Institution: University of Bristol		
Unit of Assessment: 10) Mathematical Sciences		
Title of case study: Modelling volcanic ash plumes increases safety and reduces disruption for aviation and local communities		
Period when the underpinning research was undertaken: 2012 - 2018		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Andrew Hogg	Professor of Fluid Mechanics	01/1998 - present
Mark Woodhouse	PDRA Mathematics	2011 - 2015
Period when the claimed impact occurred: 1st August 2013 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Multidisciplinary research from the University of Bristol formulated a new fluid mechanical model that increases the accuracy of predictions of volcanic ash dispersal. The new mathematical model was embodied in a free-to-use, on-line tool, PlumeRise, with over 500 registered users, including 170 practitioners with responsibility for advising on airspace restrictions and closures during eruptions. The model and tool are used by UK and international regulatory bodies, including the Icelandic Meteorological Office and Darwin Volcanic Ash Advisory Centre (Australia), for real-time aviation decision making on airspace closures and during planning for eruptive scenarios. Predictions from the model and on-line tool also inform civil risk planning globally. The Bristol team has additionally trained practitioners, helped build capacity within international agencies and have engaged with the general public to improve understanding of volcanic plume dynamics and the hazard to aviation.

2. Underpinning research

Volcanic plumes rise through the atmosphere because they are buoyant due to the rapid transfer of heat between the erupted ash and the gases in which it is suspended. As the plume rises, it mixes with the denser atmospheric air, increasing its bulk density until it is no longer buoyant and begins to intrude horizontally through the atmosphere. The height to which the plume rises is determined by the strength of the source (i.e. the rate at which ash erupts from the volcanic vent into the atmosphere) and the atmospheric conditions, such as the atmospheric stratification and the wind field.

During the 2010 eruption of Eyjafjallajökull (Iceland) and earlier eruptive events, the strength of the source was deduced from empirical relationships between observations of the height of the rise and estimations of the eruption rate for historical eruptions. These relationships, the ‘Sparks’ or ‘Mastin’ curves, are dominated by the larger eruptions in the dataset, for which wind played little or no role. The 2010 eruption of Eyjafjallajökull challenged the international community to develop better forecasting tools. As part of the UK NERC funded VANAHEIM (Volcanic and Atmospheric Near-to far-field Analysis of plumes Helping Interpretation and Modelling) consortium, and with specific funding from NERC [A], Hogg and Woodhouse (School of Mathematics), together with Phillips and Sparks, (School of Earth Sciences), formulated a new quantitative mathematical model of the fluid dynamics of this motion. This model was based upon a representation of the fundamental fluid- and thermo-dynamics, expressed through conservation, or balance, laws and encapsulated in coupled differential equations. Crucially, they included the effects of the atmospheric wind field on the mixing processes to show that the height of rise is reduced by the wind if all other atmospheric processes remain constant. This is due to the increased rate of mixing between the plume and its surroundings [1]. This predictive mathematical model allows the height of rise to be calculated as a function of the source strength and other measurable atmospheric properties; alternatively, the model can be run in reverse to determine the source strength as a function of the observed height of rise and the atmospheric parameters.

Woodhouse et al. [1] showed that for the eruptions at Eyjafjallajökull, the temporal variations in the observed height to which its plume rose could be fully rationalised by the recorded variations in the wind speed. Furthermore, estimates of the eruption rate based on empirical relationships that do not feature any dependence upon the wind speed, could be underestimated by up to two orders of magnitude and thus ash concentrations may be similarly underestimated.

Subsequent research by the Bristol research team has applied history-matching methods to deduce statistical estimates of plume properties from observations [2]; investigated calibration and sensitivity of the mathematical model [3]; contributed to the international inter-model calibration exercise [4]; formulated a novel, well-posed model for the time-dependent motion that may result from temporal variations in the source strength or other processes (and demonstrated that previous models are ill-posed) [5]; and has contributed to the development of practical systems that allow for multiple observations to be combined within a suite of models [6].

The Bristol mathematical research into modelling volcanic plumes and the online tool, PlumeRise, were highlighted in *The Business of the Environment* (NERC Strategy 2013-18) and contributed to the award of Queen's Anniversary Prize (2015) to the University of Bristol volcanology research group.

