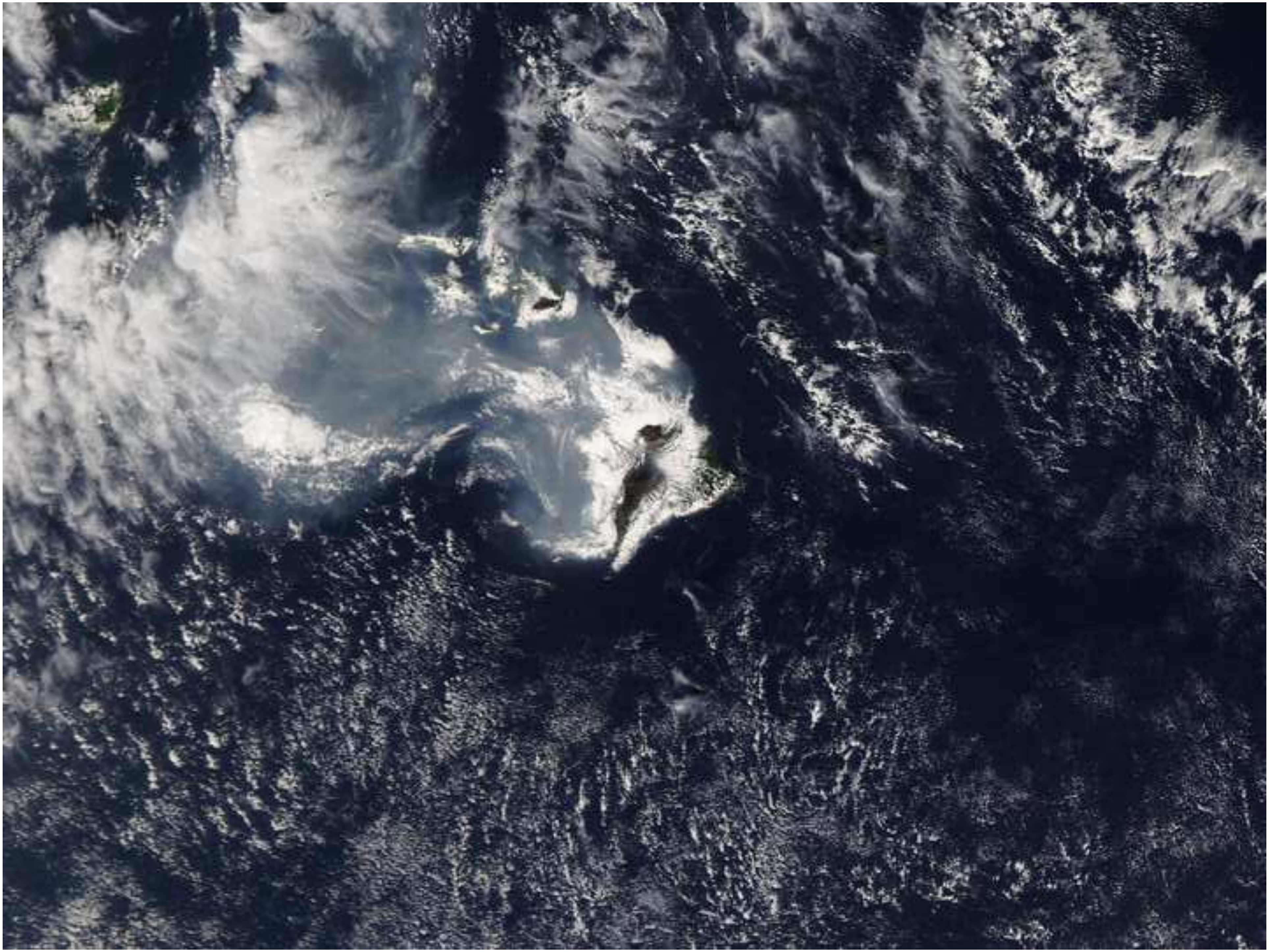

Figure 5
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