Institution: University of Bristol

Unit of Assessment: 7 – Earth Systems and Environmental Sciences

Title of case study: Volcanic Ash: Societal and economic damage from volcanic ash clouds reduced as a consequence of Bristol research

1. Summary of the impact

The ash cloud from the eruption of Iceland's Eyjafjallajökull volcano in 2010 caused the cancellation of over 100,000 flights and cost an estimated £3 billion. The much larger eruption of Grimsvötn (also in Iceland) the following year caused only 900 flights to be cancelled and its economic cost was around one per cent of that associated with the Eyjafjallajökull eruption. A key factor in this huge reduction was the improved understanding of ash clouds provided by researchers at the University of Bristol. Drawing on research conducted over two decades and immediately after the Eyjafjallajökull eruption, the Bristol team were able to inform and advise airlines and major decision-makers such as the Civil Aviation Authority, the UK Government and the European Space Agency. The input has since had a beneficial impact around the globe and has directly affected decisions and research strategies made by the Met Office and Rolls-Royce regarding operational developments associated with volcanic ash monitoring and forecasting.

2. Underpinning research

Professor Steve Sparks FRS (Channing Wills Professor, 1989-present), Professor Willy Aspinall (Cabot Professor in Natural Hazards and Risk Science, 2005-present) and Drs Matthew Watson (2004-present) and Stuart Kearns (1995-present) have written over 350 papers, spanning over 100 person-years of research on volcanology. Several strands of underpinning research place the School's academics at the forefront of their disciplines, and through that, at the focal points of discussion during and after the Icelandic ash crises. Specifically, these include the interpretation of fine ash in deposits **[1,2]**, the fragmentation and dispersion of ash **[1,4]**, statistical prediction of volcanic eruptions and repose periods **[5]**, volcanic plume dynamics **[1]**, expert elicitation **[3,5]**, Scanning Electron Microprobe (SEM) analysis of volcanic ash and glass **[6]**, and satellite observations of ash clouds **[4]**. Contributions from Bristol Earth Sciences researchers are described below:

Fragmentation, dispersion and deposition of volcanic ash are three fundamental processes that dictate an ash cloud hazard's severity and extent. The School, particularly Prof. Sparks, is responsible for seminal works on (i) mechanistic interpretation of ash layers in volcanoclastic deposits, (ii) relationships between clast size, column height and mass eruption rate, and (iii) the fluid dynamical behaviour of volcanic plumes and clouds **[1]**. Of several key parameters, composition and grain size in particular have a profound effect on the impact felt by drifting ash clouds during both airborne and depositional phases. Grain size and composition can be quantified using an SEM. Specifically, Dr Kearns' experiments, using novel techniques in electron microscopy including cryogenic electronprobe microanalysis, have been applied to a range of volcanogenic materials, and to the quantitative analysis of volcanic glass **[6]**. Using these techniques it is possible to assess the likely risk posed to populations upon exposure, a particular problem when fine, carcinogenic ash can be regularly remobilised **[2]**. At the other end of the observational scale, satellite remote sensing provides a synoptic perspective that facilitates whole-cloud observation **[4]**.

The Bristol volcanology remote sensing group, led by Watson, has developed new instruments and techniques for making high-resolution measurements of volcanic species **[4]**, and has used these to improve understanding of physical process and constrain uncertainty in observations of ash clouds. Such observations proved vital during crises, and techniques developed by Watson and others are used routinely worldwide by Volcanic Ash Advisory Centres (VAACs). The final strand of research expertise the group offered during this crisis pertains to the use of statistics to quantify risk **[3,5]**; their contributions pertinent to aircraft hazard mitigation are based upon statistical analysis of eruption likelihood given historical evidence, and the formalisation of decision making during crises through expert elicitation **[5]**.