3. References to the research

[1] **Woodhouse MJ, Hogg AJ,** Phillips JC, Sparks RSJ. (2013). Interaction between volcanic plumes and wind during the 2010 Eyjafjallajökull eruption, Iceland *J. Geophys. Res.* 118, 92-109. doi:10.1029/2012JB009592

[2] **Woodhouse MJ, Hogg AJ,** Phillips JC, Rougier JC. (2015). Uncertainty analysis of a model of wind-blown volcanic plumes. *Bull. Volcanol.* 77, 83. doi:10.1007/s00445-015-0959-2

[3] **Woodhouse MJ, Hogg AJ,** Phillips JC. (2016). A global sensitivity analysis of the PlumeRise model of volcanic plumes *J. Volcan. and Geotherm. Res.* 326, 54-76. doi:10.1016/j.jvolgeores.2016.02.019

[4] Costa A, *et al.* (**Woodhouse MJ, Hogg AJ**). (2016). Results of the eruptive column model inter-comparison study *J. Volcan. and Geotherm. Res.* 326, 2-25. doi:10.1016/j.jvolgeores.2016.01.017

[5] **Woodhouse MJ,** Phillips JC, **Hogg AJ.** (2016). Unsteady turbulent buoyant plumes *J. Fluid Mech.* 794, 595-639. doi:10.1017/jfm.2016.101

[6] Dürig T, *et al.* (**Woodhouse MJ**). (2018). REFIR- A multi-parameter system for near real-time estimates of plume-height and mass eruption rate during explosive eruptions *J. Volcanol. Geotherm. Res.* 360, 61-83. doi:10.1016/j.jvolgeores.2018.07.003

Research funding:

[A] **Hogg AJ** (Co-I), (Watson M (PI), School of Earth Sciences). Characterisation of the Near-Field Eyjafjallajökull Volcanic Plume and its Long-range Influence, NERC, 2011 – 2015, GBP547,999

[B] **Hogg AJ** (Co-I), (Phillips, JC (PI), School of Earth Sciences). FutureVolc, EC FP7-Environment. 308377, GBP48,000

4. Details of the impact

Airborne volcanic ash is a long-range hazard to lives and livelihoods and prediction of its atmospheric dispersion is vital for the accurate assessment of the risk that it poses. The Bristol model [1], enabling estimation of the mass eruption rate, and quantifying the strength of the volcanic source has been implemented in PlumeRise a free to use, web-based tool (www.plumerise.bris.ac.uk). PlumeRise has over 500 registered users and more than 95,000 separate calculations have been made for various eruptive scenarios from around the globe [a]. Users include over 170 practitioners and researchers in international and non-governmental agencies, including representatives from eight of the nine Volcanic Ash Advisory Centres (VAACs) and extensive usage by national agencies in Chile, Italy and Montserrat [a].

Increased safety and reduced disruption for aviation

Airborne ash poses a significant risk to the safety of aircraft flights, because of the possibility of severe engine damage. Nine global VAACs, created in 1997 by International Civil Aviation Organisation (an agency of the United Nations), advise airlines and regulatory authorities with the potential outcome that airspace is closed. Notably within UK and northern continental Europe, the 2010 eruption of Eyjafjallajökull (Iceland) led to the closure of airspace, the cancellation of more than 100,000 flights and an estimated economic loss across all sectors of USD5bn [b, c, d].

i) Real-time support to the Icelandic Meteorological Office

The most recent significant volcanic event in Iceland was the relatively long-lived Holuhran-Bardarbunga eruption (2014-15). The Icelandic Meteorological Office (IMO) held responsibility for monitoring and forecasting activities, both for Iceland, but also internationally. (During volcanic crises, the IMO, through a memorandum of understanding, feeds information to British Geological Survey (BGS) and UK Meteorological Office (UKMO), and the latter advises the London VAAC [b, c, e].) In their scenario planning, researchers at IMO operationally used PlumeRise to compute source conditions for their dispersion models. The lead scientist at IMO, comments *"At the time of the recent Holuhraun eruption (2014-15), the PlumeRise model was the only accessible plume model that could run with the real atmosphere"* and that *"we used PlumeRise to initialise dispersion models in our operational preparations and assessment of the potential hazards"* [e]. Furthermore, during the long-lived eruption, the Bristol team produced twice daily predictions of the potential heights of rise of the volcanic plume for a range of eruptions rates using the latest meteorological data; these plots informed the committee for Icelandic Civil Protection [e]. For future usage during volcanic crises, IMO consider PlumeRise to be one of the key tools that they will employ operationally [e]. Furthermore, the Group Leader at IMO concludes that *"it is inevitable that future eruptions in Iceland will occur and that some of these will have impacts in Iceland and beyond. The research conducted by the University of Bristol has contributed significantly to the IMO's institutional capacity to respond to volcanic eruptions."* [e].