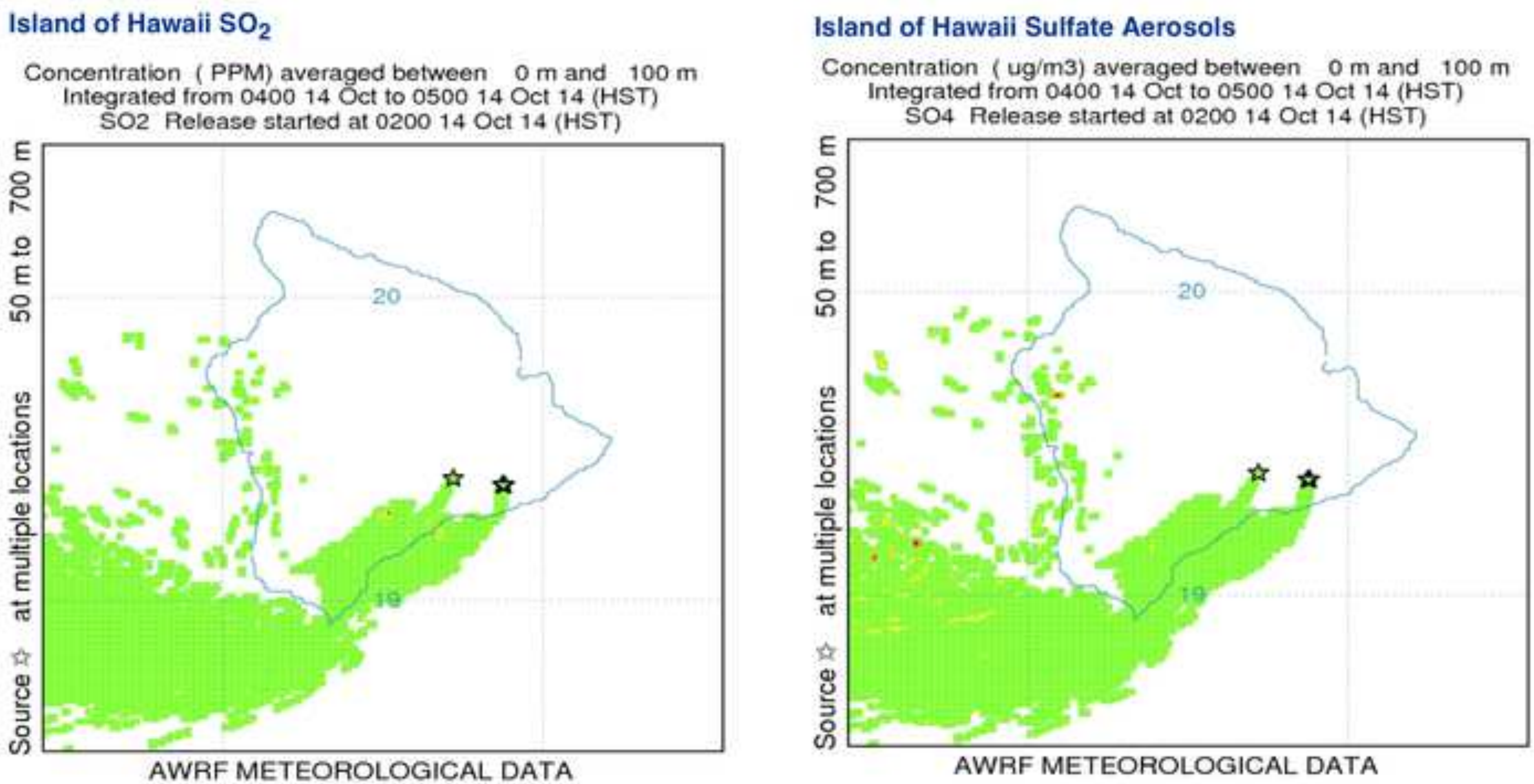

Figure 6
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