3. References to the research

[1] Sparks, R.S.J., Bursik, M.I., Carey, S.N., Gilbert, J.S., Glaze, L.S., Sigurdsson, H., and Woods, A.W. (1997), *Volcanic Plumes*. Wiley publishing. ISBN: 978-047193901. Can be supplied upon request.*****

[2] Baxter, P.J., **Bonadonna, C.**, Dupree, R., Hards, V.L., **Kohn, S.C.**, Murphy, M.D., Nichols, A., Nicholson, R.A., Norton, G., Searl, A., **Sparks, R.S.J.** and Vickers, V.P. (1999), Cristobalite in volcanic ash of the Soufriere Hills volcano, Montserrat, British West Indies. *Science* 283 (5405): 1142-1145. DOI: 10.1126/science.283.5405.1142.*

[3] Sparks, R.S.J. and **Aspinall, W.P.** (2004), Volcanic Activity: Frontiers and Challenges. In: *Forecasting, Prediction, and Risk Assessment. AGU Geophysical Monograph "State of the Planet".* IUGG Monograph 19 (150): 359-374. DOI: 10.1029/150GM28.*

[4] Watson, I.M., Realmuto, V.J., Rose, W.I., Prata, A.J., Bluth, G.J.S., Gu, Y., Bader, C.E. and Yu, T. (2004), Thermal infrared remote sensing of volcanic emissions using the Moderate Resolution Imaging Spectroradiometer (MODIS). *Journal of Volcanology and Geothermal Research* 135: 75-89. DOI: 10.1016/j.jvolgeores.2003.12.017.

[5] Aspinall, W.P., Carniel, R., Jaquet, O., Woo, G. and **Hincks, T.** (2006), Using hidden multi-state Markov models with multi-parameter volcanic data to provide empirical evidence for alert level decision-support. *Journal of Volcanology and Geothermal Research* 153 (1-2): 112-124. DOI: 10.1016/j.jvolgeores.2005.08.010.*

[6] Humphreys, M.C.S., **Kearns, S.L.** and **Blundy, J.D.** (2006), SIMS investigation of electron-beam damage to hydrous, rhyolitic glasses: Implications for melt inclusion analysis. *American Mineralogist* 91 (4): 667-679. DOI: 10.2138/am.2006.1936.

4. Details of the impact

The total cost of the Ejyafjallajökull eruption has been estimated at £3 billion by Oxford Economics in 2010 **[a]**, with seven million passengers affected by the cancellation of 107,000 flights. The net impact on UK GDP has been estimated to be £466 million **[b]**. The eruption of Grimsvötn (Iceland) in 2011, a much larger eruption, only caused the cancellation of 900 flights, with subsequent costs being on the order of 1% of that caused by Eyjafjallajökull cloud. This is, in part, due to improved understanding of ash clouds and their likely impact on UK airspace and airports by decision makers, through advice provided by the School's experts **[c]**.

During the Iceland volcanic ash crisis of 2010, Sparks, Aspinall and Watson were invited to join the Scientific Advisory Group for Emergencies (SAGE) set up by Professor Sir John Beddington (then Chief Scientific Adviser to the UK Government) to "*report directly to the Prime Minister and Cabinet Office Briefing Room (COBR)"* meetings **[b]**. Bristol University was the only institution on the committee (made up of 20 academics and senior civil servants) to have more than one representative. This was a direct result of their recognition as leaders in their fields, specifically plume dispersion **[1]**, statistical volcanology and risk **[3,5]**, and satellite and microscopic observations **[2,4,6]**. The research experience of the Bristol academics was used extensively to drive discussion within SAGE on source terms for models **[d]**, particularly application of the 'Sparks curve' which relates column height (observable) to mass eruption rate (critical model source term) **[e]**. This curve provides the underlying capability for mass estimation that is vital during stages of an eruption where observations are sparse and *"forms the basis of the quantitative concentration predictions provided by the London VAAC for the ICAP European and North Atlantic Volcanic Ash Contingency Plan"* **[e]**. Sparks also emphasised the importance of near-source fall out of ash caused by aggregation, which has helped the Met Office to increase their confidence in the standard approaches used, and to obtain a better understanding of the variability that might be expected for different eruptions **[e]**. At these meetings, Aspinall led the discussion over concerns that Katla (a volcano close to Ejyafjallajökull with apparent near-simultaneous historical eruptions) could be triggered, and determined a likelihood for (i) a larger future eruption, (ii) the importance of including volcanic ash clouds in the national risk register **[b,f]**, and (iii) the need to better integrate (and assimilate) satellite observations into Lagrangian dispersion models. It has been recognised by the UK's Department for Transport that *"the advice given by SAGE following the eruption played an important part in the Government's immediate response, with the expertise of its members helping establish the evidence base needed to make difficult operational decisions"* **[b]**.