ii) Long-term risk planning in the UK and internationally

The Bristol team have engaged frequently with the dispersion and air quality group of the UKMO, who work with the London VAAC. The Strategic Head of the group testifies that research outputs [1-6] have set the agenda for their institutional approach to plume modelling and the determination of the source term [c]. Furthermore, the freely available PlumeRise tool with its easy-to-use interface is "*hugely valuable to VAACs*" [c]. The operational usage of PlumeRise and [1] were explored in the UKMO report "Overview of volcanic ash mass eruptions rate estimation methods" [c], which determined that the model provides critical inputs to the determination of the concentration of airborne ash. PlumeRise has been used as part of UKMO training of VAAC forecasters to determine the effects of variations of source conditions on precited dispersion [c]. Additionally, the research has impacted the UKMO treatment of natural variability and uncertainty in the usage of relationships between the observed height of rise and the mass eruption rate and in future planning of volcanic scenarios through the EU-funded project, FutureVolc [B], which ran a series of mock events to test operational response [c].

The Darwin VAAC, staffed and trained by the Australian Bureau of Meteorology, has global responsibilities for monitoring threats to aviation over Indonesia and southern Philippines, regions that feature some of the world's most active volcanos. PlumeRise is a tool that they employ operationally, in planning exercises and in post-activity analysis [f]. For example, PlumeRise was used to determine the mass eruption rate of Rinjani, Indonesia (2016) to provide source conditions for ash dispersion predictions generated by the VAAC. Furthermore, the VAAC have developed a catalogue of eruption source parameters that are being used in ash dispersion modelling applications and PlumeRise was deployed to provide initial conditions for each volcano in the region [f]. This catalogue is now integrated in the operational tool that provides near real-time information for the VAAC forecasters. Recent examples of its use include the activity at Agung and Krakatau, Indonesia and Ulawun, Papua New Guinea (2019-20) [f]. The Bristol team have also provided the team at the Bureau with source code that implements the fluid dynamical model, which has been integrated with the numerical weather predictions. The PlumeRise webtool has been added to the VAAC forecasters toolbox for use during volcanic crises and the modelling framework and model outputs have influenced the Bureau's policies, procedures and own operational innovations [f]. The manager of the Darwin VAAC concludes that *"The PlumeRise model, web-interface and under-pinning research have contributed significantly to the work of VAAC Darwin and the Bureau of Meteorology, and therefore to the management of the ash hazard to aviation within our area of responsibility and more widely through our connections with the global VAAC network. The PlumeRise model supports our operational responsibilities, helping us to provide informative and science-based advice to the aviation industry."* [f].

Improved risk planning for civil society

Airborne ash has consequences beyond aviation, affecting population health and livelihoods. Following the Icelandic eruption, in 2012 'volcanic eruption' was added to the UK National Risk Register of Civil Emergencies. BGS have used the PlumeRise on-line tool to compute the effects of source variations and investigate uncertainty, thus *"providing robust information in our advisory capacity"* [b], including for the UK National Risk Register. The head of volcanology asserts that the research [1-6] and PlumeRise have *"led to significant changes in the way BGS assesses the hazard associated with volcanic ash and provides advice to government and non-governmental stakeholders".* Additionally, they are adopting a multi-parameter system for monitoring and forecasting (REFIR; [6]) in which PlumeRise as a key component [b].

In Mexico, over 26 million people live within 100km of Popocatépeti Volcano and are affected by ash fallout from its frequent eruptions during the past three decades. Ash dispersion is modelled quantitatively by the Centro de Ciencias de la Atmósfera and the national civil protection agency of Mexico (Centro Nacional de Prevención de Desastres) to forecast the hazard to communities. The strength of the volcanic source specified by [1] is a vital input to these computations [g]. The lead scientist further comments that over 15,8000 forecasts have been computed and that daily alerts have been issued since May 2015 using this methodology in which the source term specification of [1] plays a crucial role [g].

The 2010 eruption of Eyjafjallajökull provoked the international community to improve forecasting tools for volcanic plumes, and [1-6] and PlumeRise was part of the response [c]. The Bristol team were key contributors to an international exercise to collate and compare best practice in plume modelling and its operational use [4]. This plume intercomparison exercise, promoted by International Association of Volcanology and Chemistry of Earth's Interior (IAVCEI) and involving operational institutions as well as academic researchers, led to a volume of benchmarking studies in which the Bristol team played a leading role [h]. The outcome of this study underpins hazard assessment worldwide, including in Colombia, Indonesia and Japan, as noted by its coordinator, the Director of Istituto Nazionale di Geofisica e Vulcanologia (Bologna, Italy) [h]. He further confirms that the Italian Ministry of Education and Research has initiated an assessment of the resilience to the hazards posed by volcanic ash, motivated and informed by the intercomparison exercise [h].