Clear pull-through is demonstrable from the recommendations of SAGE and the Volcanic Ash Observations Review Group (VAORG), with *"short-, mid- and long-term goals being set by VAORG for the London VAAC (based at the Met Office) for improving UK volcanic ash resilience"* **[b]**. In particular, the initial report (2011) from the VAORG to the Secretary of State lists four main recommendations to which the only three academics on the committee (Watson, Sparks and Aspinall) clearly spoke; these are to (i) constrain and reduce uncertainty (Sparks, Aspinall), (ii) improve observations and their usage, particularly for satellite observations (Watson), (iii) develop *a priori* source term development (Sparks), and (iv) utilise 'expert elicitation' (Aspinall). This last point details the use of a method that pools the opinions of a group of specialists, using differential weights based on empirical testing of their abilities to judge accurately any relevant uncertainties **[3,5]**. The goal is to quantify relevant uncertainties for appropriate inclusion in decision-making. Consequently, it has been acknowledged that *"the specific sector knowledge of Bristol University staff…has been a key factor in their [sic (SAGE and VAORG's)] effectiveness"* **[b]**, and *"the input of Prof. Sparks, Dr Watson and Dr Aspinall played an important role in this forum through enhancing understanding, quantifying risks and uncertainties, and enabling sound decision-making"* **[e]**. As a result, *"a number of these recommendations have been carried out, resulting in improved modelling and forecasting capabilities, leading to a more resilient aviation sector"* **[b]**.

The Icelandic crisis was international news for weeks. During this period, whilst also interacting with Government and the London VAAC, Watson, Sparks and Dr Jeremy Phillips (also School of Earth Sciences) made dozens of media appearances over various media formats. These include, for TV: Sky News, CNN, Channel 4 News, France24, BBC News 24; radio: BBC Radio 4's Today Programme and World at One, CBS, NPR (which operates a 38-station regional radio network in the US serving a regional population of 5 million people), BBC Radio Bristol, LBC, ABC Australia, and print: New York Times, Daily Express, El Pais, LA Times, Reuters, and Veja (a weekly news magazine in Brazil, the fourth most circulated in the world). As a result, millions of the public were informed about the crisis and were able to make better informed decisions.

"The Met Office and London VAAC have benefited directly from the work of and our interactions with…the School of Earth Sciences" **[e]**. Whilst the Met Office already uses the 'Sparks curve' to estimate mass eruption rate, Eyjafjallajökull and Grimsvötn presented very different challenges in terms of determining both an accurate mass eruption rate and particle size distribution. *"During both eruptions Sparks directed discussion on accurately estimating, based on his knowledge of how weak plumes are influenced by wind and how fragmentation processes control downwind particle size"* **[e]**. The School's interactions with the London VAAC have been communicated to other VAACs around the globe **[g]**, particularly around using the 'Sparks curve' adroitly. For instance, throughout the 2011 Grimsvötn eruption, Sparks *"was a key member of a new source refinement science group arranged by the Met Office to elicit expert advice and input on this complex issue as part of the London VAAC operational response"* **[e]**. Interactions between the Met Office and Bristol is illuminating fundamental near source volcanic processes and has resulted in the generation of a real world web based tool to improve VAAC assessment and evaluations **[g]**. These interactions typify best practice in terms of academic-operational relationships **[e]**. The underpinning research conducted by Bristol researchers has *"made an ongoing contribution to the research base and directly to decisions regarding operational developments associated with volcanic ash monitoring and forecasting…which is a major step forward in national capability"* **[e]**.