The research [1-6] has also impacted other international agencies, including United States Geological Survey. Their scientific lead comments that [1] *"convinced me, and most of the modelling community that adding a cross-wind was essential if we were to use models to relate plume height to the mass eruption rate".* Furthermore, he remarks that PlumeRise "*has been a crucial advance*" and "*should be standard for operational 1D modelling*" [d]. Within his role as chair of Volcanic Ash Scientific Advisory Group, a body created in 2010 by the World Meteorological Organisation and International Union of Geodesy and Geophysics, he has advocated for the adoption of plume models by VAACs to initialise models of ash dispersion, highlighting PlumeRise *as "an exemplar of easy-to-use, robust and scientifically sound modelling tools"* [d].

Capacity building of practitioners

The Bristol team have delivered extensive training to international scientists with expertise on atmosphere dynamics [c, i]; underpinned the development and delivery of the undergraduate curriculum in volcanology at University of Lancaster; and built public understanding of volcanic plume dynamics. Woodhouse has delivered lectures and run workshops at the 1st-5th International Training Schools on Convective & Volcanic Clouds (Italy, 2015-19) on the dynamics of volcanic plumes, drawing his material from [1-6] and using PlumeRise to run through practical examples [c, i]. The organiser of the workshop confirms its reach, with participants drawn globally from 38 countries and several attendees now holding operational roles with national agencies [i]. He highlights Woodhouse's vital contribution in "*ensuring research methods are propagated rapidly and effectively to operational users*" [i].

The Programme Director for Environmental and Earth Science degrees (BSc and MSci) at the Environment Centre, University of Lancaster confirms that PlumeRise is an integral part of their module on Physical Volcanology and some final year dissertations [j]. Students are lectured on the motion of buoyant plumes and explore the mathematically-modelled dynamics using PlumeRise, which provides them with access to a state-of-the-art fluid dynamical model, without the entry barrier of research level expertise in mathematics and numerical computation. The use of PlumeRise contributes 30% of the module assessment. For these reasons, PlumeRise is judged to be a crucial part of their curriculum [j].

Improving public engagement with mathematics

Finally, the Bristol team has presented its results to the general public through open days, national science fairs (*Into the Blue*, NERC science showcase, Manchester 2016; *Big Bang* Exeter, 2017 and Bristol, 2017) and the Bristol-based *Pints of Science,* 2017. These events had considerable reach and attracted over 15000 visitors, and at *Into the Blue*, the stand was voted as the best exhibit by the visiting public. Well-received sessions with Year 6 classes in Bristol schools have also been run to explain the hazard to aviation from airborne ash and its prediction through mathematical modelling, using interactive games and classroom challenges. Feedback from the pupils included *"I learnt that you can use mathematics to predict volcanos"* and *"mathematics can calculate the height of ash clouds",* which evidence success in communicating this research to a wider audience.

5. Sources to corroborate the impact

[a] Report of registered users of PlumeRise and model computations (2020).

[b] British Geological Survey (2019). Factual Statement from Head of Volcanology.

[c] i) UK Meteorological Office (2020). Factual Statement from Head of Atmospheric Dispersion & Air Quality Group, (including ii) Overview of Volcanic Ash Mass Eruption Rate Estimation Methods, UKMO (2016) and iii) presentation to Volcanic Ash Workshop, 2015, doi:10.13140/RG.2.1.1887.4964).

[d] United States Geological Survey (2020). Factual Statement from Plume modelling lead and co-chair of Volcanic Ash Scientific Advisory Group.

[e] Icelandic Meteorological Office (2019). Factual Statement from Group Leader of Atmospheric Research.

[f] Australian Bureau of Meteorology (2020). Factual statement from VAAC Manager.

[g] Centro de Ciencias de la Atmósfera, Universidad Natcional Autónoma de México (2020). Factual Statement from Research Scientist.

[h] Instituto Nazionale di Geofisica e Vulcanologia, Italy (2019). Factual statement from Director.

[i] Università degli Studi di Padova, Italy (2020). Factual statement from Organiser and Founder of Convective and Volcanic Ash Clouds workshop.

[j] University of Lancaster (2019). Factual statement from Programme Director for Environmental and Earth Sciences.