Socio-economic impact born of Bristol's research extends beyond interaction with politicians, decision makers and the public. Immediately after the Eyjafjallajökull crisis, Dr Kearns was asked by British Airways to investigate potential volcanic ash using microscopic techniques. Results of energy dispersive X-ray microanalysis on particulate material adhering to various external surfaces of several British Airways aircraft (leading edges of wings, jet cowlings, windscreens), suggest that amongst a range of materials found, many particles <3 microns had a composition similar to that known to have erupted at Eyjafjallajökull. Engine manufactures also have a critical position in hazard mitigation. Whilst improvements in detection and prediction (developed in part through Bristol's research) are demonstrable, if the amount of ash that causes engine failure is highly uncertain, hazard mitigation remains significantly more challenging. Bristol researchers have built an excellent partnership with Rolls-Royce through interaction with the engineering team responsible for environmental engine protection which "*has been invaluable in our understanding of ash cloud detection and modelling. The interaction has also contributed substantially to our understanding of the engineering effects ash has on engines, improved the guidance we give to our customers (i.e. airlines and the defence sector) on operating our engines in volcanic ash* *environments and influenced our volcanic ash research strategy. It also meant that Rolls-Royce is seen as a global centre of expertise on the effects volcanic ash has on aircraft engines*" **[h]**.

Immediately after the Eyjafjallajökull eruption, the European Space Agency (ESA) convened a workshop in order to quickly draft a position paper **[g,i]**. The document contains a series of recommendations that carefully detail observational strategies, missions and data protocols that are now being applied across Europe; "*Research from Dr Watson underpins the report and contributes, with others, to European (ESA, EUMETSAT, EU etc) efforts towards making European airspace safer and better managed with respect to volcanic ash*" **[g]**. This report has since been used to raise finances for 3 internal projects (totalling €2.5 million) to improve satellite data retrievals, provide web-based notification services about volcanic eruptions, and to improve ash dispersion modelling by the inclusion of satellite data **[g]**.

At the time of the Eyjafjallajökull eruption, aviation authorities were *"collectively ill prepared"*, and had a limited understanding of the science behind the eruption, the formation of the plume and ash dispersal **[c]**. However, *"independent, impartial and robust scientific advice and information, from a trusted body like Bristol University, enabled us to determine an appropriate course of action in the face of various sources of conflicting information from other parts of the science community, often in the face of intense media and political pressure to resolve the crisis"* **[c]**. Research conducted at Bristol has *"made a very significant overall contribution that has improved our collective ability to react to a major volcanic event that threatens UK airspace"* **[c]**. The CAA acknowledged that research and advice provided by Bristol's Earth Sciences enabled them to *"pursue the right strategic outcomes to the benefit of the UK as a whole without compromising public safety"* **[c]**.

Research conducted at Bristol has had broad-reaching and deep impact upon a broad range of beneficiaries (for example, politicians and civil servants, decision makers and risk managers, large multinational companies and the public). All are better informed thanks to the interaction with Bristol's internationally recognised academics, and will *"ensure that for any future event the UK is even better prepared to deal with volcanic ash events and serve to further limit the impact on the UK economy and transport infrastructure"* **[c]**. Volcanic hazards are now explicit in the National Risk Register **[f]**, and risk to aviation has been significantly reduced **[c,e,g,h]**. Volcanic ash clouds are better understood, monitored and predicted due to use of Bristol's extensive research efforts.

5. Sources to corroborate the impact

[a] Oxford Economics (2010) 'The Economic Impacts of Air Travel Restrictions Due to Volcanic Ash, Report for Airbus,' Technical report, Airbus. Available from: http://www.airbus.com/company/environment/documentation/?docID=10262&eID=dam_frontend_push

[b] Government Office for Science/Department for Transport. Joint Factual Statement.

[c] Civil Aviation Authority. Factual Statement.

[d] Minutes from the SAGE/DfT/VAORG meetings. Available (not limited to 21 April) from: http://www.bis.gov.uk/assets/goscience/docs/s/10-1371-sage-volcanic-ash-minutes-21-april-2010

[e] The Met Office. Factual Statement.

[f] HM Government National Risk Register (both 2008 (no ash), 2013 (including ash). Available from: https://www.gov.uk/government/publications/national-risk-register-of-civil-emergencies)

[g] European Space Agency. Factual Statement

[h] Rolls-Royce. Factual Statement.

[i] C. Zehner (Ed.) (2012) Monitoring Volcanic Ash from Space. ESA-EUMETSAT workshop on the 14 April to 23 May 2012 eruption at volcano, south Iceland (ESA.ESRUNM 26-27 May 2012). ESA publication STM-280. DOI: 10.5270/atmch-10-01. Chapters on current position (1) and recommendations (4) lead and co-authored respectively by Watson. Available from: http://earth.eo.esa.int/workshops/Volcano/files/STM_280_web.pdf